Frequently Asked Questions

To comment on the compiled Frequently Asked Questions, please select FAQ in the 'Chapter' column of the review comment sheet (comments_ar6wg1_sod.xlsx) followed by adding the start and end page and line numbers. Please note that the page numbers are not in sequential order due to the document having been compiled from the individual chapters.

Frequently Asked Questions

FAQ 1.1: Do we understand climate change better now compared to when the IPCC started?

Yes, much better. The first IPCC report, released in 1990, concluded that human-caused climate change would soon become evident, but could not yet confirm that it was already happening. Today, evidence is overwhelming that the climate has indeed changed since the pre-industrial era, and we are virtually certain that human activities are the principal cause of that change. With much more data and better models, we also understand more about how the atmosphere interacts with the oceans, ice, snow, vegetation, and land surfaces of the Earth. Computer climate simulations have also improved significantly, incorporating many more natural processes and providing projections at much finer resolutions.

Since 1990, large numbers of new instruments have been deployed to collect data in the air, on land, at sea, and from outer space. These instruments measure temperature, clouds, winds, ice, snow, ocean currents, sea level, soot and dust in the air, and many other aspects of the climate system. New satellite instruments have also provided a wealth of increasingly fine-grained data, and additional data from older observing systems and even hand-written historical records have now been integrated into observational datasets. Ice cores, sediments, fossils, and other evidence from the distant past have taught us much about how Earth's climate has changed throughout its history.

Understanding of major relationships within the climate system has improved. For example, we now know that most of the excess heat in the overall climate system is being retained in the oceans, and that even the deep ocean is warming up. As another example, in 1990 relatively little was known about exactly how or when the gigantic ice sheets of Greenland and Antarctica would respond to warming. Today, much more data and better models of ice sheet behaviour provide evidence of unexpectedly high melt rates that may lead to major changes within this century, including substantial sea level rise.

The major natural factors contributing to climate change on timescales of decades to centuries are volcanic eruptions and variations in the sun's energy output. Today, data show us that incoming energy from the sun has not increased overall in the last century, and that major volcanic eruptions have occasionally cooled the planet for relatively short periods of time (typically several years). The main human causes of climate change are heat-absorbing gases emitted by burning fossil fuels, which warm the planet, and tiny particles in the air, such as soot from burning coal, which can have either warming or cooling effects depending on their size, colour, and location. Since 1990, we have more and better observations of these human factors as well as improved historical records, resulting in more precise estimates of human influences on the climate system.

While most climate models in 1990 focused on the atmosphere, using highly simplified representations of oceans and land surfaces, today's Earth system simulations include detailed models of oceans, ice, snow, vegetation, and often many other variables. An important test of models is their ability to simulate Earth's climate over the period of instrumental records (since about 1850). Several rounds of such testing have taken place since 1990, and the testing itself has become much more rigorous and extensive. As a group and at large scales, models have predicted the observed changes reasonably well in these tests. Since there is no way to do a controlled laboratory experiment on the actual Earth, climate model simulations can also provide a kind of "alternative Earth" to test what would have happened without human influences. Such experiments show that without our influence, the observed warming would not have occurred.

Finally, climate models predict that human influences on the climate system should produce specific patterns of change, and we see those patterns in our observations. For example, nights are warming faster than days, satellite measurements show that less heat is escaping to space, and the lower atmosphere (troposphere) is warming but the upper atmosphere (stratosphere) is cooling. These confirmed predictions are all evidence of changes driven primarily by increases in greenhouse gas concentrations rather than natural causes.

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FAQ 1.1, Figure 1: [PLACEHOLDER]

[END FAQ 1.1, FIGURE 1 HERE]

FAQ 1.2: Where has climate change become most apparent?

In the 1930s, the planet's land areas were first observed to be warming and it was suggested that increasing atmospheric carbon dioxide concentrations were part of the explanation. However, it was not certain at the time whether the observed warming was part of a long-term trend or a natural fluctuation – the signal of global warming had not yet become apparent. By the 1980s, as the planet continued to warm, the changes in temperature had become more obvious and are now unequivocal. Changes in other variables such as rainfall patterns, sea-ice area, and extremes have also now become apparent in many regions.

The signs of climate change are most obvious at the global scale, but they are increasingly clear on smaller spatial scales. Imagine you had been monitoring temperatures at the same location for the past 150 years. What would you have experienced? When would the warming have become noticeable in your data? The answers to these questions depend on where on the planet you are.

Observations and climate model simulations both demonstrate that the largest long-term warming trends are in the high northern latitudes, and the smallest warming trends are in tropical regions. However, the year-to-year variations in temperature are smallest in the tropics, meaning that the changes there are more apparent, relative to the range of past experiences, than at higher latitudes (see FAQ 1.2, Figure 1).

This early emergence of the signal of climate change in tropical regions has important implications. It is not necessarily the size of the change which is most important for climate-related risks. Instead, it can be the size of the change relative to the natural fluctuations of the climate to which ecosystems or society are already adapted. If the climate is pushed further away from the lived experience to become unprecedented then the risks are potentially larger. This is happening fastest in regions which tend to have higher populations and are more vulnerable to climate change. In the future, the pattern of temperature change is expected to continue to show the largest temperature changes at high northern latitudes, with the most apparent warming in the tropics. The tropics also stand to benefit the most from mitigation in this context, as limiting global warming will also limit how far the climate shifts relative to the past.

Signals in other climate variables are continuing to become apparent at smaller spatial scales and shorter timescales. For example, changes in mean rainfall are becoming clear in some regions, but not in others, mainly due to the larger variability relative to the size of the long-term trends. However, extreme rainfall is becoming more frequent, suggesting increases in risk from inland flooding. Sea levels are also clearly rising on many coastlines, implying increasing risk of inundation from coastal storm surges, even though there may be no clear long-term trend in the number of storms reaching land. A decline in the amount of Arctic sea ice is apparent, both in area covered and in its thickness, with implications for polar ecosystems, but the long-term trends in Antarctic sea ice are less clear.

How the signal of climate change emerges depends on natural fluctuations of the climate and these fluctuations in turn depend on the region where you live and also on the specific change you are looking at, e.g. temperature, precipitation or sea level. Both the pattern of change and the natural fluctuations need to be considered when assessing the impact and risks from climate change.

[START FAQ 1.2, FIGURE 1 HERE]

FAQ 1.2, Figure 1: Observed variations in regional temperatures since 1850 (data from Berkeley Earth). Northern America (40-64N, 140-60W) has warmed by a larger amount than Tropical America (10S-10N, 84W-16W), but the background variations are also much larger in Northern America (shading represents 1 and 2 standard deviations of natural interannual variations). The signal of observed temperature change emerged earlier in Tropical America than Northern America even though the changes were of a smaller magnitude.

[END FAQ 1.2, FIGURE 1 HERE]

FAQ 1.3: What can past climate teach us about the future?

Rising greenhouse gas concentrations are driving a suite of profound changes to the earth system, including warming, sea level rise, increases in climate and weather extremes, ocean acidification, and ecological shifts. Past climate variability over the last centuries to millennia serves as the most relevant baseline against which to measure anthropogenic changes in climate. Farther back in time, larger reorganizations of the earth system provide critical information about the rates and magnitudes of physical, chemical, and ecological changes under a suite of different greenhouse gas concentrations.

The vast majority of instrumental observations of climate begin during the late 20th century, during a period of rapid anthropogenic warming, and as such reflect the altered physics and chemistry of the anthropogenic era. So-called paleoclimate records of past environmental change capture a rich spectrum of Earth's history that climate scientists use to inform future climate changes in a variety of ways. Given that it will take several millennia for the earth system to come into equilibrium with present-day atmospheric greenhouse gas concentrations, past climate states help scientists understand the true sensitivity of the earth system to both small and large changes in climate forcing.

At their most basic level, records of past climate change serve as a critical backdrop for current anthropogenic climate trends, in many cases allowing for the separation of natural variability and greenhouse-induced trends in earth's climate. In recent millennia, atmospheric CO_2 concentrations were relatively stable, such that changes in solar irradiance and volcanic eruptions represented the primary drivers of global climate variability. During this time, global temperature varied by less than 0.5°C and sea level varied by no more than 10cm. Exceptionally high-resolution records spanning the last several centuries allow for the quantification of past climate extremes such as severe drought, El Niño events, wildfires, and tropical storms. Indeed, the last millennia provides a wealth of data that climate scientists use to probe the relationship between the global climate state and the character of climate extremes. As such, it offers a rich testbed for climate models that are used to project 21st century climate changes, which must account for natural as well as solar-, volcanic-, and greenhouse-forced climate variability.

Rising greenhouse gas concentrations reflect large-scale changes in the Earth's carbon cycle, such that studies of past changes in carbon fluxes and associated climate changes are highly relevant to projections of future anthropogenic climate change. Over the last million years, Earth has transitioned from glacial climate states characterized by markedly lower atmospheric CO_2 concentrations (200 parts per million) to interglacial climate states (280-300 parts per million) every ~100,000 years. Profound shifts in polar ice sheet mass, sea ice extent, sea level, ocean circulation, global temperature, precipitation patterns, and climate extremes accompanied these glacial-interglacial shifts. Abundant evidence of abrupt climate change during the last glacial period illustrate the potential for rapid climate responses to much slower changes in climate forcing – a high-risk but highly uncertain scenario for 21st century climate changes.

Much further back in geologic time, deep-sea sediments record a climate state when changes in the Earth's carbon cycle caused atmospheric CO_2 concentrations to climb to ~1000ppm – similar to levels expected in coming decades if emissions continue unabated. During this time, roughly 50 million years ago, global temperatures were as much as 8°C warmer, sea level was more than 20m higher, and ocean pH varied appreciably. While the rates of present-day atmospheric CO_2 change, temperature change, ocean pH change, and sea level rise are much higher than they were during past geologic intervals, these "hothouse" worlds hold key lessons for our climate future. This is especially true as models that were constructed and tested against instrumental climate data are charged with projecting climate changes that occur under vastly different conditions than today.

[START FAQ 1.3, FIGURE 1 HERE]

FAQ 1.3, Figure 1: Schematic of global temperature, atmospheric carbon dioxide concentrations, and global sea level during previous warm periods as compared to the pre-industrial era, present-day, and future climate change scenarios.

[END FAQ 1.3, FIGURE 1 HERE]

FAQ 1.4: How do we calculate global temperature change?

Global surface temperature change is calculated by analysing billions of thermometer readings, taken all over the globe, since the late-19th century. Some analysis methods use statistical techniques to account for areas where there are fewer measurements, such as the polar regions. Adjustments to the historical temperature readings are required because measurement standards have changed over time and these differences need to be accounted for to ensure a consistent record. Multiple independent groups of scientists work with an ever-increasing number of readings and produce very similar estimates for how global temperatures have changed since the late-19th century.

The surface temperature of the world has, on average, increased by around 1.1°C since the late-19th century – hence the term 'global warming'. Land areas have warmed more than ocean areas, with the Arctic warming fastest. Multiple scientific organizations produce global temperature datasets that rely on long-term measurements of the air near the surface over land and of the water at the ocean surface, collected by ships, buoys and satellites. Much like having multiple watches that may be set differently but still consistently count seconds and minutes, the numerous temperature measurements may all be calibrated slightly differently but still give comparable changes. For that reason, it is easier to measure temperature change than it is to measure the absolute average temperature of the Earth's surface.

