CLIMATE SCIENCE

A perspective for business leaders

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GLTE

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FOREWORD

Climate change is rewriting the competitive landscape. Regulation, investment flows, and customer preferences – all are pushing businesses to reinvent the way they grow. Far-sighted business leaders are responding now to these forces. Not only do they see the risks that this transition will bring; more importantly, they also appreciate the opportunities that will be generated in the shift to a low-carbon economy.

However, many feel hampered by a widespread lack of understanding, or in some cases a deep scepticism relating to the underlying climate science that is driving this agenda. That is why I initiated this project, with the aim to provide an independent, clear, logical and compelling analysis of the state and frontiers of climate science, in a form that is tailored to the needs of business leaders, senior executives and other key stakeholders.

I am delighted that Royal Dutch Shell, DNV GL and Tata Consultancy Services have joined Statkraft in sponsoring this project. Together we hope that the information this document provides will help businesses create a hard leverage point for positive change based on the latest scientific frontiers, and enabling executives to make more informed decisions.

Christian Rynning-Tønnesen, CEO, Statkraft

This report will be periodically updated to reflect the latest climate science. Visit **www.xynteo.com** to read the up-to-date version.

1. EXECUTIVE SUMMARY

We need greenhouse gases. Carbon dioxide, water vapour and other trace gases act to trap heat and keep the planet warm. Without them Earth would be frozen and lifeless.

But you can have too much of a good thing. Since the Industrial Revolution, humans have been emitting large quantities of greenhouse gases, mainly by burning fossil fuels and turning forests into farmland. This has raised global temperature and had a host of other effects on our climate.

Despite its importance to informed decision-making, climate science has become a controversial and poorly communicated topic. Virtually all scientists agree that the climate is changing and that human activities are driving most of that change, while outside the scientific community these conclusions are often doubted. Most of the non-technical literature on climate change is often skewed by politics or prejudice.

We believe that business leaders need an unbiased view of the evidence, so **our objective is to present the latest climate science in an accessible form and unfiltered through a political agenda.**

The deadly and destructive Hurricane Sandy hit in 2012, becoming the second-costliest storm in US history.

Climate change is already evident in many of Earth's systems. Global temperatures are rising, and so are sea levels. Glaciers are melting and permafrost is thawing. Oceans are becoming more acidic. Rainfall patterns are shifting, while some forms of extreme weather are becoming more frequent and severe.

These effects are almost certain to intensify over the 21st century. For businesses they will present new risks and new opportunities. Understanding the up-to-date scientific findings is critical for CEOs, senior executives and anyone who wants to remain informed and competitive in a warming world.

Large-scale reviews of climate science are published elsewhere, notably by the Intergovernmental Panel on Climate Change (IPCC). The first part of their Fifth Assessment Report on climate science (AR5) was published in September 2013.

This document is not intended to be an abbreviated version of that thousand-page review; rather it is **a focused analysis of the latest findings that are most relevant for business**. In assembling these findings, we have used scientific reports from both within and outside the IPCC, seeking out the most relevant and reliable research from many of the world's most respected scientific institutions. Nevertheless the IPCC's latest report is a convenient reference point and will be cited throughout the text.

FAST FACT

The effects of **climate change** are almost certain to **intensify** over the 21st century

KEY MESSAGES:

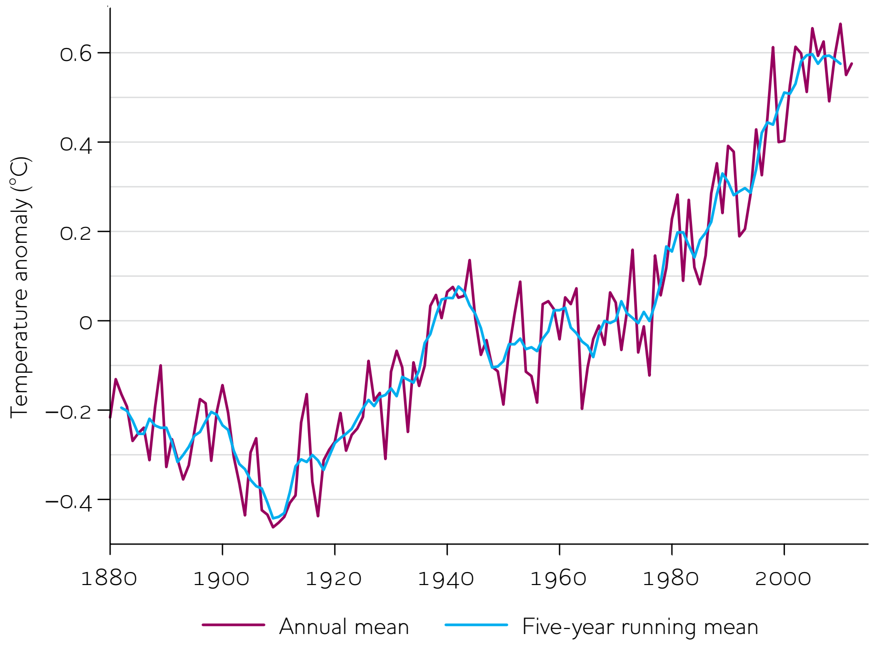
- Greenhouse gases emitted by human activities are responsible for most of the warming observed in recent decades. Although natural factors such as changes to the sun's output and volcanic activity also affect the climate, they cannot explain recent warming.
- Earth has warmed by about 0.85°C since the beginning of the last century. If carbon emissions follow the present high trajectory, by the end of this century temperatures are projected to reach 3.2 to 5.4°C above pre-industrial levels.
- Continued warming will have other effects on the climate system by the end of the 21st century, including:
  - A rise in global sea level that could reach 1.5 metres.
  - More heatwaves and droughts.
  - More storms and floods.
  - Impaired supplies of fresh water.
  - An increase in the ocean's acidity by 100 to 200% above pre-industrial levels.
  - Loss of ice, snow and permafrost.

2. HOW THE EARTH IS WARMING

Overview

Average global temperature **increased by about 0.85°C between 1901 and 2012**. Most of that, **around 0.72°C, has occurred since 1951** (see figure 1).[1]

FIGURE 1: GLOBAL TEMPERATURE



Temperatures measured by weather stations, ships and satellites, are used to calculate this global average across land and sea.

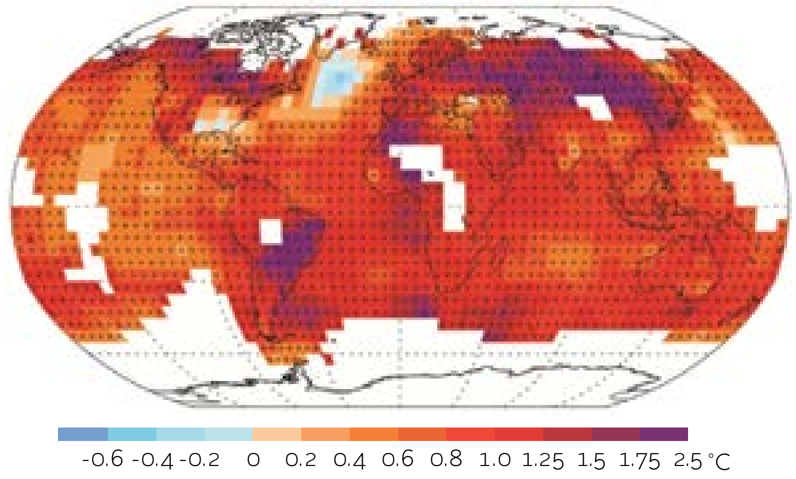
(Source: Adapted from NASA Goddard Institute for Space Studies. Plotted relative to the average temperature from 1951 to 1980.)

Warming is not uniform (see figure 2). For example, **Arctic temperatures have increased much faster than the global average rate** over the past century.[2]

The rate of warming varies over time owing to short-term factors, including natural climate cycles.[3] For example, there was little if any rise in average air temperatures in the period from 1998 to 2012,[4] which is most likely the consequence of a cool phase in the tropical Pacific ocean (see section 3, 'The role of natural factors').

Oceans absorb heat and so act as a buffer for rising temperatures. Since 1955, the top 700 metres of the ocean has warmed by an average of 0.18°C and the top two kilometres by 0.09°C,[5] **accounting for 90% of the energy the Earth has gained since the 1960s**.[6] Heat is also reaching the deep ocean below 4,000 metres.[7]

FIGURE 2: LOCAL WARMING 1901–2012



Climate change varies strongly from place to place. Some of the greatest warming is far inland and near the poles.

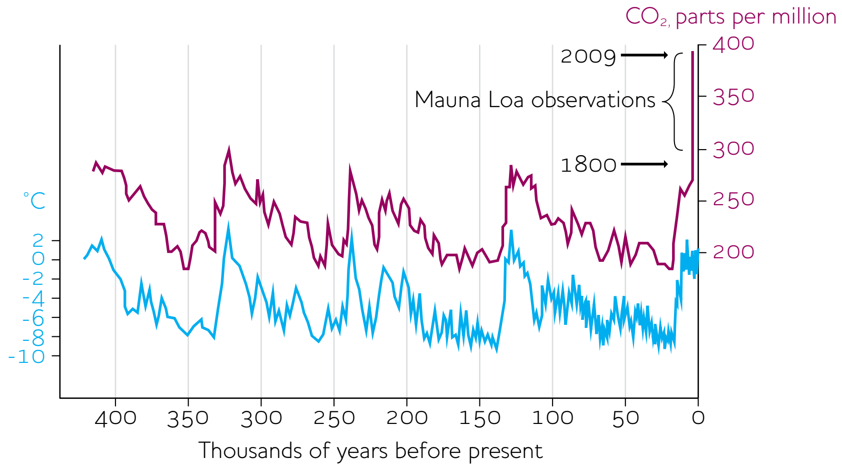
(Source: IPCC Fifth Assessment Report)

To put the rate of this recent warming in perspective, scientists have reconstructed past temperatures on many different timescales. Measurements from weather stations give a robust global temperature record back to about 1850. Further back in time scientists can calculate temperatures approximately using ice cores, ocean sediments, corals, tree rings and pollen buried in ancient lake mud.