Several issues arise when estimating changes in global temperature from a large set of measurements spread unevenly across the globe. One is how to deal with areas where measurements are sparse or mostly unavailable, such as close to the poles. While different groups producing temperature records all perform rigorous analyses in order to handle the fact that the measurements are not evenly distributed around the globe, they differ somewhat in how they treat areas with little or no information.

Another challenge is determining how to combine measurements taken over the ocean with measurements taken over land. Traditionally, measurements of the temperature of ocean surface water (taken from ships or buoys) have been combined with air temperature measurements over land (typically measured at 2 metres above the surface). However, analyses with global climate models have tended to use simulated air temperatures everywhere, not just over land. As air temperatures over the ocean can be expected to warm slightly faster than surface water, it is important to be consistent when comparing temperature measurements to models.

Importantly, adjustments do need to be made to historical temperature measurements to account for differences in how the readings were taken. For example, the standard time of day of recording temperature has changed in many regions, as has the type of equipment used on both land and on ships. If these differences were not accounted for then the record would not be consistent. When these adjustments are made, the observed total warming since the late 19th century is smaller than if the uncorrected data is used.

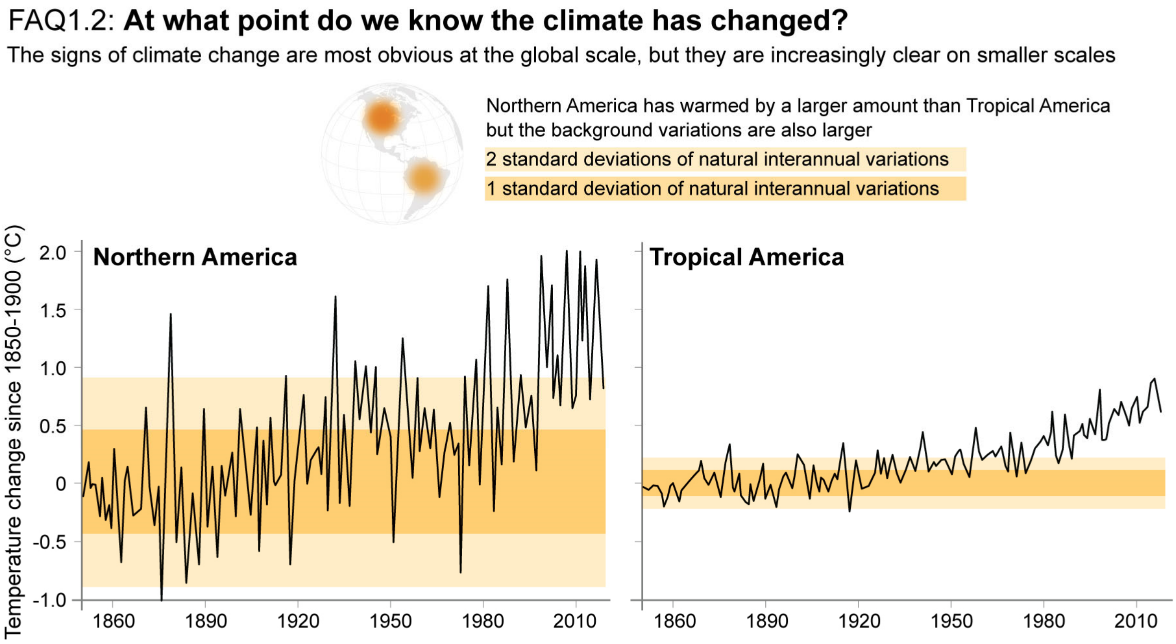
Lastly, calculating how much global temperatures have changed over time requires choosing a baseline reference period for comparison. Because temperatures vary naturally from year to year, scientists normally compute averages over at least 10 years to obtain a representative value – but which range of years to choose? For current temperatures, they naturally use recent decades; both 1995–2014 and 2009–2018 are used in various places in the AR6. The period before significant human influence is more difficult to define, partly because measurements were much more sparse in the 18th and 19th centuries. The period from 1850 to 1900 is used as an approximate representation of pre-industrial global temperatures, although there were probably human-induced changes before then.

[START FAQ 1.4, FIGURE 1 HERE]

FAQ 1.4, Figure 1: Suggestion: Global map of measurement site/point densities. With a side list of all the different techniques (e.g., buoys, satellites, ships etc – could have icons for each?) Present placeholder is from Rennie et al. (2014).

[END FAQ 1.4, FIGURE 1 HERE]

FAQ 1.1, Figure 1: [PLACEHOLDER]



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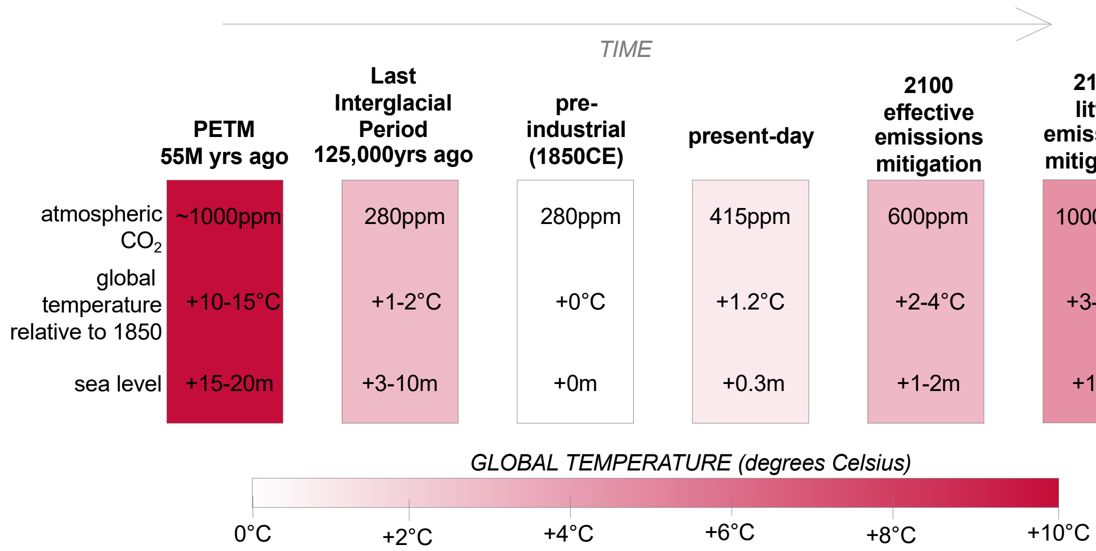

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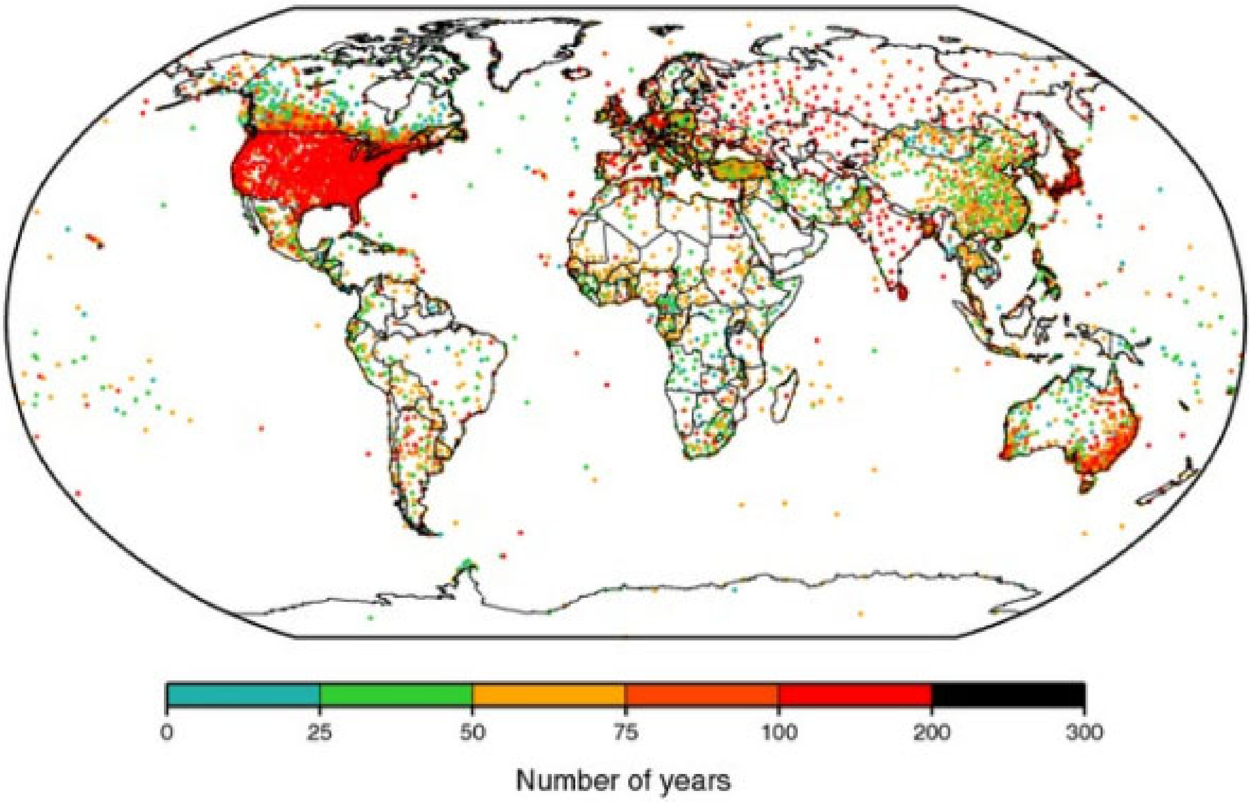

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Frequently asked questions

FAQ 2.1: The Earth's temperature has varied before. How is the current warming any different?

Summary: *Earth's climate has changed naturally over thousands of years, but both the rate and the global synchronicity of recent warming are unusual. The recent warming has reversed a long-term cooling trend and global temperature is likely higher now than it has been for millennia.*

While climate can be described by many variables, the temperature of the planet's surface is a key indicator of its overall climate state, and global mean surface temperature is fundamental to characterizing and understanding global climate change, including Earth's energy budget. A rich variety of geological evidence shows that temperature has changed throughout Earth's history. An assortment of widely distributed natural archives, such as ocean and lake sediments, glacier ice and tree rings, shows that there were times in the past when the planet was cooler, and times when it was warmer. While our confidence in quantifying large-scale temperature changes generally decreases the farther back in time we look, scientists can still identify several major differences between the recent warming and those of the past.

It's been a very long time since it's been this warm. Averaged over the globe, surface temperatures of recent decades were *likely higher* than anytime during the past 2000 years, and perhaps even much longer. Prior to the 20th century, global average temperature was slowly decreasing for as long as 6000 years. There is ongoing scientific discussion about whether the world is warmer now than it was before this long cooling trend began, and if so, we need to look back about 125,000 years, when sea level was around 8 metres higher, to find temperatures that were warmer than now. Regardless of how long it's been since it was this warm, the recent warming has reversed a long-term global cooling trend.

It's warming rapidly. Over the past 2 million years, Earth's climate has cycled between glacial periods, when ice sheets grew over vast areas of the northern continents, and interglacial periods that separate the ice ages. Intervals of rapid warming coincided with the collapse of Pleistocene ice sheets, heralding interglacial periods such as the present Holocene Epoch, which began about 12,000 years ago. During the shift from the last glacial period to the current interglacial, the total temperature increase was about 5°C. That change took about 5000 years, although the transition was not smooth, with a maximum warming rate of about 1.5°C per thousand years. In contrast, Earth has warmed nearly 1°C since 1850–1900. However, even the best reconstruction of global average temperature during the last deglacial period is still too coarsely resolved for direct comparison with a period as short as the past 150 years. But for the past 2000 years, we have higher-resolution records, mainly from tree rings, that show the rate of global warming during the last 50 years has exceeded the rate of any other 50-year period.

It's warming almost everywhere. When temperatures rose in the past, some regions warmed while others did not. For example, the North Atlantic region warmed more than many other regions and at different times during the Medieval Warm Period, between around 950 and 1250. While the pattern of recent warming shows similarities to past warmings – continents have warmed more than the ocean, and the Arctic more than the tropics – its footprint is more globally consistent than other climate fluctuations over at least the past two millennia.

Temperature fluctuations of the past occurred at times and at rates that can be attributed to large-scale processes that cause temperature to change, including changes in Earth's orbit, volcanic activity, and other natural influences. In contrast, the unusualness of recent warming in itself implicates the build-up of greenhouse gases as the driver of the recent warming. This, together with abundant evidence presented elsewhere in this report (including FAQ 3.3), shows that recent warming is unique in that it is primarily caused by human activities.

There is at least one other major difference between what we are experiencing now and previous warming periods: the human population has grown from fewer about 500 million to more than 7 billion in just the last four centuries, and that expansion has been accompanied by the development of modern societies and infrastructure. That growth has also put tremendous stress on ecosystems everywhere. As a result, not only is recent warming unusual in its rapidity and global extent, but also in its impact on ecological and societal systems. Warming is causing sea level rise, which can wreck coastal communities; it's affecting habitats, which exacerbates species extinction; and it's shifting water resources, which threatens food and water security. These and other effects of recent warming are occurring on top of stresses that make humans and nature vulnerable to changes in ways that they have never before experienced.

[START FAQ 2.1, FIGURE 1 HERE]

FAQ 2.1, Figure 1: Observational evidence for the unusualness of recent warming.

[END FAQ 2.1, FIGURE 1 HERE]

FAQ 2.2: What is the evidence for climate change?

Summary: *The evidence for climate change rests on more than just increasing surface temperatures. Evidence abounds from a broad range of indicators that collectively leads to the inescapable conclusion that we are witnessing rapid changes to all aspects of our global climate. We are seeing changes in the atmosphere, oceans, cryosphere, and throughout the biosphere. Our scientific understanding depicts a coherent picture of a warming world from the depths of the oceans to high in the atmosphere and at all points in between since the late 19th century.*

We have long observed our changing climate. From the earliest scientists taking observations in the 16th and 17th centuries to present we have seen a revolution in our ability to observe and diagnose our changing climate. Today we can observe diverse aspects of our climate system from space, from aircraft and weather balloons, using a range of ground-based observing technologies, and using instruments that can measure to great depths in the oceans.

Observed changes across a diverse range of key indicators of the climate system clearly point to a climate that has warmed since the Industrial Revolution. Global mean land and ocean surface temperature has increased since the late 19th century, with each of the last four decades being warmer than any decade that preceded it. Changes are also apparent in a variety of societally relevant weather and climate extremes. The temperature of the troposphere (i.e., the lowest 6 km-10 km of the atmosphere) has risen, with associated increases in atmospheric water vapor and evidence of rising precipitation. Aspects of atmospheric circulation have evolved as well, including a widening of the tropical Hadley Circulation, an expansion in the subtropical dry zone and a poleward shift of mid-latitude storm tracks.

Change has also transmitted to the depths of the global oceans. The heat content of the global oceans has increased since the 1970s, with more than 90% of the excess energy accumulated in the climate system being stored in the oceans. This has caused ocean warming and consequently ocean water to expand, which in turn has contributed to the observed increase in global sea level in the past century. The global ocean has also increased in acidity since the early 20th century as a result of increased carbon dioxide concentrations, and oxygen loss has occurred in the upper ocean since the 1970s.

Significant changes are also evident over the Cryosphere, the portion of the Earth where water is seasonally or continuously present as snow and ice. There have been decreases in Arctic sea ice area and thickness since the mid-1970s. Spring snow cover in the Northern Hemisphere has fallen since the late-1970s. In addition, there is an observed warming and thawing since the 1970s in many permafrost regions. The planet's two ice sheets (Greenland and Antarctica) are shrinking, as are the vast majority of glaciers worldwide, contributing strongly to the observed sea level rise.

Many aspects of the biosphere are also changing. Over the last century, long-term ecological surveys encompassing mammals, birds, invertebrates, and plants show that a broad array of species has generally moved poleward and upslope. There have been general increases in vegetation activity and extent (i.e., global greening) since the early 1980s, and the length of the growing season has increased over much of the extratropical Northern Hemisphere since at least the mid-20th century. There is also strong evidence that various phenological metrics for many species of marine organisms have changed in the last half century.

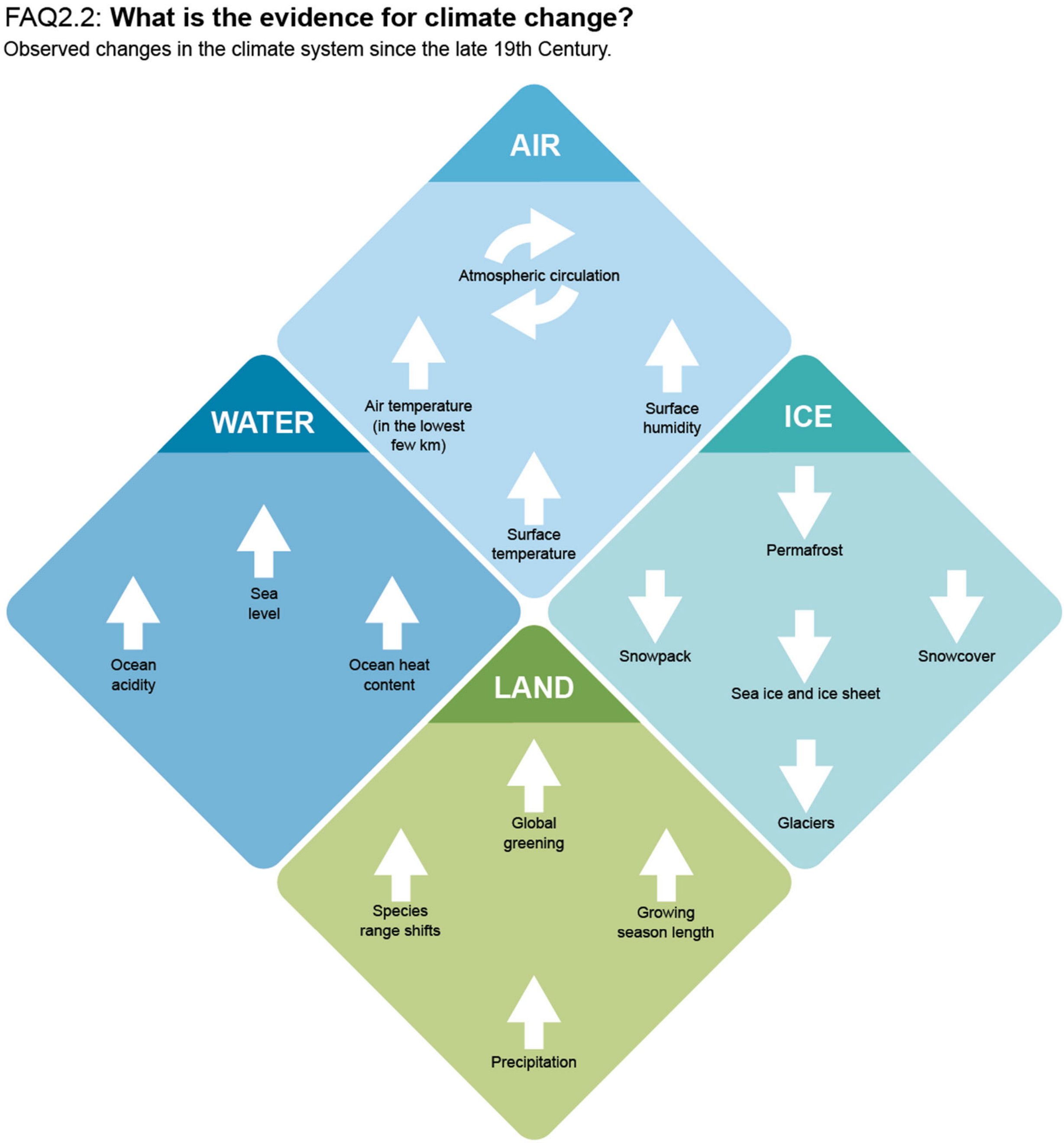
Change is apparent across many components of the climate system. It has been observed using a very broad range of techniques and analysed independently by numerous groups around the world. The changes are consistent in pointing to a climate system that has undergone rapid warming since the industrial revolution.

[START FAQ 2.2, FIGURE 1 HERE]

FAQ 2.2, Figure 1: Synthesis of significant changes observed in the climate system since the late 19th century. Independent analyses of many components of the climate system that would be expected to change in a warming world exhibit trends consistent with warming.

[END FAQ 2.2, FIGURE 1 HERE]

FAQ 2.1, Figure 1: Observational evidence for the unusualness of recent warming.



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Frequently Asked Questions

FAQ 3.1: How much of recent Climate Change is Actually Natural Variability?

Natural variability refers to variations in climate which are caused by processes other than human influence. It includes variability that is internally generated within the climate system, for example via modes of variability like the El Niño-Southern Oscillation, as well as externally driven climate variations driven by changes in solar brightness and by aerosols released from volcanic eruptions. Internally-driven natural variability corresponds to a redistribution of energy within the climate system that is most clearly observed as regional-scale fluctuations in climate. Externally driven natural variability is driven by changes to Earth's energy balance, and its impacts are most clearly observed in large scale climate indices like global mean surface temperature. While both forms of natural climate variability can cause large-scale climate changes, their influence on multidecadal trends is relatively small. This means that natural variability may play a prominent role in changes observed over one or two decades. However, as the observational period becomes longer, human-induced forcing changes become the dominant contributor to the observed climate changes, such that the large scale warming observed since 1900 is almost entirely driven by human influence.

Paleoclimatic records (indirect measurements that span back thousands of years) and computer models all show that global temperatures have, and are always changing – and that these changes can occur for many reasons. One of these reasons is natural variability, which refers to variations in climate that are either internally generated within the climate system or externally driven by natural forcing changes. As well as variations in solar brightness and volcanoes, changes in Earth's orbital characteristics can also create natural radiative forcing changes and have been related to large climate changes of the past. However, the orbital changes operate on very long time scales, meaning that they have had very little influence on the changes observed over the past century.

To understand which aspects of observed climate change have been caused by natural variability, scientists use climate model simulations. When only natural climate drivers are used to force climate models, which implicitly generate their own natural internal variability, the resulting simulations are generally called naturally-forced similations. These simulations show small variations in climate in response to volcanic eruptions, variations in solar brightness, and internal models of climate variability, but they do not show long-term warming trends comparable to that observed. Only when human influences, particularly greenhouse gases, are included do the models simulate warming comparable to that observed.