Sediments hold the fossil skeletons of small organisms that preserve chemical clues to the climate going back many millions of years. They show that 50 million years ago, for example, the Earth was around 10°C warmer than today.

Ice cores give us a detailed temperature record back for about 800,000 years (see figure 3). Over this period the climate has repeatedly shifted between ice ages – up to 8°C colder than today – and mild interludes similar to the last few thousand years.[8] Warming and cooling have often happened rapidly**, but there is no evidence that Earth has warmed as quickly as it is doing today for at least 50 million years.**

FIGURE 3: ANCIENT AND MODERN



Air bubbles in Antarctic ice reveal that temperature has tracked CO_2 closely for hundreds of thousands of years. Modern measurements show that CO_2 is now far above this prehistoric range.

(Source: Adapted from Woods Hole Research Center.)

AS WELL AS WARMING

More evidence for climate change:
- Ice, snow and permafrost is melting
- Sea level is rising
- There are more heatwaves and heavy rainstorms
- The growing season in northern latitudes is becoming longer
- The geographical ranges of species and diseases are changing

— FAST FACT —

The **climate** has **changed** in the past but never before **this quickly**

An increase of 0.85°C seems small compared with seasonal and daily variations, but it is already enough to make extreme high temperatures much more frequent. Mean summer temperatures that would have been anomalously high in the middle of the last century (occurring on average less than 0.2% of the time in a given location) became quite commonplace by the period 2006 to 2011, happening 4 to 13% of the time.[9] As well as shifting the range of variation to higher temperatures, climate change may also increase the severity of these variations.[10]

What we have learned recently

1. **The Arctic may be warming faster than ever.** Over the past century, the Arctic has warmed at about twice the global average rate. For the decade from 2000 to 2010, one study shows a rate three to four times the global average.[11]
2. **The Southern Hemisphere is also warming.** Previous temperature data had been much sparser than for the north, and showed no evidence of warming over Antarctica. New data shows that that the Southern Hemisphere is definitely warming, including most of continental Antarctica.[12]

Ice, snow and permafrost are melting at an alarming rate.

3. THE ROLE OF NATURAL FACTORS

Overview

Before the Industrial Revolution, climate varied in response to natural events such as volcanic activity and changes in the amount of energy arriving from the sun. These things still play their part today. Several volcanic eruptions during the 20th century appear to have had a brief cooling effect, for example. Natural factors that affect the climate come in two main categories – external factors and internal variability.

External factors change the amount of heat entering or leaving the climate system:

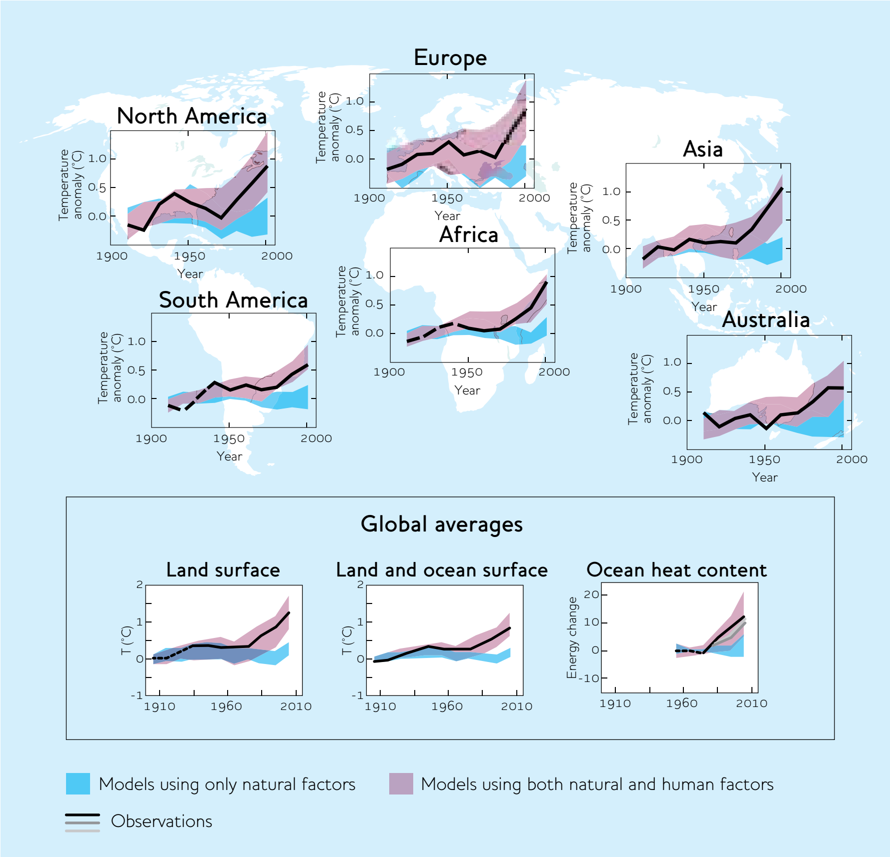
- The activity of the sun affects the amount of solar radiation that reaches Earth (see section 3a).
- Cycles in our orbit change the amount of sunlight reaching Earth over millennia.
- Volcanic eruptions add particles to the atmosphere that block sunlight and can cool the Earth substantially for a year or two.
- Natural changes to the Earth's carbon cycle – from volcanic eruptions and shifts in ocean circulation, for example – alter the concentrations of CO_2 and methane in the atmosphere.

Internal variability moves heat around within the climate system:

- Climate patterns such as the El Niño/La Niña-Southern Oscillation can move heat between ocean and atmosphere, affecting air temperature over periods of up to a few decades (see 'What caused the hiatus', page 11).[13]

All of these factors operate on different timescales and many have different regional impacts. However, climate models consistently find that natural factors alone cannot explain the warming seen over the past half century[14] (see figure 4). According to the IPCC's 2013 report, it is "likely" (more than 66% probability) that natural external factors have affected global temperature by between -0.1 and +0.1°C since 1951, and the same for internal variability.[15] The remaining warming over that period is "extremely likely" to have come from human activity (see section 4; and for the IPCC's definitions of likelihood see Appendix, page 42).

FIGURE 4: FINGERPRINTS



Blue shading marks the range of climate model results for simulated worlds where only natural factors affect temperature. Purple marks models in which both natural and human factors are included. The black lines mark observations. This shows that the pattern of warming in time and place does not match natural factors alone – human emissions must be included.

(Sources: IPCC Fourth and Fifth Assessment Reports)

Volcanoes disgorge fine particles into the the atmosphere that can cool the planet for a year or two.

WHAT CAUSED THE HIATUS?

After a period of rapid temperature rise from around 1970, warming of the atmosphere slowed down or stopped over the last 15 years. From 1998 to 2012, the warming trend was between -0.05 and +0.15°C per decade.[16]

Because of internal variability in the climate system, **such decade-long pauses are to be expected.**[17] The early and mid-20th century even saw periods of cooling.

In their AR5 report, **the IPCC attributed the recent hiatus to a combination of three things** – internal variability, cooling by airborne particles from volcanic eruptions, and the downward phase of the solar cycle.[18] However, they gave *low confidence* to the contribution from particles, and the solar effect is small (see section 3a).

The latest research suggests just one main cause: heat being absorbed by the ocean. Several models now come to this conclusion.[19] For example, a model that incorporates observed water temperatures in the Pacific can reproduce the hiatus in global air temperature.[20] It also fits the regional pattern of measured temperature changes, and the seasonal pattern (while global winter temperatures fell from 1998 to 2012, summer temperatures continued to rise).

So the hiatus was probably caused by **cooler water coming to the surface in the tropical Pacific and absorbing heat from the atmosphere.** This is very similar to the well-known La Niña cooling pattern, but longer lasting. Climate models do generate such sea-surface fluctuations, but as yet they are unable to forecast *when* such phenomena will happen – a block to decade-scale climate forecasting.

Models suggest that during such pauses, most of the heat sucked from the atmosphere is carried down to the deep ocean below 300 metres.[21] Ocean temperature measurements are not yet precise enough to confirm this for the period 1998 to 2012, although they do show that the heat content of the oceans continued to increase – so the planet as a whole was still warming.

If this picture is right, then **when the tropical Pacific switches back to a warm surface state, global warming will accelerate.**

What we still need to learn

1. **Clouds are a large source of uncertainty.** Clouds reflect sunlight, trap heat from below, and radiate their own heat to space. The net effect of low-level clouds is to cool the planet, while high-level clouds have a warming effect. The question is how clouds will be affected as temperature rises: will they amplify or dampen global warming? Models have not been very effective at capturing individual cloud formation, mainly because it happens on scales too fine for these simulations to handle explicitly. Particles from human and natural sources also affect the formation and properties of clouds by uncertain amounts.[22] But the match between models and observations is improving,[23] and some recent research indicates that higher temperatures may reduce the amount of low-level cloud-cover – which would amplify warming.[24]

FAST FACT

Changes in the **sun** cannot explain **recent warming**

2. **Internal variability is not fully understood**. Some natural fluctuations in weather and ocean circulation could have an appreciable effect over periods of a few decades,[25] and one study suggests that internal variability may have been responsible for as much as a third of the late-20th century warming.[26] Global warming may also change the pattern of natural climate cycles.[27]

The role of solar variation

The sun is not constant. Over the past four billion years it has grown about 30% brighter, and its light output varies on shorter timescales as well. However, there is no evidence that variations in the sun could be responsible for the warming of the past few decades.

Since 1978, researchers have used satellites to reliably measure the intensity of sunlight reaching Earth. They see that over an 11-year cycle the sun regularly brightens and fades again.[28] The overall intensity of sunlight changes by about 0.1% during each cycle, enough to have some effect on global temperature. [29] A fading sun has probably made a small contribution to the recent warming hiatus. But with a regular 11-year cycle up and down, this variation cannot account for the global warming observed over several decades.