In reality, what both of these pieces of information combine to mean, is that on short time scales of a decade or less natural climate variability can dominate the human-induced warming trend, leading to periods with little warming. However, over periods longer than about twenty years, the impact of natural forcing is smaller than the human-induced warming-trend. Thus, warming will always be experienced. Another way to think of this is, although humans are causing recent increases in global temperatures, natural variability plays a role in how fast or slow temperatures rise. Much like riding a bike over hilly terrain, the bike is always going forward but the presence of the hills will either reduce or increase the speed.

[START FAQ 3.1, FIGURE 1 HERE]

FAQ 3.1, Figure 1: (Upper left) Climate model estimate of human-induced change in global average temperature. (Lower left) Representation of natural global average temperature variability from a climate model. (Right) The combined signal, which is similar to that observed. Overlying blue lines represent temperature changes during a period with strong naturally driven cooling, while red lines represent temperature changes during a period with strong naturally driven warming.

[END FAQ 3.1, FIGURE 1 HERE]

FAQ 3.2: Are Climate Models Improving?

Yes, climate models have improved and continue to do so. Models are now more suitable for capturing the complexities and small-scale processes of the climate system and compare better with observations for key climate variables. For decades, models have shown that changes to the climate come from man-made greenhouse gas emissions, but now our understanding of the impacts of these changes, and of the changes yet to come, are better than ever before.

Since the 1950s, scientists have used computer models to understand the Earth's climate. Fundamentally, models have improved due to advances in technology that allow for greater sophistication and more complex computer simulations, resulting in models that compare more closely with real-world observations of climate change. However, even the models used in the First Assessment Report of 1990 had skill at reproducing many aspects of climate, and their projections have since been generally validated by the actual evolution of climate.

Fundamentally, climate models generally solve equations based on the laws of physics (fluid mechanics, thermodynamics, light and infrared radiation, to name a few), usually by representing atmosphere, ocean, and land with discrete grid points distributed around the globe. The quantity and spacing of grid points defines the resolution – more grid points with less space between them result in higher-resolution simulations of Earth's climate system. Scientists also use more complex models called Earth System models that complement climate physics with representations of land and ocean biology (which are important for simulating carbon dioxide), atmospheric and oceanic chemistry, and sometimes more components, such as ice sheets.

The internal make-up of models continues to evolve, making them more suitable for simulating a variety of climate processes. This evolution is driven by improvements in our understanding of the climate system, our ability to represent that understanding of processes in terms of computer code, and the availability of increasingly powerful computers needed to run such code. The most recent generation of models often has improved resolutions in the atmosphere, ocean, and land domains. Higher resolution means, for example, that the ocean components of some climate models now explicitly simulate the 100 km-scale eddies that are responsible for much of oceanic heat transport. Unlike the previous generation of models, many of the latest-generation models now simulate higher levels of the atmosphere (above 50 km in altitude), meaning that coupling processes between the upper and lower atmosphere are now more realistic.

Earth system models that simulate changes in greenhouse gas and aerosol concentrations in response to changes in emissions (rather than having these changes prescribed) are becoming more common. For carbon dioxide concentrations, this means that these models include interactive representations of the absorption of carbon dioxide by plants on land and by the ocean and how these systems respond to climate and environmental change, including for example the impacts of ocean warming and acidification on ocean biology.

Progress in climate modelling is gradual, and more remains to be achieved. For example, it is still impossible to explicitly simulate atmospheric convection globally for multidecadal timescales. However, key aspects of climate are now better simulated than in previous model evaluations. We know this through comparisons against observational estimates, often using multiple climate variables. For example, model simulations of near-surface temperature, precipitation, and sea-level pressure compare better against their observational references for recent decades (for which these references are most reliable; FAQ 3.1, Figure 1), although in most cases the improvement is only gradual. A prime example is surface temperature, which was already well simulated in previous intercomparisons, so simulations of surface temperature only improved marginally in the current generation of models. Precipitation, a key aspect of climate which was problematic in previous evaluations, is now better captured than in the previous generation of models (see also FAQ 7.1). However, climate models still do not operate at the resolution of about 1 km needed to realistically represent clouds. An evaluation of the simulations informing the last three Assessment Reports of IPCC shows that for most atmospheric metrics (three of which are shown in Figure 1), the models of each generation as a group outperform those of the previous generation regarding the simulation of mean climate. Such improvements in comparison with observations illustrate the increasing skill of models at simulating current climate.

[START FAQ 3.2, FIGURE 1 HERE]

FAQ 3.2, Figure 1: Centred pattern correlations between models and observations for the annual mean climatology over the period 1980–1999 for three different variables: surface air temperature, precipitation and sea level pressure. Results are shown for individual CMIP3 (black), CMIP5 (blue) and CMIP6 (brown) models as short lines, along with the corresponding ensemble average (long line). The correlations are shown between the models and the reference observational data set. In addition, the correlation between the reference and alternate observational data sets are shown (solid grey circles). To ensure a fair comparison across a range of model resolutions, the pattern correlations are computed at a resolution of 2.5º in longitude and 2.5º in latitude. Only one realization is used from each model from the CMIP3, CMIP5 and CMIP6 historical simulations. (Figure produced with ESMValTool v2.0.0b2.)

[END FAQ 3.2, FIGURE 1 HERE]

FAQ 3.3: How do we Know Humans are Responsible for Climate Change?

Synthesizing information from observations of climate change, from paleoclimate records that can show changes over the past thousands of years, and from computer models that can simulate past climate change based on physical principles, allows us to clearly identify the dominant role of humans in driving recent climate change.

Climate is influenced by a range of factors. The main natural drivers of climate change on timescales of decades to centuries are variations in the sun's brightness, and large volcanic eruptions which cause an increase in the number of small particles (aerosols) in the upper atmosphere for several years, which reflect sunlight and cool the surface. The main human drivers of climate change are increases in the concentration of greenhouse gases, which trap infrared radiation near the surface and warm the climate, and of aerosols from burning fossil fuels and other sources, which, like those produced naturally by volcanoes, on average have a cooling influence by increasing the reflection of sunlight. Multiple lines of evidence demonstrate that human drivers are the main cause of recent climate change.

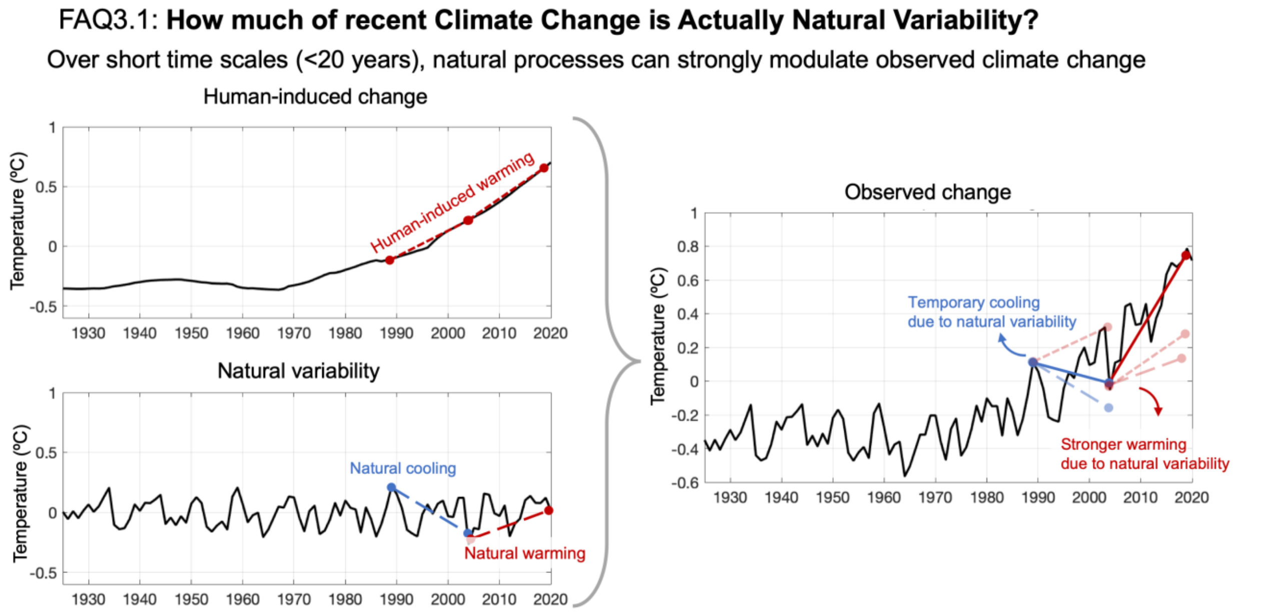
Firstly, the current rates of increase of the concentration of the major greenhouse gases (carbon dioxide, methane and nitrous oxide) are unprecedented over at least the last 22,000 years. Multiple lines of evidence show that these increases are the results of human activities. The basic physics underlying the warming effect of greenhouse gases on the climate has been understood for more than a century, and our latest understanding is encapsulated in the latest generation climate models. Like weather forecasting models, climate models represent the state of the atmosphere on a grid, and simulate its evolution over time based on physical principles. They include a representation of the ocean, sea ice and the main processes important in driving climate and climate change. Results consistently show that such climate models can only reproduce the observed warming (black line in FAQ 3.3, Figure 1) when including the effects of human activities (orange band in FAQ 3.3, Figure 1), in particular the increasing concentrations of greenhouse gases. These climate models show a dominant warming effect of greenhouse gas increases (grey band, which shows the warming effects of greenhouse gases by themselves), which has been partly offset by the cooling effect of increases in atmospheric aerosols (blue band). By contrast, simulations that include only natural processes, including internal climate variability related to El Niño and other similar variations, as well as variations in solar brightness and emissions from large volcanoes (green band in FAQ 3.3, Figure 1), are not able to reproduce the observed warming – they simulate much smaller temperature trends, indicating that these natural factors cannot explain the strong warming rate observed.

An additional line of evidence for the role of humans in driving climate change comes from comparing the rate of warming observed over recent decades with that which occurred prior to human influence on climate. Evidence from tree rings and other paleoclimate records shows that the rate of increase of global mean surface temperature observed over the past fifty years far exceeded that which occurred in any previous 50-year period over the past 2000 years. Taken together this evidence shows that humans are the dominant cause of observed global warming over recent decades.

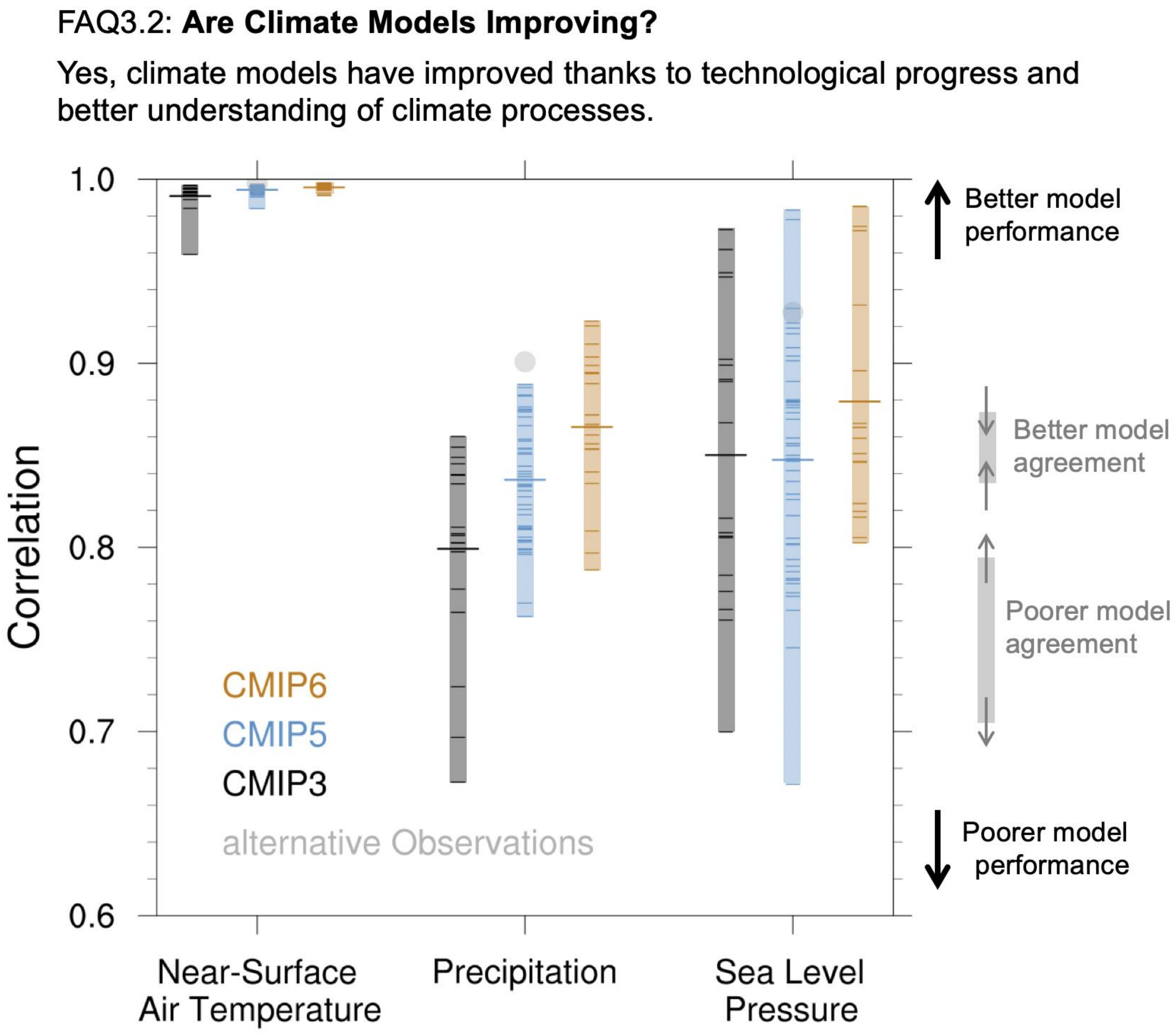
[START FAQ 3.3, FIGURE 1 HERE]

FAQ 3.3, Figure 1: Global average changes in surface air temperature in observations (HadCRUT4), compared to climate model simulations of the response to all human and natural forcings (grey band), greenhouse gases only (red band), aerosols only (blue band) and natural forcings only (green band). Solid coloured lines show the multi-model mean, and coloured bands show the 5–95% range of individual simulations.

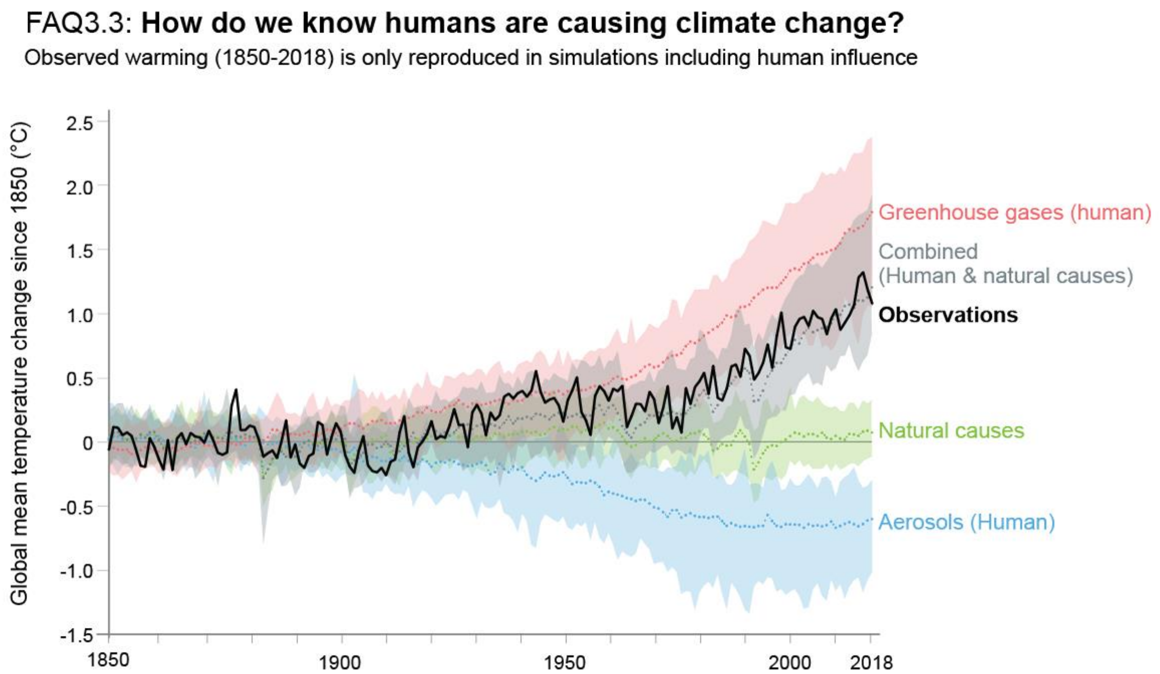
[END FAQ 3.3, FIGURE 1 HERE]



FAQ 3.1, Figure 1: (Upper left) Climate model estimate of human-induced change in global average temperature. (Lower left) Representation of natural global average temperature variability from a climate model. (Right) The combined signal, which is similar to that observed. Overlying blue lines represent temperature changes during a period with strong naturally driven cooling, while red lines represent temperature changes during a period with strong naturally driven warming.



FAQ 3.2, Figure 1: Centred pattern correlations between models and observations for the annual mean climatology over the period 1980–1999 for three different variables: surface air temperature, precipitation and sea level pressure. Results are shown for individual CMIP3 (black), CMIP5 (blue) and CMIP6 (brown) models as short lines, along with the corresponding ensemble average (long line). The correlations are shown between the models and the reference observational data set. In addition, the correlation between the reference and alternate observational data sets are shown (solid grey circles). To ensure a fair comparison across a range of model resolutions, the pattern correlations are computed at a resolution of 2.5º in longitude and 2.5º in latitude. Only one realization is used from each model from the CMIP3, CMIP5 and CMIP6 historical simulations. (Figure produced with ESMValTool v2.0.0b2.)



FAQ 3.3, Figure 1: Global average changes in surface air temperature in observations (HadCRUT4), compared to climate model simulations of the response to all human and natural forcings (grey band), greenhouse gases only (red band), aerosols only (blue band) and natural forcings only (green band). Solid coloured lines show the multi-model mean, and coloured bands show the 5–95% range of individual simulations.

Frequently Asked Questions

FAQ 4.1: What Can We Say about How the Climate Will Change over the Next Twenty Years?

Many aspects of the climate system, including global average temperatures, Arctic sea ice cover, and sea levels, have shown clear increasing or decreasing trends in recent decades, and we expect most of these trends to continue for at least the next twenty years. Our confidence in that conclusion derives from the expectation that radiative forcing from greenhouse gases will continue to increase as a result of continued emissions, from our understanding of the physics of the climate system, and from our confidence in model simulations of the global-scale changes that will result from the increase in radiative forcing. However, estimates of the magnitude of these near-term changes are much more uncertain, mainly because natural internal variability can in the near term mask – and for some quantities even overwhelm – the response of the climate to increased radiative forcing.

There is a clearly recognized societal need for information about climate change over the near term, defined here as the next twenty years. When providing this information, however, we must distinguish between two different contributions to the changes we expect to see. The first contribution is the expected response of the climate system to the increase in radiative forcing implied by the continued emissions of greenhouse gases over the next twenty years in virtually all available scenarios. A second contribution arises from the natural internal variability caused by chaotic processes in the atmosphere and the ocean, ranging from localized weather systems to larger-scale patterns and oscillations that change over months, years, or decades. In the near term, natural internal variability plays a major role relative to the response to increased radiative forcing, so time averages or trends calculated over twenty years contain a substantial chaotic element.

Natural internal variability can be predicted to some extent, provided that model simulations are started from accurate observations of the current state of the climate system. Near-term climate predictions do not attempt to forecast individual weather events, but instead provide information such as how much warmer or colder future years will be on average, compared to the year just passed. Forecast quality or 'skill' is achieved because some elements of the climate system, primarily the oceans, vary on long time scales such as years to decades. Current climate models have some skill in predicting these slow variations, such that useful statements about the future state of natural internal variability can be made out to about ten years ahead. However, looking ahead for twenty years, there are indications that for most quantities of interest, natural internal variability will never be predictable. This implies that natural internal variability causes some uncertainty that can at best be quantified accurately but that cannot be reduced.

FAQ 4.1, Figure 1 illustrates the near-term interplay between natural internal variability and the expected response to further increased radiative forcing for two important indicators of global climate change, the globally averaged surface air temperature and the Arctic sea ice area in September. The figure shows projected changes relative to the time-average over the period 1995–2014 for simulations with different climate models and one low-emission and one high-emission scenario. Viewed over all simulations, the global temperature tends to increase, and the sea-ice area tends to decrease, but each individual simulation shows the large influence of natural internal variability. One source of uncertainty, however, is not pronounced over the next twenty years. The choice of emissions scenario has little impact on the results – in stark contrast to simulation results for the end of the 21st century shown by the bars to the right of the figure. This reduced dependence on the scenario arises because virtually all scenarios assume that greenhouse gas emissions will continue over the next twenty years, leading to increased greenhouse gas concentrations and hence increased radiative forcing over the near term.

Since the period 1995–2014 has been warmer than the period 1850–1900 by about 0.9°C, we notice from FAQ 4.1 Figure 1 that a global warming of 1.5°C above the pre-industrial level may well occur within the next twenty years.

[START FIGURE FAQ 4.1, FIGURE 1 HERE]

FAQ 4.1, Figure 1: Simulations over the period 1995–2040, encompassing the recent past and the near-term future, of two important indicators of global climate change, (a) globally averaged surface air temperature, and (b), the area of Arctic sea ice in September. Both quantities are shown as deviations from the average over the period 1995–2014. The grey curves are for the historical period ending in 2014; the colours refer to one low- and one high-emission SSP scenario as shown in the inlet. In (a), the bars to the right show the range of simulated values for year 2100. In (b), some models simulate an ice-free Arctic in September already in the near term, which is why they show no further decrease. [Placeholder figure, based on eleven currently available CMIP6 models. To be updated with other CMIP6 models and, possibly, shading for indicating uncertainty.]

[END FIGURE FAQ 4.1, FIGURE 1 HERE]

FAQ 4.2: How Quickly Would We See the Effects of Reducing Greenhouse Gas Emissions?

Over many decades, reductions in greenhouse gas emissions would limit the amount of surface warming and changes in many other aspects of the climate system. In the first few decades after emissions reductions begin, however, the effects on the climate system will be difficult to diagnose, both because the climate system takes some time to respond to the emissions reduction and because natural internal variability will mask the climate system response to the reductions. Emissions reductions are expected to leave a discernible fingerprint on atmospheric CO_2 concentrations after about ten years and on global surface temperature after about 20–30 years. An effect of mitigation on regional precipitation trends is expected only later in the 21st century.