Some researchers have **claimed that there may be a longer-term upward trend in solar output** over recent centuries. A study in 1995 suggested that such a trend could account for half of the observed global warming since 1860.[30] However, this calculation was based on assumptions that have now largely been refuted (for example, observations of other sun-like stars seemed to show that they could be in high and low states of activity, but more recent data show that these are in fact two chemically different types of star).

A more recent physical model of the sun's magnetic activity suggests **a very gradual brightening by about 0.1% since the 18th century,**[31] which would be enough to raise global temperature by no more than about 0.15°C.[32]

And over the past few decades, **satellite observations show no sign of an increase in solar brightness between cycles.**[33]

INDIRECT EFFECTS

Less obvious effects of solar variation could influence our climate:

- During each solar cycle, the sun's output of **ultraviolet radiation can change by about 1.3%**. In the fading phase of the last cycle, from 2004 to 2007, the decline in UV was even greater.[34] Ultraviolet heats the stratosphere and affects the pattern of high-altitude winds. The effect on global temperature is not clear, however.
- Energetic particles from deep space called cosmic rays may help to seed clouds on Earth.[35] When the sun is at a high point in its cycle, its magnetic field shields Earth from cosmic rays. In theory that could reduce cloud cover and warm the planet. But since the 1950s there has actually been a slight upward trend in cosmic rays detected on Earth, so this mechanism does not seem to be contributing to global warming.

4. THE ROLE OF HUMAN ACTIVITY

Overview

Climate scientists agree that the main factor behind global warming is human emission of greenhouse gases (GHGs) – primarily carbon dioxide, CO_2. **The level of CO_2 in the atmosphere rose from about 280 parts per million (ppm) during pre-industrial times to 393 ppm in 2011. For a week in May 2013 it exceeded 400 ppm. It is now higher than at any time in at least the past 800,000 years.**

The increase is also much faster than in previous episodes of climate change.[36] Bubbles of ancient air trapped in ice cores show that at the end of each ice age, CO_2 rose by only about 80 ppm over a period of 5,000 years[37], which in prehistoric terms amounts to a sudden climatic transition.

All the available evidence strongly suggests that this rise in greenhouse gases has caused the majority of the recent rise in global temperature. First, climate models can match the warming observed over the past century only by including the effects of greenhouse gas emissions (see figure 4). In addition, the geographical pattern of warming matches that predicted from an increase in greenhouse gases, as does the fact that the stratosphere is cooling, and that night-time temperature is rising faster than daytime. Recent research has **reinforced the conclusion that human emissions of GHGs are responsible for most of the warming observed in recent decades**.[38] According to the IPCC's 2013 report, **"It is extremely likely (more than 95% probability) that human influence has been the dominant cause of the observed warming since the mid-20th century".**[39]

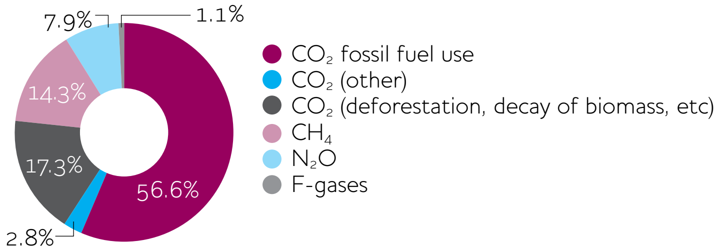
Human greenhouse gas emissions are responsible for most of the global warming of recent decades.

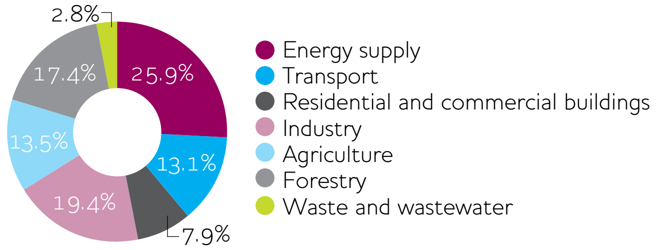
FAST FACT

Carbon dioxide levels have **increased** by about **40%** in the past 2 centuries

GREENHOUSE GASES

Greenhouse gases (GHGs) are generated by various natural and human sources (see figure below). They trap infrared radiation emitted by Earth's surface and atmosphere. That reduces the flow of heat to space and therefore warms the planet.





Source: Adapted from IPCC Fourth Assessment Report

Long-lived GHGs persist in the atmosphere for years to millennia, continuing to warm the climate long after they are first emitted:

- **Carbon dioxide** levels have increased by about 40% in the past two centuries, mainly due to the use of fossil fuels and deforestation. Some of the CO_2 being emitted now will remain in the atmosphere for many centuries.
- **Methane** is generated by agriculture (especially livestock), fossil fuel production, and the disposal of waste in landfill, as well as by natural sources including wetlands and oceans. Methane is a much more powerful greenhouse gas than CO_2, but is lost from the atmosphere in a few decades.
- **Nitrous oxide** is emitted by artificial fertilisers, and also in small quantities from fossil fuel combustion.
- **Halocarbons** (eg, chlorofluorocarbons) are the most powerful GHGs and some persist for millennia, but they are present in very small quantities. They were used as refrigerants and in other products and industrial processes before they were found to damage the ozone layer in the upper atmosphere, and were regulated internationally.

GREENHOUSE GASES

Short-lived GHGs persist from days to months:

- **Tropospheric ozone** (ozone in the lower atmosphere) is created by chemical reactions with carbon monoxide, nitrogen oxides, methane and other gases, all of which are emitted during human activities.
- **Water vapour** is the most abundant GHG in the Earth's atmosphere. Human activities have only a small direct influence on levels of water vapour, but a large indirect influence because rising temperature increases the atmosphere's capacity to hold moisture. That means water vapour acts as an internal feedback to amplify climate change. It also exerts more complex effects by forming clouds (see section 3).

OTHER HUMAN EFFECTS

As well as our GHG emissions, human activity can affect the climate through:

- **Black carbon**, or soot, from burning vegetation, wood and fossil fuels. It absorbs sunlight and so heats the atmosphere.
- **Sulphate particles**, from industrial pollution. These reflect sunlight and cool the atmosphere.
- **Changing reflectiveness of Earth's surface**. For example, replacing forests with agricultural land or desert increases the amount of sunlight reflected.

What we have learned recently

Black carbon plays a greater role in warming than we thought. A new study estimates that soot emitted by fires and fossil fuels is the second most important human influence on the climate, after CO_2, and says that many models underestimate the effect of black carbon by a factor of three.[40]

5. WHAT THE FUTURE HOLDS

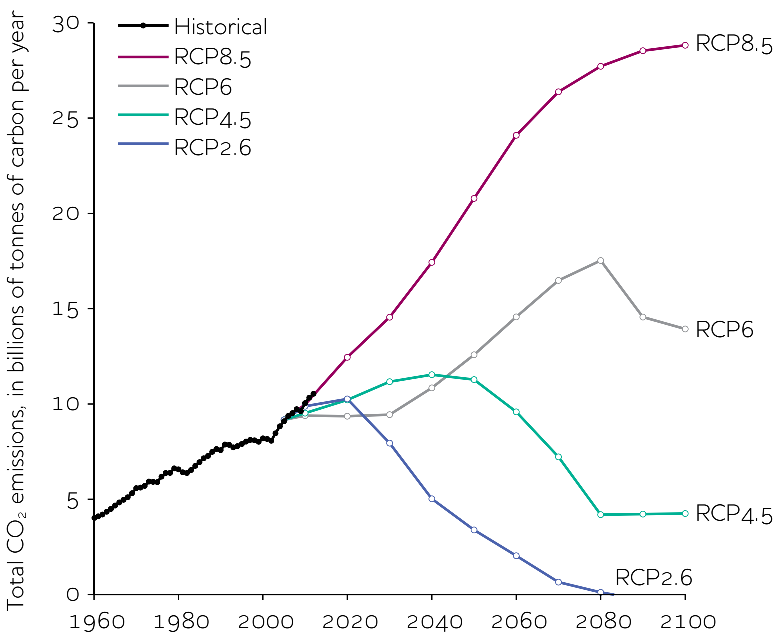
5a. GREENHOUSE GAS EMISSIONS

Overview

Four different futures are used for climate projections in the AR5. These "representative concentration pathways" (RCPs) cover a range of possibilities for population, technology and economic development.[41]

At the high end, RCP 8.5 reflects "business as usual": rapid population growth and slow adoption of new technologies, resulting in high carbon emissions. By contrast, RCP 2.6 assumes very strong mitigation, with emissions falling rapidly after a peak in the early 21st century (see figure 6).[42] Practically speaking, we can call these worst-case and best-case outcomes, respectively.

FIGURE 5: PATHS FOR THE FUTURE



Four future emissions pathways are used in the latest climate models, ranging from the high end "business as usual" RCP 8.5, right down to a future of aggressive mitigation, RCP 2.6, in which net CO_2 emissions actually go negative by the end of the century. (The International Energy Authority [IEA] uses a different set of emissions scenarios running to 2035. The IEA 450 scenario is close to RCP 2.6. IEA New Policies is fairly similar to RCP 4.5, while IEA Current Policies is about half way between RCP 6 and RCP 8.5.)

(Source: Adapted from Glen Peters/ CICERO)

Peak temperature will depend more on cumulative emissions than their timing. To have a 66% chance of staying within a 2°C warming target, the **cumulative global emissions budget is estimated at 1,000 billion tonnes of carbon.**[43] (That is considering only CO_2 emissions. If methane and other more powerful greenhouse gases are included, the budget goes down to 800 billion tonnes or less). About 530 billion tonnes had already been emitted by 2011.

DRIVING EMISSIONS

Up:

- **Population growth**. All else being equal, more people will consume more resources, releasing more greenhouse gases.
- **Economic growth**. All else being equal, growth will tend to mean higher resource consumption and rising emissions.

Down:

- **Technology**. Technological development in energy generation and use could reduce the amount of greenhouse gases emitted per person or per unit of GDP.
- **Carbon mitigation**. Deliberate measures could be taken to reduce greenhouse gas emissions or remove them from the atmosphere.

NOW	2100
In 2011, the mean global concentrations of the main greenhouses gases were measured at:[44] • CO_2: 391 parts per million (ppm) • Methane: 1,803 parts per billion (ppb) • Nitrous oxide: 324 ppb	**In 2100, gas concentrations set by the various pathways used in AR5 range from:**[45] • CO_2: 421 ppm (for RCP 2.6) to 936 ppm (for RCP 8.5) • Methane: 1,254 to 3,751 ppb • Nitrous oxide: 344 to 435 ppb

Approximately 530 billion tonnes of carbon had already been emitted by 2011.

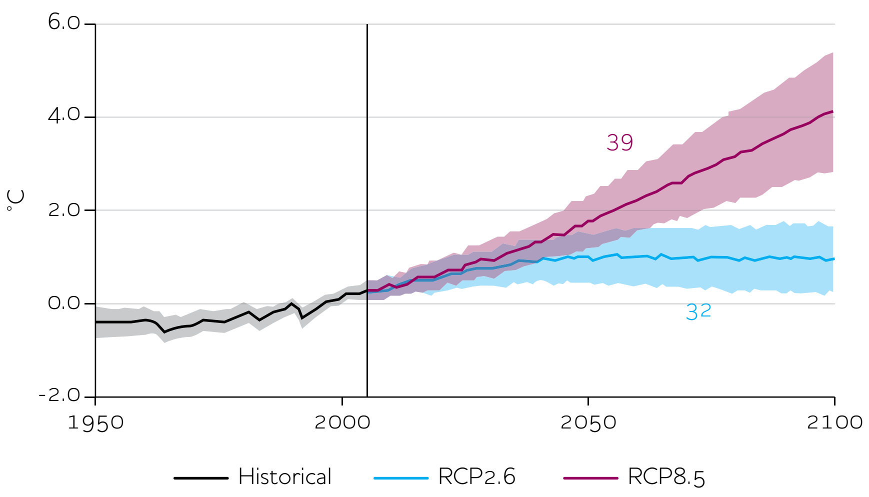
5b. WARMING

Overview

Because the oceans act as a buffer, the atmosphere does not respond instantly to increasing greenhouse gases; instead there is a time-lag in atmospheric warming. This means that greenhouse gases already emitted by human activity have locked the planet into 0.3 to 0.7°C of warming, on top of the 0.85°C increase we have already experienced.[46]

Climate models predict that if emissions go on unabated (the RCP 8.5 scenario), then global temperature is likely to rise by 2.6 to 4.8°C during the 21st century, reaching 3.2 to 5.4°C above pre-industrial levels. For the strong mitigation RCP 2.6 scenario, models predict a likely rise of 0.3 to 1.7°C in the 21st century, reaching 0.9 to 2.3°C above pre-industrial.[47]

FIGURE 6: PROJECTED TEMPERATURE CHANGE



Projections of global temperature change under high and low emissions. Shading shows the range of model outputs for each pathway, and the number of models involved is given next to each graph.

(Source: IPCC Fifth Assessment Report.)

Many experts argue that **warming greater than 2°C above pre-industrial levels would pose a high risk of causing dangerous interference to the Earth's climate.**[48]

MODELS OF EARTH

To predict what might happen to Earth's climate in the future, scientists build computer models that simulate the atmosphere, oceans and land surface.

These models are based on the known physics of:

- How air and water behave under the effects of gravity, pressure and heat flow, while sandwiched to the surface of a rotating planet
- How each gas in the atmosphere absorbs and emits different wavelengths of light

Global Climate Models (GCMs) cover the whole atmosphere and ocean. No existing computer could track every eddy and gust of wind, so to simplify things **the atmosphere and ocean are pixelated:** divided up into three-dimensional grids. Atmosphere grid boxes are about a hundred kilometres across and a few hundred metres deep in state-of-the-art global models. Regional models have higher resolution.

Each property of the air or water inside a box, such as pressure and temperature, is represented with a single number. The model then calculates how neighbouring boxes affect one another, to predict how air and water move and how their temperature and other properties change. In the short term, that is what we call weather. Climate models do not need to predict what the weather will be on 7 February 2033; instead their aim is to **predict the average weather over very long periods**.

To add in the carbon cycle, a GCM can be coupled with models of vegetation and soils. That makes an Earth System Model, such as HADGEM-2, developed at the UK Meteorological Office's Hadley research centre.[49] There are several such models, and each one is run many times over to gauge the range of natural variability in the climate.

Some processes, such as convection and the growth of clouds, happen on scales smaller than a GCM's grid. Each of these is handled with a separate physical model called a parameterisation. For example, the rate of evaporation from the sea surface is calculated from local humidity, temperature and wind speed, according to an approximate formula. Such formulas can be checked and improved by comparison with field observations, but parameterisations remain a source of uncertainty within climate models.

The spread of possibilities for future climate can be judged by comparing the results of several different models, although only to a certain extent, because they are not entirely independent. Many make similar physical assumptions, and some share sections of computer code.[50]

Models may all be neglecting some factors that affect climate, but **their results have been tested**. This is done by running a model for the conditions of the 20th century and comparing its output with actual observations. According to the IPCC "**there is *very high confidence* that climate models reproduce the observed large-scale patterns and multi-decadal trends in surface temperature**".[51]

FAST FACT

By the end of the 21st century **global temperature** could have risen by up to **5.4°C** above pre-industrial levels

What we still need to learn

1. **The climate's response to rising CO_2** depends on some processes that are not fully understood, especially feedback from clouds and atmospheric particles (section 3, 'The role of natural factors'). Satellite observations are beginning to constrain these feedbacks, but a longer record of data is needed.[52]
2. Even if all processes were fully understood the **picture is still blurred by internal variability** of the climate: short-term jitter that makes it difficult to judge precisely how sensitive[53] the climate is to CO_2. This source of uncertainty will be reduced only gradually over time, as researchers build more detailed models of the oceans and other systems, and are able to compare longer model runs with observations.

FAST FACT

In the past few decades,

60–75%

of Arctic sea ice has

disappeared

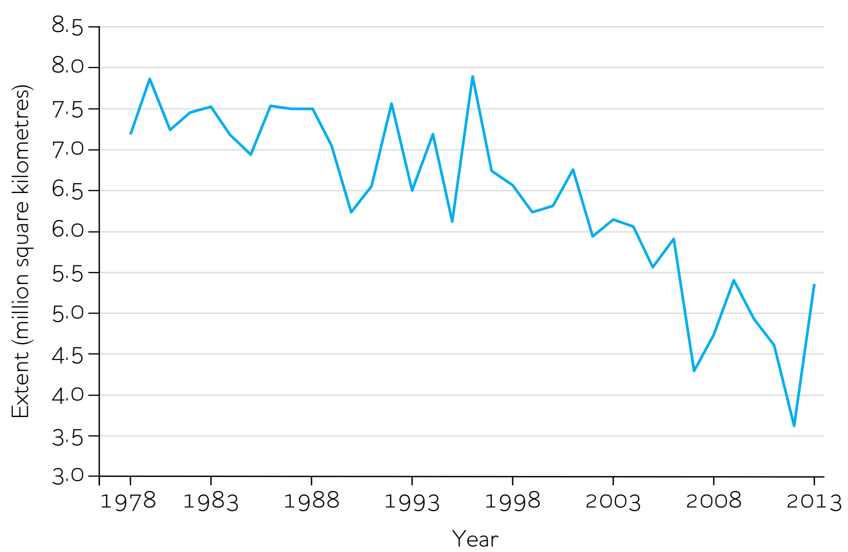
5c. SNOW, ICE AND FROZEN GROUND

Overview

The Earth's snow, ice and frozen ground, together known as the **cryosphere**, make up the second largest component of the climate system after the oceans in terms of mass and capacity to store heat.[54]

The cryosphere is one of the most sensitive indicators of climate change. Worldwide, **glaciers are retreating**, and the great ice sheets of Greenland and Antarctica are slowly shrinking. Greenland alone is losing more than 270 billion tonnes of ice per year.[55] The most dramatic change is in the Arctic (see figure 7), where over the last 30 to 40 years **60 to 75% of sea ice volume has disappeared**,[56] and data indicates that the ice has not retreated this far for at least 1,400 years.[57] The IPCC are now confident enough to pin this at least partly on human activity, which they say is "*very likely* to have contributed to Arctic sea ice loss since 1979".[58]

FIGURE 7: SHRINKING ARCTIC SEA-ICE



Sea ice coverage in the Arctic, measured at its summer minimum in September each year by satellite observation. Although some years show an apparent 'recovery' the longer-term trend is clearly downwards.

(Source: Adapted from National Snow and Ice Data Center)

Greenland's ice sheets are shrinking at a rate of more than 270 billion tonnes of ice per year.

Later this century, sea ice will probably vanish from the Arctic summer. Glacier melting will accelerate, raising sea level. Permafrost will thaw in some areas, releasing more greenhouse gases.