Reducing emissions of CO_2 – the most important greenhouse gas – would slow down the increase in atmospheric CO_2 concentrations; however, concentrations will only begin to decrease when emissions approach zero. This delay in response is a manifestation of the very long lifetime of CO_2 in the atmosphere. As a consequence, the radiative forcing will first also continue to increase, although at a detectably smaller rate after about ten years. This smaller rate of increase in radiative forcing is expected to lead to a smaller rate of global surface warming. But this reduction in the rate of warming will be overlain by natural internal variability, which is caused by chaotic processes in the atmosphere and the ocean, such as the ever-changing weather. Detecting whether surface warming has indeed slowed down will thus be difficult in the decades right after emissions reductions begin.

There has been some recent research on this detection problem, but not enough for a broad quantitative consensus to have emerged. A number of issues need to be considered. For example, there is no unambiguous definition of a no-mitigation emissions pathway against which emissions reductions can be defined. Furthermore, this detection problem – which is analogous to detecting human-induced climate change in the observed record of the past – becomes more difficult on the regional scale and for many quantities other than temperature.

FAQ 4.2 Figure 1 illustrates when the benefits of mitigation may be detectable for globally averaged surface air temperature for two scenarios: one where emissions begin to fall after 2020 (SSP1-2.6) and one without mitigation (SSP3-7.0). For each year from 1995 to 2100, the figure shows the temperature trend over the preceding twenty years. The uncertainty arising from natural internal variability in the climate system is represented by simulating each scenario fifty times with the same climate model but starting from slightly different initial states in 1850; for each scenario, the differences between individual simulations are caused entirely by simulated natural internal variability. The average over all fifty simulations represents the expected climate response for a given scenario. The climate history that will actually unfold under each scenario would consist of this expected response combined with the contribution from natural internal variability.

Diagnosing the time of detection of mitigation benefit depends on the criterion applied: how certain does one want to be? For the model chosen here, which is relatively sensitive to higher greenhouse gas concentrations and therefore shows a relatively large difference between scenarios, it takes a bit over twenty years before detection is certain. Certain detection is displayed in FAQ 4.2 Figure 1 by the lack of overlap between the ranges of each scenario. Less-than-certain detection can be diagnosed earlier. With the same level of natural internal variability but smaller differences in the responses to different scenarios, detection would occur later than displayed here.

Detection of a discernible effect of CO_2 emissions reductions on atmospheric CO_2 concentrations is expected earlier than for temperature, after about ten years assuming reductions as in Scenario SSP1-2.6. A detectable effect of mitigation on regional precipitation trends is expected only later in the 21st century under the same scenario. In summary, the benefits of mitigation are clearly discernible in crucial climate variables such as global temperature only after a delay of a few decades – a delay that might cause a substantial communication challenge.

[START FIGURE FAQ 4.2, FIGURE 1 HERE]

FAQ 4.2, Figure 1: Illustrating when the benefits of emissions reduction might become detectable in globally averaged surface air temperature. The figure shows twenty-year linear trends, and the time axis is defined such that in each year, the trend over the preceding twenty years is displayed. Shown are the results from a single CMIP6 model, CanESM5, run under one scenario that can be considered to represent no mitigation (SSP3-7.0) and one scenario that represents mitigation (SSP1-2.6). For each scenario, the model is run fifty times with very slightly different conditions for the year 1850 (each scenario simulation starts from the end of a historical simulation ending in 2014). Differences between individual runs are caused by simulated natural internal variability and can be considered an uncertainty that cannot be reduced. The figure shows the average of all fifty simulations as full-drawn lines and the individual simulations as shaded lines. Three time periods are highlighted, by showing the distribution of simulated twenty-year trends for each scenario, calculated retrospectively in years 2040 (trend over the near-term period), 2060 (trend over the mid-term period), and 2100 (trend over the long-term period). The filled circle shows the average over all fifty simulations, and the bars show the ranges of simulations in each scenario.

[END FIGURE FAQ 4.2, FIGURE 1 HERE]

FAQ 4.3: At a Given Level of Global Warming, What are the Spatial Patterns of Climate Change?

As the planet warms, climate change does not unfold uniformly across the globe, but some patterns of regional change show clear and direct relationships to increases in global average temperature. For example, the Arctic warms more than other regions, land areas warm more than the oceans, and the Northern Hemisphere warms more than the Southern Hemisphere. In cases like these, we can infer the direction and magnitude of some regional changes – particularly temperature changes – for any given level of global warming.

There are two main advantages to identifying a robust pattern of regional change – one for which there is *high confidence* based on strong evidence and a good understanding of the physical process involved – for a given level of global warming. First, such a pattern enables us to make statements about expected regional change that are largely independent of the various future scenarios used to project global temperature changes. As long as different scenarios result in the same global warming level, irrespective of the time when this level is attained in each scenario, we can with *high confidence* specify the expected regional change that would result from this warming. Second, we can reliably make projections for warming levels that have not been directly analysed or simulated explicitly. For example, if a change pattern per degree Celsius of global surface warming is identified reliably, the expected regional change can be calculated for any global warming level by simple multiplication ('scaling') of the pattern. This approach can be highly efficient for studies of climate impacts at regional scales. When patterns of changes are robust, impact assessments can readily be performed for all levels of global warming, for all future time periods, and for all scenarios.

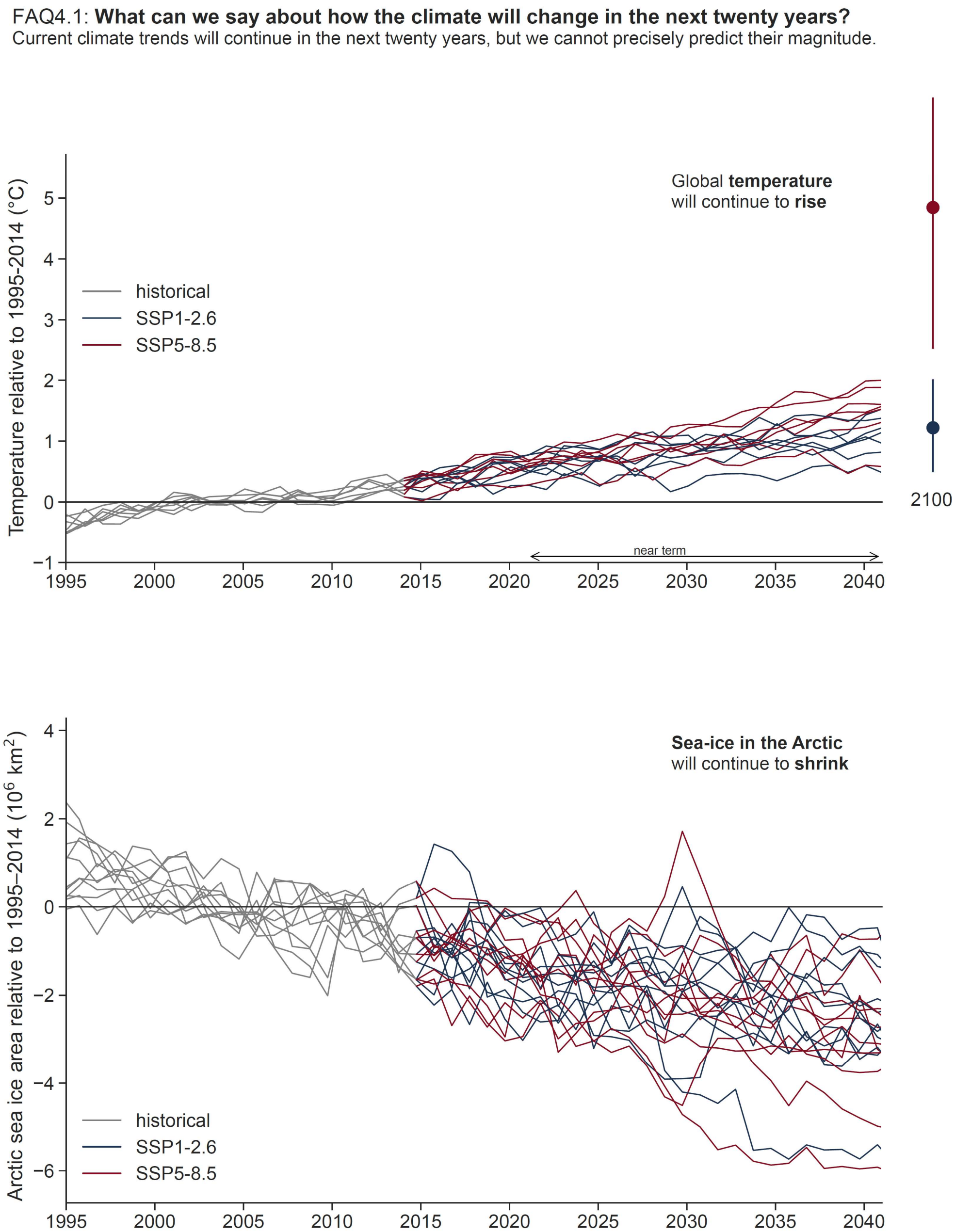
Pattern scaling has some well-known strengths and weaknesses. It yields robust estimates for temperature changes at a given level of global warming, but there are limitations in areas of high natural internal variability that become particularly evident at low levels of warming and for seasonal changes, for areas with strong feedbacks due to melting snow or sea ice, and for areas with large differences between transient and very-long-term changes. Patterns are less robust for precipitation changes, for reasons that are likewise quite well understood. Global and regional changes in precipitation depend not only on changes in globally averaged temperatures but also on human influences on regional climate, such as emissions of particulate matter (known as aerosols) and land-use changes. Furthermore, regional precipitation changes are more strongly influenced by natural internal variability in the atmosphere, meaning that any given surface warming level can result in quite different spatial changes in precipitation. Pattern scaling can still be applied to precipitation changes, but the uncertainties are larger than for temperature changes.

Finally, there are climate variables for which pattern scaling is not appropriate. For example, robust patterns cannot be established for changes in snow or sea ice cover, because both snow and ice vanish completely if certain temperature thresholds are crossed. If snow cover in an area melts completely, there can be no further melting, and the simple proportionality lying behind pattern scaling no longer applies. Changes in these bounded variables are better described by whether a threshold is crossed or not.