CAUSES

CLIMATE CHANGE AFFECTS THE CRYOSPHERE:

- **RISING TEMPERATURE**
  This can melt snow and ice and thaw frozen ground.
- **INCREASED RAIN OR SNOW**
  Heavier precipitation from a warmer climate and changed atmospheric circulation can lead to local increases in snow or ice.
- **CHANGING AIR AND OCEAN CIRCULATION**
  This can bring warmer water into contact with sea ice and with ice shelves, which normally help to restrain the flow of glaciers into the sea.[59]
- **BLACK CARBON (SOOT)**
  Soot from coal and diesel combustion and agricultural fires[60] can be deposited on snow where it absorbs solar radiation as heat, and so **accelerates snowmelt**.[61] This effect is greater in the Arctic than the Antarctic, which is more remote from sources of black carbon.[62]

EFFECTS

THE THAWING CRYOSPHERE AFFECTS HUMAN ACTIVITY:

- **SEA-LEVEL RISE**
  Meltwater from the Greenland and Antarctic ice sheets is adding about 0.6 millimetres per year to sea level.[63] This could accelerate in the future and cause a very large rise in sea level (see section 6a, 'Sea-level rise').
- **GROUND DESTABILISATION**
  Faster and earlier thaws can damage infrastructure such as ice roads, oil and gas pipelines and drilling rigs that rely on seasonally frozen land, rivers and lakes.
- **ECOLOGICAL CHANGE**
  Organisms dependent on sea ice, such as the polar bear, are among the most directly affected, and tundra ecosystems may also be threatened.
- **FRESH WATER AVAILABILITY**
  Runoff from ice and seasonal snowmelt is a vital source of water for human use and for fresh-water ecosystems.[64] Rising temperatures can cause this runoff to occur earlier in the season and more quickly, reducing the flow of fresh water later in the summer. Melting glaciers will initially provide more water, sometimes causing floods; then as they diminish so will the amount of water they provide.
- **EASIER ACCESS TO THE ARCTIC**
  The melting of sea ice is opening new shipping routes in the Arctic as well as easing access to natural resources such as oil and gas.
- **HYDROELECTRIC ENERGY**
  New opportunities for hydroelectric energy will appear in the USA, Canada, Russia, Scandinavia and Greenland.[65]

FEEDBACKS

THE THAWING CRYOSPHERE ALSO CREATES FEEDBACKS THAT CAN AMPLIFY CLIMATE CHANGE:

- **REFLECTION**
  Snow and ice reflect sunlight back into space, helping to keep the climate cool. As snow and ice melt, darker land or sea is exposed and absorbs more heat, amplifying global warming. This feedback is thought to play a central role in the high warming rate in the Arctic, where temperatures have risen at least twice as fast as the global average in recent decades.[66]
- **GASES RELEASED FROM PERMAFROST**
  Evidence from past climates and recent observations suggest that thawing permafrost can release CO_2 and methane into the atmosphere, potentially causing rapid and extreme warming (see Section 6h: tipping points).[67]

NOW	2100
• The Greenland and Antarctic ice sheets are shrinking, as are ice caps and glaciers around the world. • Arctic sea ice is retreating. • Antarctic sea ice is advancing in some areas, retreating in others. • Permafrost is thawing in some areas. • Seasonal snow cover is shrinking.	• Summer sea ice in the Arctic is projected to disappear entirely or almost entirely unless greenhouse gas emissions are strongly mitigated. Only in RCP 2.6 (the "best case" emissions pathway) is a substantial amount of sea ice projected to remain.[68] • Antarctic sea ice will retreat too, though much less quickly. • Melting of the Greenland and West Antarctic ice sheets may become all-but irreversible. • Permafrost area is virtually certain to shrink. Under RCP 8.5, models project a global loss of roughly 80%.[69]

What we have learned recently

1. **Thawing permafrost and melting ice is already releasing methane** into the atmosphere (see Section 5j, 'Tipping points').[70]
2. **Advancing sea ice in parts of Antarctica** is probably caused by stronger winds blowing from the land, pushing existing ice out to sea and exposing more water to freeze.[71]
3. **By contrast, Antarctic ice shelves are weakening.** These thick, floating shelves of ice act to restrain glaciers flowing from the interior of Antarctica, but relatively warm water is thinning them from beneath, leading to accelerating glaciers.[72]

What we still need to learn

The complex flow of ice within glaciers will determine the fate of the Greenland and West Antarctic ice sheets, which could potentially add several metres to global sea level (see section 6a, 'Hazards: sea-level rise' and section 6g, 'Tipping points'.) Ice dynamics is not well understood, although new research is improving the situation. For example, satellite observations of Antarctica show a network of glaciers stretching thousands of kilometres inland, demonstrating that ice is carried from the interior of the continent mainly through these channels – like tributaries of a river system – rather than by large-scale deformations of the ice sheet.[73] Sub-ice networks of water are thought to lubricate the flow of these glaciers.

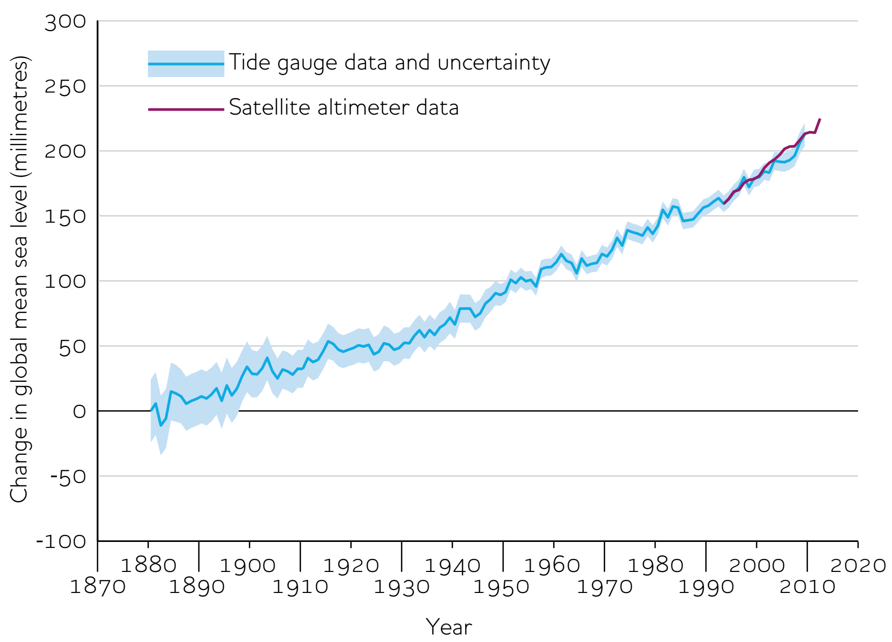
6. HAZARDS

6a. SEA-LEVEL RISE

Overview

Global sea level is currently rising at more than three millimetres per year (see figure 8). The scale and speed of future rises is debated, but some recent estimates are that **sea level could rise by as much as 1.5 metres during the 21st century if the increase in greenhouse gas emissions is not abated**.[74]

FIGURE 8: HIGH SEAS



Satellites confirm what tide gauges were already showing: sea level is rising, and rising faster in the most recent decades.

(Source: Adapted from Commonwealth Scientific and Industrial Research Organisation.)

Sea level rises mainly because of **melting land ice** (which flows as water into the oceans) and **thermal expansion** (ocean water expands as it warms).

Predictions of sea-evel rise use one of two main methods:

- **Process-based models** calculate the thermal expansion of the sea and the melting of glaciers to add up all the separate contributions.
- **Semi-empirical models** seek a relationship between sea level and temperature from past observations. This approach produces higher sea-level projections than process-based models.

The IPCC's new report bases its estimates mainly on process-based models, and projects a global average sea level rise of 0.53 to 0.97 metres for unmitigated emissions (RCP 8.5), and 0.28 to 0.60 metres for strong mitigation (RCP 2.6).[75] (All these figures are compared with average sea level between 1986 and 2005). Process-based models have improved since the 2007 AR4 report, but they still underestimate historical observed sea-level rise over the 20th century, so they may be giving conservative estimates of future rise.

According to semi-empirical models, sea level by 2100 could be appreciably higher. For RCP 8.5, estimates range from about 0.7 to 1.65 metres.[76]

Beyond 2100 **sea level will rise for centuries even if emissions are stabilised**, because of greenhouse gases already in the atmosphere and heat stored in the ocean, which will continue to melt the ice sheets.[77]

Currently, melting ice sheets are making a moderate contribution to sea-level rise, but they could reach a point where collapse is relatively rapid – perhaps on a timescale of centuries or less. Or they may melt slowly but irreversibly, locking in a long-term rise in sea level[78] (see 'Tipping points', page 33). This cannot be predicted with confidence because the internal dynamics of glaciers and ice sheets are not well understood.[79]

Greenland holds enough ice to raise global sea level by seven metres; the West Antarctic ice sheet could add three to five metres.[80]

The West Antarctic ice sheet may be especially vulnerable because much of it is grounded below sea level, meaning that water could flow in and undermine it. That could even become a concern this century. In the AR5, the IPCC mention that the collapse of marine-based sectors of the West Antarctic ice sheet could cause global sea level to rise substantially above their estimates: "There is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century."[81]

A rise in sea levels could pose one of the greatest threats to populations, economies and infrastructure in low-lying island and coastal regions, especially as tropical storms may become more violent, generating larger storm surges (see section 6c, 'Hazards: storms and floods'). Cities and settlements in the river deltas of Africa and Asia are among the most vulnerable and least able to spend on defence and adaptation.[82] Floods could also threaten major cities in the developed world such as New York and Miami. One 2013 study calculates that if flood defences are not improved, total economic losses could reach a trillion dollars per year by 2050.[83]

Sea level will rise more in some areas, less in others, because of changes in ocean currents and the shifting burden of ice. The ice sheets are so heavy that they depress the Earth's crust, and their gravity pulls water in around them – so as the ice melts both those effects will lessen. **Some of the fastest-rising sea levels are expected along the US east coast and around the equator.**[84]

What we have learned recently

Groundwater pumped out for human supplies also adds to sea-level rise. Previously considered negligible, it may have contributed 13 to 25% of observed sea-level rise according to two studies.[85] Groundwater mining could add between five and 20 centimetres to sea levels in the 21st century.[86]

FAST FACT

By the end of the century **sea level** could have risen by up to **1.5 metres**

6b. HEATWAVES AND DROUGHT

— FAST FACT —

Powerful **Category 4 and 5 storms** are already becoming more common

Overview

As the world warms, it is virtually certain that temperatures considered extreme today will become more frequent, while extreme cold will become rarer.

Trends in extreme weather are hard to measure, as these are rare events and most regions lack long-term records, but the number of extremely hot days has increased since 1950.[87] Research suggests that over the past few decades, heatwaves – very high temperatures lasting several days – have become more frequent.[88] The IPCC considers **heatwaves *very likely* to become more frequent and longer lasting this century**.[89]

Some regions have also seen longer and more intense droughts**,** especially southern Europe and West Africa.[90] Drought depends on rainfall as well as temperature, making it more complex to predict, but total precipitation is expected to change in a way that enhances regional extremes. So **already dry areas such as the subtropics will probably see more droughts**.[91]

Even in the "best case" scenario RCP 2.6, both heatwave and drought risks increase. The higher the emissions pathway, the greater the risk.

Because there is a limit to how far humans can physiologically adapt to heat stress, unmitigated climate change could eventually result in some regions becoming uninhabitable,[92] although only for global warming of more than 7°C.

HEAT HAZARDS	• **Drought** can be caused when higher temperatures lead to more evaporation, or if shorter winters or earlier snowmelt reduce the summertime water supply. In turn, drought can prevent plants from cooling the air, increasing the intensity of a heatwave. • **Hot weather may become prolonged more often**, because as polar regions warm up, the jetstream is expected to meander more slowly, blocking the movement of weather systems. (The same goes for cold and wet weather.)
EFFECTS	• **Heat-related deaths** from cardiovascular and respiratory illnesses will rise, while deaths from cold will fall. • Drought's main threat is to **agriculture.** Even modest warming of 2°C above preindustrial levels would expose about 8% of the world's population to new or aggravated water scarcity, according to a recent study (and see 'Hazards: food and water').[93] Extreme heatwaves can damage crops even in the absence of drought.[94] • Drought can also affect **power generation** because river water is used for cooling nuclear and fossil-fuel powerplants, as well as driving hydroelectric plants (see section 6f, Hazards: food and water).

What we have learned recently

Researchers have improved their ability to attribute individual events to warming. Although it is not possible to say with certainty that a particular event such as the 2003 heat wave in Europe was caused by climate change, studies have calculated the probability that certain events will occur for a given climate, **and concluded that some extremes would have been highly improbable without greenhouse-gas induced warming**.[95]

6c. STORMS AND FLOODS

Overview

Warm air can hold more moisture, so in a warming world **extreme rainstorms are almost certain to become more intense.** Downpours have already become more frequent in some regions.[96]

Precipitation becomes a serious problem when it overwhelms river systems and leads to flooding. This also depends on other factors, including soil moisture and changing land use, making prediction complex. But models project that over the coming decades **already wet regions, especially near the equator, will see more downpours and more floods**.[97]

According to one study, increases in extreme precipitation could be underestimated by most models when compared with observations.[98]

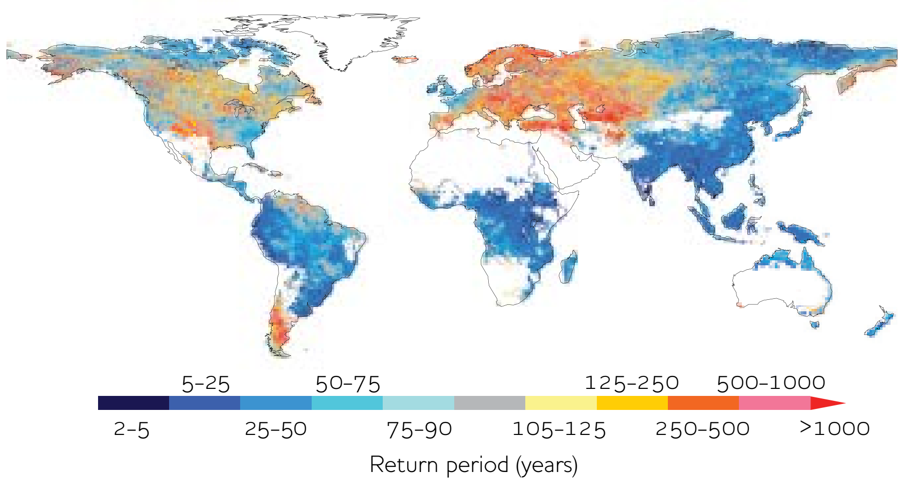
The intensity of hurricanes and other tropical cyclones is likely to be boosted by increased evaporation from warmer seas. Powerful category four and five storms are already becoming more common, while weaker storms become less common, according to recent research. One study concludes that "the proportion of Category 4 and 5 hurricanes has increased at a rate of 25 to 30% per °C of global warming". In the future, the IPCC concludes that maximum wind speeds and precipitation rates are likely to increase further.[99]

Coastal flooding is expected to increase, mainly because of a combination of rising mean sea levels and higher storm surges as cyclones become more intense.[100]

Material damage from extreme weather increased eight-fold between the 1960s and the 1990s in inflation-adjusted terms, a faster increase than population or economic growth.[101]

What we have learned recently

Flooding is predicted to increase most in southeast Asia, peninsular India, East Africa and the northern Andes, according to a new study that compares 11 different climate models.[102] The same study predicts a **decrease** in flooding across most of North America, Europe and central Asia. The overall effect is to expose a larger population to flooding: under the RCP 8.5 "worst case" scenario it goes up from around 20 million people today to about 100 million in 2100.



Flooding is projected to become more frequent (blue) in a majority of areas, but rarer (warm colours) in others, if greenhouse gas emissions are unmitigated (RCP 8.5 – the "worst-case" pathway). For each location, this map refers to a level of flood that would have been a once-in-100-year event in the climate of the late 20th century. It shows how that expected return period is projected to change by the period 2071 to 2100. The darkest blue marks places where such floods are projected to happen on average every two to five years.

(Source: Hirabayashi et al., "Global flood risk under climate change," Nature Climate Change, 3, pp. 816–821 [2013])

6d. EXTREME WAVES

Overview

The largest ocean waves can threaten ships, drilling platforms and wind turbines. In many regions these extreme waves are growing in size. Models project that in some regions **global warming will probably increase wave height further, especially in some crucial shipping areas** such as the North Atlantic.

WIND AND WAVE

- **Waves are built up by wind** blowing over the sea surface. Local wave heights will increase if wind speeds increase, or if the wind blows uninterrupted for a longer time or over a greater distance.
- **Rolling waves called swells** can travel thousands of kilometres and boost the size of locally generated waves. Swells generated by storms in the Southern ocean are expected to increase in size, and add to wave height as far away as the North Atlantic.[103]
- **Significant wave height** captures wave conditions in a single number, roughly equal to the average trough-to-crest height of the highest third of waves seen at any one time and place. Ships are designed to withstand sea conditions rare enough to occur only once in 20 years, which in the North Atlantic means a significant wave height of at least 16 metres.[104]
- **Very rare "rogue waves"** can reach more than twice the significant wave height, and tend to be very steep, making them even more dangerous. Warming may increase the number of rogue waves.[105]

Since the 19th century, wave height has been recorded systematically by visual observation from ships. More recently, fixed buoys, marine radar and satellites have measured wave height, and models have been used to calculate wave height retrospectively based on the weather conditions.

Each method has some shortcomings. Models are indirect. Ships steer clear of storms. Buoys sample only a few locations. The satellite record is brief, so it may not fully reflect long-term trends. They give differing numerical results, but all show that over the past half century **extreme wave height has increased in the North Atlantic, the Southern Ocean and the Northern Pacific.**[106]

In the future, **wave height is very likely to increase in the Arctic** as global warming melts sea ice to expose more water. Elsewhere, future wave height is harder to predict as it depends on changing weather patterns, but a number of studies predict that by the end of the 21st century, **extreme wave heights are likely to increase further in parts of the North Atlantic and northern Pacific.** [107]

For once-in-20-year sea conditions, some of the forecasts predict increases of up to two metres in significant wave height (see box). According to one study on the structural collapse of ships, a half-metre increase could raise the probability of failure by 50%.[108]

As well as posing a risk to shipping and offshore installations, larger waves could damage some shallow-water ecosystems,[109] **affect coastal facilities such as ports, and increase coastal erosion.**

6e. OCEAN ACIDIFICATION

Overview

Seawater has absorbed 25 to 30% of the CO_2 emitted by human activity.[110] This has changed the ocean's chemistry. When CO_2 dissolves in water it forms an acid, and **the acidity of the ocean has already increased by 30%.**[111]

If carbon emissions continue unabated, models predict that by the end of the 21st century the ocean's acidity will be 200% higher than its preindustrial level.[112] Even in a mid-range emissions scenario that is predicted to be at least 100% higher, making the ocean **more acidic that it has been for at least the past 20 million years.**[113] Ocean chemistry will probably not recover for tens of thousands of years.

In Earth's past, major episodes of ocean acidification have been accompanied by large-scale extinctions among plankton and other marine species, many of which adapt to a narrow range of acidity.

ACID SEAS

CO_2 emissions affect ocean acidity through two mechanisms:

- **Some CO_2 is absorbed** by the ocean, where CO_2 reacts with water to form carbonic acid.
- **Warming reduces the solubility of CO_2** in the ocean, which partially reduces the rate of ocean acidification.[114]

A more acidic ocean has consequences for:

- **Sea creatures** that build their shells or skeletons from calcium carbonate, which will die above a certain level of acidity
- **Sea grasses,** which may benefit from higher levels of CO_2
- **Global warming,** which could be amplified if acidification reduces the emission of cooling sulphates from the ocean into the atmosphere.[115]

Coral reefs are built from calcium carbonate and so are under threat as the ocean becomes more acidic.

— FAST FACT —

The ocean's
acidity
has increased by
30%

Many organisms including **corals, plankton and molluscs** build their shells and skeletons out of calcium carbonate.

As the ocean's acidity rises, **such structures may begin to dissolve**, with the effect differing in strength for different organisms.[116] Many of these organisms are at the base of food chains, so acidification may threaten not just individual species but the ecosystems they support as well as related fisheries and tourism.