[START FAQ 4.3 FIGURE 1 HERE]

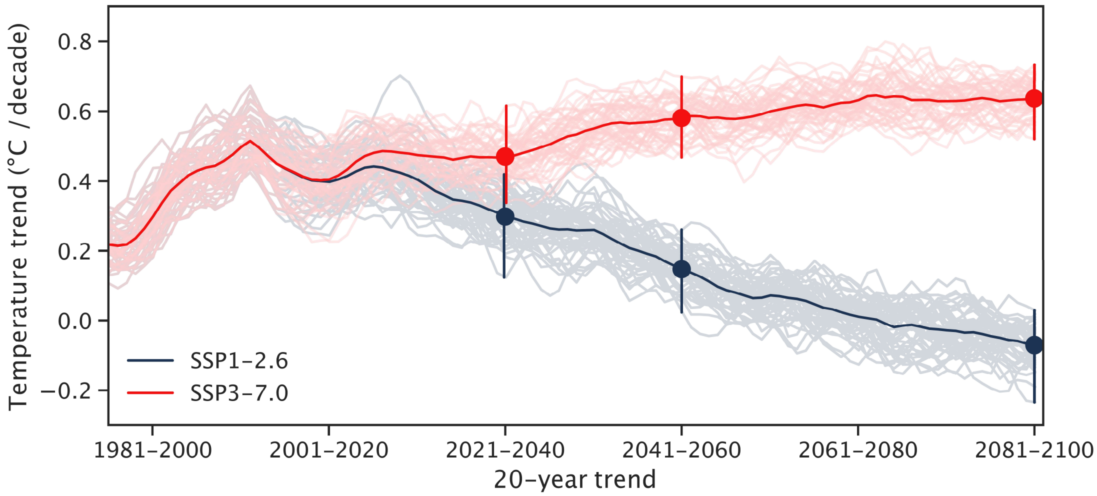
FAQ 4.3, Figure 1: Example for a robust warming pattern, which is presented here as the average of fourteen CMIP6 models using the scenario SSP3-7.0. Surface warming relative to 1850–1900 is shown for time periods over which the globally averaged surface warming is 1.5°C, 2°C, and 3°C, respectively. We recognise the strong warming over the Arctic, generally stronger warming over land than over the ocean, generally stronger warming in the Northern Hemisphere than in the Southern Hemisphere, and less warming over the central subpolar North Atlantic.

[END FIGURE FAQ 4.3, FIGURE 1 HERE]



FAQ 4.1, Figure 1: Simulations over the period 1995–2040, encompassing the recent past and the near-term future, of two important indicators of global climate change, (a) globally averaged surface air temperature, and (b), the area of Arctic sea ice in September. Both quantities are shown as deviations from the average over the period 1995–2014. The grey curves are for the historical period ending in 2014; the colours refer to one low- and one high-emission SSP scenario as shown in the inlet. In (a), the bars to the right show the range of simulated values for year 2100. In (b), some models simulate an ice-free Arctic in September already in the near term, which is why they show no further decrease. [Placeholder figure, based on eleven currently available CMIP6 models. To be updated with other CMIP6 models and, possibly, shading for indicating uncertainty.]

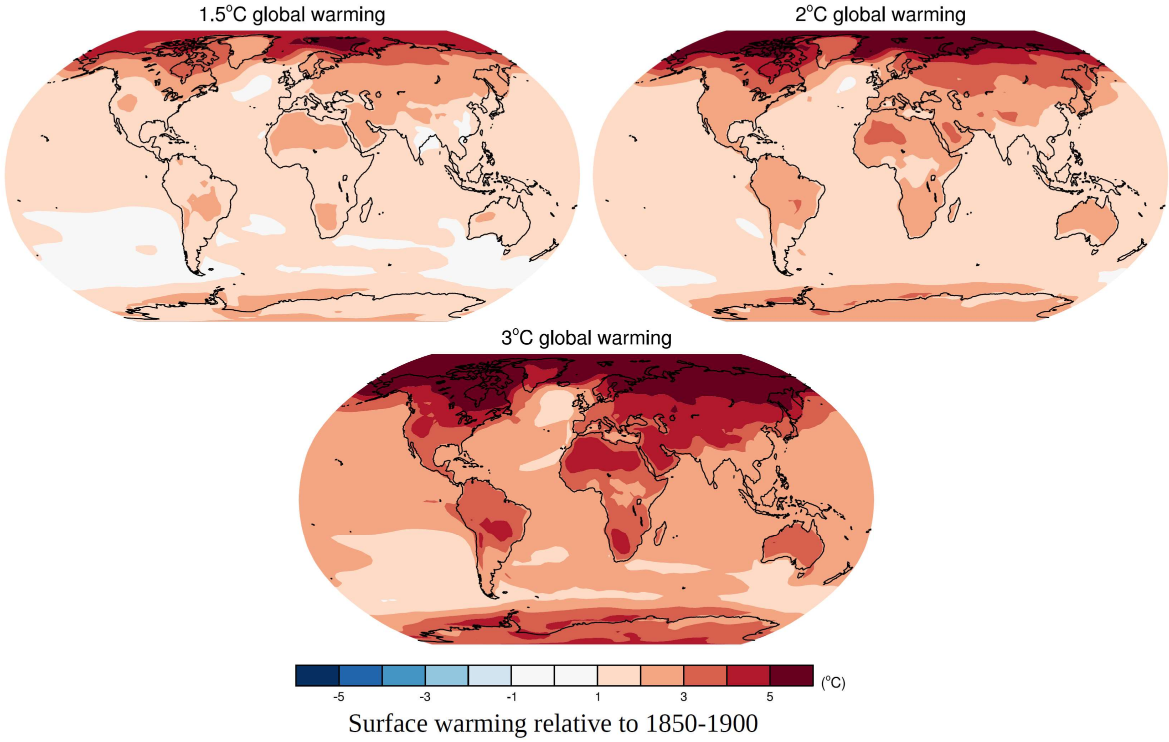
FAQ4.2: **How quickly would we see the effects of reducing greenhouse gas emissions?**
It will take 20 to 30 years to see the effect of greenhouse gas reduction on global temperature



FAQ 4.2, Figure 1: Illustrating when the benefits of emissions reduction might become detectable in globally averaged surface air temperature. The figure shows twenty-year linear trends, and the time axis is defined such that in each year, the trend over the preceding twenty years is displayed. Shown are the results from a single CMIP6 model, CanESM5, run under one scenario that can be considered to represent no mitigation (SSP3-7.0) and one scenario that represents mitigation (SSP1-2.6). For each scenario, the model is run fifty times with very slightly different conditions for the year 1850 (each scenario simulation starts from the end of a historical simulation ending in 2014). Differences between individual runs are caused by simulated natural internal variability and can be considered an uncertainty that cannot be reduced. The figure shows the average of all fifty simulations as full-drawn lines and the individual simulations as shaded lines. Three time periods are highlighted, by showing the distribution of simulated twenty-year trends for each scenario, calculated retrospectively in years 2040 (trend over the near-term period), 2060 (trend over the mid-term period), and 2100 (trend over the long-term period). The filled circle shows the average over all fifty simulations, and the bars show the ranges of simulations in each scenario.

FAQ 4.3: What are the spatial patterns of climate change?

Climate change is not uniform, warming will be stronger in the Arctic, the Northern Hemisphere and on land



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Frequently Asked Questions

FAQ 5.1: Is the rate at which nature removes carbon from the atmosphere slowing down?

For decades, nature has removed about half of the carbon dioxide (CO_2) that human activities have emitted to the atmosphere by increasing the amount of carbon stored in vegetation, soils and oceans. This removal of CO_2 has thus roughly halved the rate at which atmospheric CO_2 concentrations have increased, and therefore slowed down global warming. There is as yet no observable evidence that this natural removal is slowing down or that the processes underlying this removal are changing.

Since CO_2 concentrations in the atmosphere have been measured, commencing in 1958, only about half of yearly emissions from the combustion of fossil fuels and land-use change (for example, deforestation) have remained in the atmosphere. Natural carbon sinks, processes on land and oceans that remove CO_2 from the atmosphere, have removed the other half of the emissions.

The key land process that removes CO_2 from the atmosphere is plant photosynthesis, which for most plants increases as the concentration of atmospheric CO_2 rises, due to what is known as the CO_2 fertilisation effect. In cold regions, longer growing seasons due to global warming also contribute to increased land CO_2 uptake.

A large part of the CO_2 captured by photosynthesis is lost back to the atmosphere through respiration or natural disturbances (such as fires and wind throw). Human activities (for instance, de- and reforestation, land degradation, nitrogen deposition, air pollution) also influence the net removal of carbon by the land biosphere. The net balance between removals by photosynthesis and losses is the carbon sequestered which we call the net land carbon sink.

The processes involved in how much carbon is ultimately sequestered is affected by climate factors, and so as climate changes, the amount of carbon sequestered will change too. Regionally, extreme temperatures and droughts tend to reduce the land sink, a process that is for instance, often observed during El Niño years, a periodic climate event during which parts of the Earth's surface have well above average temperatures. The natural land sink varies strongly from year to year, making it challenging to detect long-term trends.

In the ocean, the CO_2 uptake is driven by several factors: the difference in CO_2 concentration between the atmosphere and the surface ocean (approximately the upper 50 m but change seasonally), the chemical capacity of seawater to take up CO_2 (or buffering capacity), wind speeds at the ocean surface, and the use of CO_2 in photosynthesis by phytoplankton. All these processes are known to be dependent on temperature, with a tendency to weaken ocean uptake under warmer conditions. The CO_2-enrich surface ocean water is transported to the deep ocean in specific zones around the globe (such as the Northern Atlantic and the Southern Ocean), effectively storing the CO_2 away from the atmosphere for many decades to centuries.

Remarkably, both the land and ocean sinks have been growing largely proportional to the increase in CO_2 emissions. This has made the airborne fraction, the fraction of yearly CO_2 emissions staying in the atmosphere, to remain on average unchanged over the last six decades despite continuously increasing CO_2 emissions from human activities. There is currently no evidence that the land or ocean sink are slowing down.

The fact that both the land and ocean sink respond to excess anthropogenic CO_2 in the atmosphere, suggests that the absolute amount of CO_2 removed by the land and ocean will vary in proportion to future anthropogenic emissions. This implies that if countries manage to strongly reduce global CO_2 emissions or reach net zero or negative emission levels, these sinks will become smaller. Regardless the future trajectory of emissions from human activities, the ocean sink will become smaller in the future because the buffer capacity to continue uptake CO_2 will diminish at the same time the warming of the ocean will further reduce its capacity to remove CO_2. For the land sink, model simulations suggest that if emissions are not reduced sufficiently to cap warming at 2°C, the combined effect of reduced the CO_2 fertilisation effect and climate change is likely to weaken the land sink in the second half of this century. In summary, CO_2 sinks will change in the future and understanding the magnitude of change will be important to design mitigation pathways.

[START FAQ 5.1, FIGURE 1 HERE]

FAQ 5.1, Figure 1: Overview of the global carbon budget and the fraction of CO_2 remaining in atmosphere, land and ocean from 1960 to 2019. Estimates are derived from atmospheric observations, process-based models, data-driven ocean flux products, and atmospheric inversions (Le Quéré et al., 2018a). Dots denote yearly values, lines are the seven years running mean.

[END FAQ 5.1, FIGURE 1 HERE]

FAQ 5.2: Can thawing permafrost on land or under the ocean substantially increase global temperatures?

Carbon released as carbon dioxide (CO_2) or methane (CH_4) as a result of increased rates of decomposition in thawing permafrost soils may add an additional amount of warming, that is significant enough that it should be considered in carbon estimates, but does not appear to be a process that will lead to runaway warming. Warming of frozen sediments beneath the ocean and deeper on land appears to be a weaker potential source of greenhouse gases.

Across Arctic ecosystems, where deep soils remain frozen throughout the year, there are enormous amounts of carbon in accumulated soil organic matter: more than twice the amount of CO_2 that is currently in the atmosphere. This carbon has built up over thousands of years, through the growth of plants that become thick organic litter layers when they die, which then can be buried into deeper, permanently-frozen soil layers, where the cold conditions slow the rate of their decomposition for as long as the soils remain frozen. These processes have led permafrost soils to act as carbon sinks historically, but experiments have shown that, by warming these ecosystems, the carbon in these soils will begin to decompose rapidly and return to the atmosphere as either CO_2 or CH_4, which are both important greenhouse gases. Climate models project that much of the near-surface permafrost (<3m depth) throughout the Arctic would thaw under moderate (2–3°C) to high amounts (more than 4°C) of global warming, and thus the carbon stored in this ecosystem is at risk.