The Southern and Arctic Oceans and the Pacific coast of North America are especially vulnerable, as cold water can hold more CO_2. Along the Pacific coast of North America, for example, water acidic enough to dissolve calcium carbonate shells is already seen each spring time. Although this is a natural phenomenon, **the range of acidic water is spreading**.[117]

Even hitting tight emissions targets may not be enough to preserve many coral reefs. In October 2013, the International Programme on the State of the Ocean released a report concluding that "at CO_2 concentrations of 450–500 ppm (projected in 2030–2050), erosion will exceed calcification in the coral reef building process, resulting in the extinction of some species and decline in biodiversity overall."[118]

What we have learned recently

1. **Parts of the ocean may become hostile to shell-building organisms earlier than anticipated**. It had been thought that atmospheric concentrations above 600 ppm (a level that will be passed before the end of the century unless action is taken to reduce emissions) might render Southern Ocean and the Arctic Ocean unable to support some organisms that build carbonate shells. Recent studies find that this threshold could be crossed at a level of 450 ppm, which is likely to be reached by mid century.[119]
2. **Ancient climate records are providing insight into past ocean acidification**. In one review, researchers concluded that the current rate of CO_2 release could cause chemical changes in the ocean unparalleled in the past 300 million years.[120]
3. **Acidification could amplify global warming**. Some marine organisms emit dimethyl sulphide, which goes on to form sulphate aerosol particles in the atmosphere, which reflect incoming sunlight. A new study concludes that in a more acidic ocean, organisms generate less dimethyl sulphide.[121] By reducing our reflecting shield of sulphate particles, that would amplify climate change – an effect not yet included in climate models.

Acidification also affects industries reliant on the ocean, such as fisheries and tourism.

6f. FOOD AND WATER

Overview

Climate change is already affecting water and food resources, and is expected to have an even greater impact over the coming century.[122]

Drought is the greatest concern, with already dry regions likely to become drier.[123] In many models, much of the world becomes increasingly arid, including **most of the Americas, Australia, southeast Asia, Africa, southern Europe and the Middle East**. According to one study, people living in these regions may see **a switch to persistent severe droughts** in the next 20 to 50 years.[124]

Loss of mountain glaciers will reduce summertime river flow in some areas. For example, meltwater from the Himalaya forms an important summer supply to the Indus and Brahmaputra river basins,[125] while Andean glaciers supply parts of South America.[126]

Where total rainfall increases, it may move to the wrong season. That could be as damaging as drought, unless facilities can be built to capture and retain fresh water.[127] An excess of rainfall can also wash away soils, waterlog crops or bury them under silt.

Higher temperatures will have a direct effect on crops, positive or negative depending on the location,[128] with extreme heatwaves especially damaging.[129] Warming of 1 to 3°C will probably increase crop yields slightly in some high-latitude regions, but significantly reduce them in lower latitudes. **Warming above 3°C is projected to reduce the potential for global food production**.[130]

FIGURE 10: WATER STRESS, 2095

- Exceptionally less stressed (<0.125x)
- Extremely less stressed (<0.125–0.357x)
- Significantly less stressed (<0.357–0.500x)
- Moderately less stressed (<0.500–0.588x)
- Wetter but still extremely high stress (<0.588 and baseline water stress (2095) >80%)
- Near normal conditions (<0.588–1.7x)
- Drier but still low stress (>1.7x and baseline water stress (2095) >10%)
- Moderately more stressed (1.7–2x)
- Severely more stressed (2–2.8x)
- Extremely more stressed (2.8–8x)
- Exceptionally more stressed (>8x)
- Missing data (no data)
- Uncertainty in magnitude
- Uncertainty in direction

Changes in water stress by 2095, in a high-emissions scenario similar to RCP 8.5, as assessed by the World Resources Institute. Under lower emissions scenarios, the changes are less severe.

(Source: Interactive maps available at www.wri.org/our-work/project/aqueduct)

FOOD AND WATER FUTURES

Climate change is expected to impair fresh water resources:[131]

- Warming will **reduce the supply of fresh water** in many regions.
- Shifting weather patterns, and the loss of glaciers and seasonal snowpack could **change the timing of fresh water availability**.
- Floods, rising sea level and increasing evaporation could **contaminate fresh water resources** with salt and other substances.

With consequences for:

- **Crop yields.** Increased atmospheric CO_2 can boost yields, but higher temperatures and drier soils tend to decrease them. Switching to less water-hungry crops can help, but the overall effect is expected to be negative for many parts of the world during the 21st century. More frequent floods, droughts, heat waves and forest fires are also liable to reduce agricultural production.[132]
- **Human health.** For example, drought can lead to malnutrition and the spread of infectious diseases. The World Health Organisation estimates that the effects of climate change already claim 150,000 lives per year.[133]
- **Aquatic ecosystems and fisheries,** which are vulnerable to changes in temperature and chemistry of seas and rivers, as well as weakening ocean circulation.[134] In the Arctic, marine ecosystems will change as sea ice retreats,[135] because nutrient-rich waters at the ice edge are a prime site for plankton growth; while ice loss may also promote increased photosynthesis. The net effect on fisheries is highly uncertain.
- **Electricity generation**. Many power plants use river water for cooling, and, by mid-century, lower river flow and higher water temperature could reduce generating capacity by 6.3 to 19% in Europe and 4.4 to 16% in the United States.[136] Hydroelectric plants depend on water flow and are vulnerable to climate change in some regions.[137] Hydraulic fracturing or 'fracking' for gas and oil production is also water intensive, as is carbon capture and storage.

And knock-on effects:

- Reduced food production, combined with increasing demand from population and economic growth, could **drive up food prices** 10 to 60% by 2030.[138]
- Worsening scarcity of water and food could cause **human migration** out of particularly stressed regions, and increase the likelihood of **war**.

What we have learned recently

Climate change is already lowering yields. A recent study calculates that the global production of maize and wheat between 1980 and 2008 was 3.8 and 5.5% lower, respectively, than it would have been in the absence of rising temperatures.[139]

6g. TIPPING POINTS

Overview

Abrupt climate change has happened in Earth's past,[140] and in theory it could happen again. Some element influencing climate, such as the amount of greenhouse gases in the atmosphere or the reflectivity of the Earth's surface, could cross a key threshold and trigger a transition to a new climate state.[141] Such thresholds have been called 'tipping points'. The term usually implies that the transition would be relatively rapid – on a timescale of decades or less – and often that it would be effectively irreversible.[142]

Most climate scientists agree that if emissions continue unabated, some tipping points will be reached eventually, but there is little consensus and much uncertainty. **It is especially unclear whether any of these events will occur soon**.

In the AR5, the IPCC imply that it is unlikely we will hit a tipping point in the 21st century: "There is no evidence for global-scale tipping points in any of the most comprehensive models."[143] They may be too conservative on this point, because so little is known about most tipping points. In particular, these models fail to capture the detailed processes underlying permafrost thaw and ice-sheet collapse.

Some recent research suggests we may be more likely to hit tipping points than was previously thought.[144] One survey of climate scientists concluded that **if global warming exceeds 4°C, hitting at least one tipping point will become more likely than not**.[145]

Even if the probability is not so high, tipping points present a great risk. **The consequences of collapsing ice sheets, drying Amazon or runaway permafrost thaw would be catastrophic.**

FAST FACT

Warming has already lowered global production of maize and wheat

Warming and deforestation could dry out the Amazon rainforest.

— FAST FACT —

The Amazon could rapidly shift to grassland if **10%** of existing forest is **cut down**

TIPPING POINTS

- **Permafrost thaw**. As Arctic soils thaw out, they can decompose and release methane and carbon dioxide, generating further warming. This is already happening in some parts of the Arctic. At some point, as yet unknown, this could become so serious that warming runs away, caught in a vicious circle of feedback. Permafrost varies in its properties from place to place and it has not been mapped in detail, making this process very difficult to model. However, many scientists believe that the permafrost contains very large amounts of carbon, making this perhaps the most serious of the potential tipping points. (And see under 'What we have learned recently').
- **Ice sheet collapse**. The West Antarctic ice sheet rests on ground below sea level, which may make it mechanically unstable, and susceptible to rapid collapse on a timescale as short as a few decades. In Greenland, melting could become irreversible because of two feedback mechanisms: exposed land or water absorb more heat than ice and snow, and glacier surfaces become warmer as melting reduces their elevation. The tipping threshold of the Greenland ice sheet could be very low (see below) – although it would probably take several centuries to melt.[146]
- **Drying Amazon**. Warming and deforestation could dry out the Amazon rainforest. Transpiration from the trees helps to maintain a damp local climate, so when too much of the forest is lost a tipping point could be reached. Some models predict up to 70% of the rainforest will be gone by the end of the century, replaced by savannah.[147] As well as the loss of biodiversity, this would release large amounts of CO_2, amplifying climate change.
- **Circulation shutdown.** A global conveyor belt of ocean currents is driven by the sinking of cold salty water in the North Atlantic. This process could slow or halt as temperatures rise and more fresh water is flushed into the North Atlantic from increased river flow and melting ice. If circulation is slowed or shut down, it will have many consequences for global climate including colder winters in Europe. Climate scientists generally agree that a shutdown is not likely to happen this century.
- **Shifting monsoons**. The Indian summer monsoon has changed its strength and variability in the past, and models suggest that it could suddenly weaken, leading to much more frequent droughts.[148] Predicting whether this will happen is difficult partly because the monsoon is subject to conflicting influences. Rising greenhouse gas concentrations and consequent warming may increase the intensity of the monsoon.[149] On the other hand, aerosol particles from industrial pollution reflect solar heat and are thought to weaken the monsoon – a process that may already be happening.[150] Meanwhile, some models predict that the West African monsoon could also be disrupted, which would increase precipitation over the Sahel and Sahara, leading to greening—a possible rare example of a positive climate tipping point.[151]

What we have learned recently

1. **The Greenland ice sheet could be highly sensitive to warming.** Earlier research put its threshold at 3.1°C above pre-industrial temperatures.[152] According to a recent study, however, the ice sheet's eventual disappearance will become inevitable at a threshold somewhere between 0.8 and 3.2°C above pre-industrial levels.[153] As 0.8°C of warming has already taken place, this threshold may already have been passed. In July 2012, NASA satellites observed melting over 97% of the ice sheet's surface.[154]
2. **Permafrost tipping points may be more serious than was thought.**[155] In the Fifth Assessment's highest warming scenario RCP 8.5, the Arctic will have warmed by about 7.5°C in 2100, which according to one study could cause permafrost to emit 380 billion tonnes of methane and carbon dioxide.[156] A large area of especially carbon-rich permafrost in north-eastern Siberia contains an estimated 500 billion tonnes of carbon, and a recent study suggests that 9°C of local warming – possible this century given amplified warming in the Arctic – could release some three-quarters of its carbon over about a century.[157] In 2010 researchers reported that another huge reservoir of carbon – permafrost buried under frozen sea beds off the north coast of Siberia – could be more vulnerable to thawing than land-based permafrost.[158] **Methane is already seeping out** from coal beds and natural gas deposits that had been trapped under glaciers and permafrost.[159]
3. **The Amazon may be more delicate** than previously thought. New research concludes that a rapid shift from forest to grassland could happen if more than about 10% of the existing forest is cut down.[160]
4. Some scientists think that **Arctic sea ice passed a tipping point** when it receded in 2007.[161]

7. THE FIFTH ASSESSMENT REPORT OF THE IPCC – THE PHYSICAL SCIENCE BASIS

Overview

In October 2013, the Intergovernmental Panel on Climate Change released their first full-scale survey for six years. 'Climate Change 2013: The Physical Science Basis',[162] part of the organisation's Fifth Assessment Report (AR5), is the result of work by several hundred scientists to contribute, review and combine existing climate research to produce a consensus.

In most respects, **the conclusions of the AR5 are strikingly similar to those of the IPCC's last comprehensive report, the AR4**, in 2007. While there are a few significant differences (see box), both reports conclude that the main cause of global warming over the past century is human emissions of greenhouse gases, and that warming and its hazardous side effects will accelerate over the next few decades. In general the conclusions of the AR5 are more confident than the AR4, being based on updated observations and more detailed models.

The range of projections for the future is roughly the same. That too is no great surprise, because **the largest uncertainty about the coming century is not scientific but political – how much carbon dioxide and other greenhouse gases will we emit?**[163]

AR5 VERSUS AR4

Inputs:

- Observations of the whole climate system have improved since the AR4. They also encompass an extra six years of data, which is significant where more advanced technology such as satellite observation has only been recently deployed. For example, the ARGO network of ocean probes[164] was only completed in 2007.
- Models have higher resolution. They also give a more realistic treatment of the carbon cycle and the behaviour of vegetation, and include more components of the climate – more types of airborne particle, for example.[165] The understanding of several geophysical processes including glacial dynamics and the water cycle has also improved.

Conclusions:

- Both assessments attribute warming mainly to human emissions of greenhouse gases, but where the AR4 considered this conclusion "very likely" (having a probability of more than 90%), the AR5 is more confident, calling it "extremely likely" (more than 95%).
- Since the AR4, evidence of human influence has grown in warming of the atmosphere and the ocean, changes in the global water cycle, reductions in snow and ice, sea level rise, and changes in some climate extremes.
- The AR5 directly attributes much of the loss of Arctic sea ice to human activity.
- Projections of sea-level rise in the AR5 are higher, partly because the models now allow future increases in the flow of ice through the glaciers of Greenland and Antarctica.
- The AR5 is more confident that extreme high sea levels (storm surges on top of steadily rising seas) will occur more often by 2100 ("very likely" versus "likely" in the AR4).
- The AR5 sets out a cumulative global emissions budget of one trillion tonnes of carbon (see section 5a). Hitting that level would give us a roughly even chance of avoiding warming above 2°C.

By its nature, **such a large group often has to err on the side of caution** in order to reach a document that all participants can agree on. After the AR4, the IPCC was criticised for overstating the future melting of Himalayan glaciers – a mistake that was soon rectified, but gathered a lot of unwelcome media attention. So **while the AR5 is by far the most authoritative and detailed description of the present state and possible future of the climate, some of its conclusions may be conservative**.

This document includes a few differences with the AR5:

- **We include a method of projecting sea-level rise** that gives somewhat higher values than the one chosen by the IPCC (see section 6a, 'Hazards: sea-level rise'). With both, we can represent the full range of results coming out of climate science.

— FAST FACT —

The main cause of **global warming** over the past century is **human emissions** of greenhouse gases

- **Our assessment of tipping points is less optimistic than the AR5 consensus**. The majority of climate scientists consider that Earth will probably not hit a major tipping point this century. But if it does, then the downside would be extremely serious – so we think it important to discuss the more pessimistic studies as well (section 6g).
- We also have access to research too recent to have been included in the AR5. For example, new studies pin the recent warming hiatus mainly on a cool phase of Pacific ocean circulation (see section 3, 'The role of natural factors'), where the AR5 gave a more open verdict.

8. FREQUENTLY ASKED QUESTIONS

Climate science is a dynamic field, involving debate and uncertainty (see, for example, 'What we still need to know' in the preceding sections). However, some well-established conclusions are often called into question by critics outside the climate-science community. Here we present some frequently asked questions to which the science already has firm or fairly firm answers.

Do we know the Earth is really warming?

High-quality global temperature measurements go back 150 years.[166] These records have been analysed carefully by independent research groups, and they show that average global surface temperatures have increased by about 0.9°C over that time (see section 2).

Has global warming stopped?

No, but the warming of the atmosphere has paused. The rise in global air temperature was slow or even zero between 1998 and 2012, probably because of a natural climate cycle bringing cooler water to the surface of the tropical Pacific (see section 3). Measurements show that the Earth as a whole continued to warm, with heat going into the oceans.

Is Arctic sea ice actually increasing?

There was more ice in summer 2013 than in 2012, but this is just short-term variation. The long-term trend is clearly and rapidly downwards (see section 5c). Even in summer 2013, the sea ice covered less area than in any satellite-mapped year before 2007.[167] The ice is also getting thinner.

Can warming be explained by changes in the output of the sun?

The sun does change in brightness, waxing and waning over an 11-year cycle enough to nudge global temperatures up and down by about 0.1°C, but there has been no long-term increase in brightness that could explain the warming trend of the past half century (see section 3).

How does warming today compare with past climate change?

It is extremely rapid. Earth's climate has always varied in response to natural causes, sometimes warmer and sometimes colder than today. Compared with many prehistoric changes, the climate change of the past century is modest in scale; but it is happening quickly (see section 2). In a historical context it is already substantial: temperatures are probably higher now than at any time in the past two thousand years.[168]

Did CO_2 drive warming in the past, or was it the other way around?

It was almost certainly both. Ice-core records show that around the end of each ice age, temperatures in Antarctica started to rise 600 to 1,000 years before the rise in CO_2, implying that CO_2 did not trigger warming. That initial warming is thought to have been caused by cyclical changes in Earth's orbit, which match the sequence of ice ages. The slightly higher temperatures would then have triggered the release of CO_2 from the oceans, amplifying the initial change.[169] This release of CO_2 is thought to have been enough to cause about half of the warming that ended the ice ages.[170] (There is also evidence that the timing of temperature versus CO_2 is different outside Antarctica. A recent study using about 70 to 80 proxy records of temperatures from different parts of the planet suggests that CO_2 lagged temperature only very briefly, and after that it actually lead the rise in average global temperatures.[171])

— FAST FACT —

Human CO_2 emissions reached a record

31.6

gigatonnes in 2011

Are humans or natural events behind the recent increase in atmospheric CO_2?

Humans. Natural flows of CO_2 between land, sea and air are huge (hundreds of gigatonnes each year) but they are usually in balance. That is, the rate of flow into the atmosphere is about equal to the rate of absorption from the atmosphere.[172] One useful analogy is to picture carbon flows like the water running into a bath (from a tap) and at the same time running out of the bath (down the drain). If the input and output are in balance, large amounts of water may be running through the system but the level in the bath stays the same. A relatively small addition of water may then tip the balance and cause the bath to overflow. In the same way, before the onset of the Industrial Revolution, ice-core records show that atmospheric concentrations of CO_2 stayed between 180 and 300 parts per million for at least the past 800,000 years. Now human CO_2 emissions (which reached a record 31.6 gigatonnes in 2011[173]), mainly from fossil fuel combustion, have tipped the balance. As a consequence, atmospheric levels have increased with unprecedented speed, reaching 400 parts per million in some places during the spring of 2012. Once in the atmosphere, CO_2 can linger for many centuries, so CO_2 emissions from human activities accumulate over time. (See section 4.)

MORE EVIDENCE THAT THE RISE IN CO_2 IS BEING DRIVEN BY HUMAN ACTIVITY:

- The other two sources that might have put so much CO_2 into the atmosphere are the ocean and the Earth's vegetation, but measurements show that these are currently absorbing more than they emit.
- One heavier form of carbon, C-14, has decreased in the atmosphere. That indicates the new carbon has come from fossil fuels, which do not contain C-14, rather than biological sources, which do.
- The timing of the increase in atmospheric CO_2 coincides with the onset of the Industrial Revolution.

Is Antarctica warming too?

Yes. Based on limited observations, scientists previously believed that temperatures in the interior of the Antarctic continent were roughly steady, and the mass of the East Antarctic ice sheet might be increasing slightly. With more data, it has become clear that Antarctica is warming, and losing ice.[174] (See section 5c.)

Can the science be trusted?

Some errors were identified in the IPCC's 2007 Fourth Assessment Report, including an overestimate of the future melting rate of Himalayan glaciers. Those errors did not affect the report's main conclusions on the causes of warming during the last 150 years.

In 2009, emails were hacked from the University of East Anglia's Climate Research Unit (CRU). They included statements by climate scientists that were interpreted by some commentators to imply manipulation of the data. However, four independent investigations of the CRU cleared the climate scientists of any wrongdoing.[175]

The large body of evidence showing the scale of warming, and its probable causes, has proved to be robust.

APPENDIX: IPCC AR5 LIKELIHOOD TERMINOLOGY

LIKELIHOOD OF THE OCCURRENCE/OUTCOME	
Virtually certain	> 99% probability
Extremely likely	> 95% probability
Very likely	> 90% probability
Likely	> 66% probability
More likely than not	> 50% probability
About as likely as not	33 to 66% probability
Unlikely	< 33% probability
Very unlikely	< 10% probability
Extremely unlikely	< 5% probability
Exceptionally unlikely	< 1% probability

ENDNOTES

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