Thawing of permafrost carbon has already been observed to have begun due to the rapid warming experienced in the Arctic, where air temperatures have increased twice as fast as the global average. With this thawing there are measurements showing very old carbon frozen for thousands of years being emitted to the atmosphere and transported into waterways. There are many processes that can speed up the loss of carbon from these northern ecosystems. Melting of massive blocks of ice in the soils can cause the landscape to sink and erode. Ponds and lakes that are common in some Arctic ecosystems can expand and move across the landscape. Thick surface organic layers can dry out in warmer summers and catch fire, leading to further permafrost thaw. Some processes may partially offset carbon losses: warming also releases nutrients during decomposition to increase soil fertility, and warmer and longer growing seasons favour plants to grow and store carbon, which is being observed in some regions of tundra.

While these processes are complex, they are beginning to be included in models that represent the climate and the carbon cycle in an interactive manner. The projections from these models show a wide range in the estimated strength of a carbon-climate self-reinforcing loop, of approximately 20 ± 13 PgC as CO_2 per °C global temperature change, and also provide some clear insights. Firstly, this extra warming is strong enough that it must be included to estimate the total amount of emissions permitted to stabilise the climate at a given level. However, it is not so strong that they would lead to warming that is greater than the warming from fossil fuel burning. Finally, emissions of greenhouse gases from permafrost are projected to be higher under high emissions scenarios.

In addition to carbon within permafrost soils, concern has been raised about carbon frozen in sediments deep below the soils of permafrost ecosystems or frozen in ocean sediments, known as methane hydrates or clathrates, which are methane molecules locked within a cage of ice molecules. Hydrates are stable at low temperatures and high pressures, conditions that are found below permafrost and in ocean sediments. As global warming affects both the permafrost and the oceans, there are concerns this warming could destabilise hydrates, releasing methane into the atmosphere and significantly exacerbating climate change.

The global marine hydrate reserve is currently estimated at 2000 PgC, which is smaller than initially thought. Global warming takes millennia to penetrate into the deep ocean and reach these hydrates, so the hydrate that could be destabilised during a century timescale is a small fraction of the total estimated marine hydrate reserve. Finally, even when methane is released from hydrates, most of it is expected to be either consumed or oxidised to carbon dioxide in the ocean before reaching the atmosphere. The most complete modelling of these processes to date suggests a release of less than 5 $TgCH_4\ yr^{-1}$ over the next century, which is less than 2% of current anthropogenic methane emissions.

[START FAQ 5.2, FIGURE 1 HERE]

FAQ 5.2, Figure 1: [Figure Placeholder: Schematic of the processes that affect permafrost thawing (what speeds up or slows down the release of GHG emissions.)]

[END FAQ 5.2, FIGURE 1 HERE]

FAQ 5.3: Can negative emissions reverse climate change?

Negative emissions refer to the deliberate removal of carbon dioxide (CO_2) from the atmosphere. If deliberate CO_2 removal exceeds anthropogenic CO_2 release, emissions are said to be net negative. The effect of negative emissions on atmospheric CO_2 depends on the balance between anthropogenic CO_2 releases, deliberate removals and removals by natural carbon sinks. Generally, net negative emissions result in a decline in atmospheric CO_2. However, because of the delayed reaction of many climate system components such as vegetation, soils, the deep ocean, ice sheets, a decline in atmospheric CO_2 would not result in immediate attenuation of climate changes. While some parts of the Earth's climate system such as surface air temperature would follow a decline in atmospheric CO_2 quite rapidly, others would take decades to millennia to react.

Negative emissions refer to removal of carbon dioxide (CO_2) from the atmosphere by deliberate human activities; that means, in addition to the removal that would occur naturally. The term negative emissions is often used as synonymous with carbon dioxide removal (CDR). Negative emissions can compensate release of CO_2 into the atmosphere by human activities. They could be achieved by strengthening marine and/or terrestrial CO_2 sequestration or by removing CO_2 directly from the atmosphere. If negative emissions are greater than anthropogenic CO_2 releases, emissions are said to be *net* negative.

In the absence of negative emissions, the CO_2 concentration in the atmosphere (a measure of the amount of CO_2 in the atmosphere) results from a balance between anthropogenic CO_2 release and removal by natural processes on land and in the ocean (natural 'carbon sinks'). If CO_2 release exceeds removal by carbon sinks, the CO_2 concentration in the atmosphere would increase; if CO_2 release equals removal the, atmospheric CO_2 concentration would stabilise; and if CO_2 removal exceeds release, the CO_2 concentration would decline. This applies in the same way to ***net*** emissions (that is the sum of anthropogenic releases and deliberate removals)

If the CO_2 concentration in the atmosphere starts to go down, the Earth's climate would respond to this change. Some parts of the climate system have a delayed reaction to a change in CO_2 in the atmosphere and a decline in atmospheric CO_2 through net negative emissions would therefore not imply a simultaneous attenuation of climate change. Recent studies have shown that surface air temperature starts to decline within a few years following a decline in atmospheric CO_2. Other components of the climate system, however, such as vegetation, soils, the deep ocean, ice sheets, take decades to millennia to react to the decline in atmospheric CO_2. For these components, net negative emissions would not result in an immediate attenuation of changes caused by CO_2. For instance, warming, acidification and oxygen loss of the deep ocean would take centuries to reverse following a decline in the atmospheric CO_2 concentration. Sea level rise due to warming and expansion of seawater would continue for centuries even if large amounts of negative emissions would be implemented.

A class of future scenarios that is receiving increasing attention, particularly in the context of ambitious climate goals, such as the 1.5°C and 2°C goals included in the Paris Agreement, are so-called 'overshoot' scenarios. In these scenarios slow emission reductions in the near term are compensated by net negative CO_2 emissions in the later part of this century, which results in a temporary breach or "overshoot" of a specific temperature level. Due to the delayed reaction of several climate system components it follows that the temporary breach of a temperature goal level would result in additional climate changes (compared to a scenario that reaches the goal level without overshoot) that would take decades to many centuries to reverse, with longer reversal times for scenarios with larger overshoot.

In conclusion, negative emissions can only reverse climate change to a limited degree. Some parts of the Earth's climate system such as surface air temperature would follow a decline in atmospheric CO_2 within a few years, while others such as sea level rise would take multiple centuries to reverse.

[START FAQ 5.3, FIGURE 1 HERE]

FAQ 5.3, Figure 1: [Figure suggestion – Time series of responses of climate system components with short to long response time scales (short term would include things like surface air temperature, long term would be warming, acidification and oxygen loss of the deep ocean, sea level etc.).]

[END FAQ 5.3, FIGURE 1 HERE]

FAQ 5.4: What is the remaining carbon budget?

The remaining carbon budget is to the total net amount of carbon dioxide emission that can still be emitted by human activities, while managing to keep global warming below a specific maximum temperature threshold. Several choices and value judgments have to be made before it can be unambiguously estimated. When combined with all CO_2 emissions that have been emitted to date, also a total carbon budget compatible with a specific temperature limit can be defined.

The term remaining carbon budget is used to describe the total net amount of carbon dioxide that human activities would still be allowed to release into the atmosphere while keeping global warming to a specific temperature threshold, like 1.5°C or 2°C relative to pre-industrial levels. Underlying the concept of a remaining carbon budget is our understanding that global warming is roughly linearly proportional to the total net amount of carbon dioxide emissions – also referred to as cumulative carbon dioxide emissions – that are released into the atmosphere by human activities. This characteristic only holds true for carbon dioxide, because of the specific way carbon dioxide behaves in the Earth system. The concept of a remaining carbon budgets comes with some direct implications. It means that to halt global warming, global emissions of carbon dioxide need to be reduced to net zero levels. It also means that if emissions are not reduced in the next decade, deeper and faster reductions in carbon dioxide emissions are required thereafter.

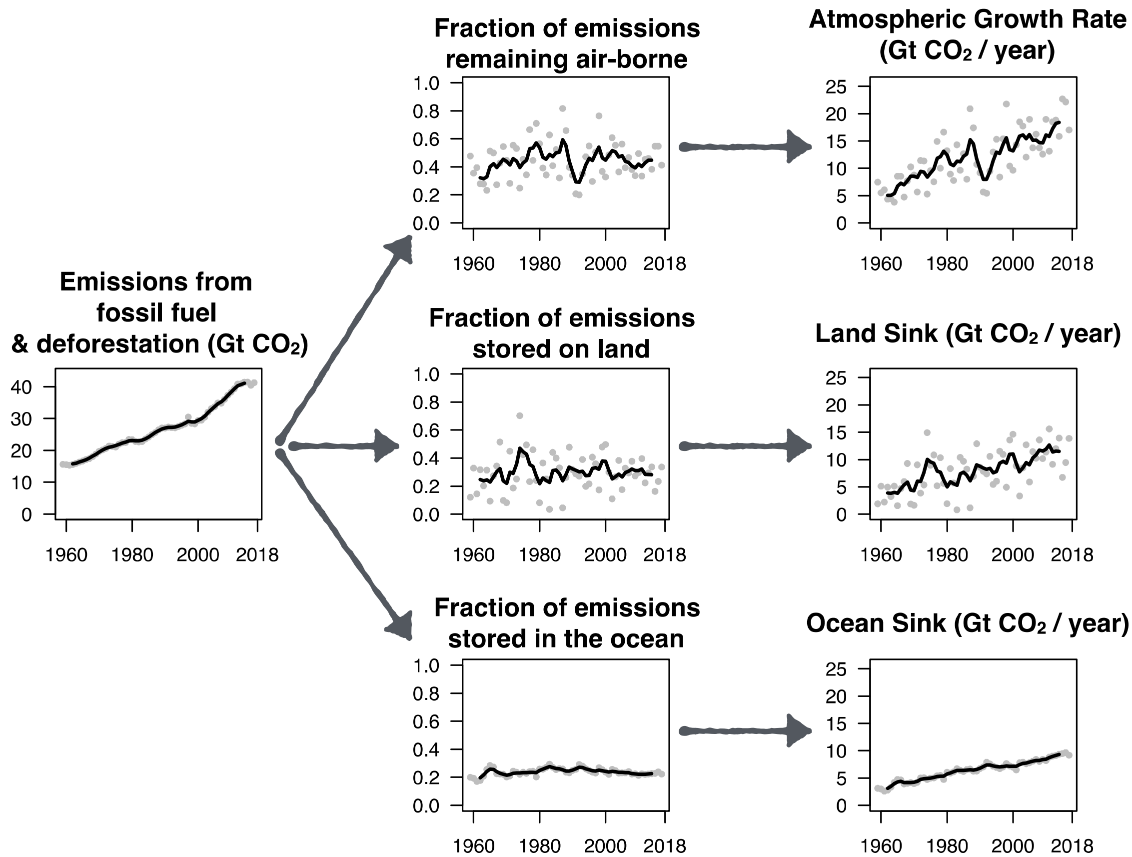
The size of the remaining carbon budget can be estimates but is conditional on a set of choices. These choices include the global warming level that is chosen as a limit (for example, 1.5°C or 2°C relative to pre-industrial levels), the probability with which we want to ensure that warming is held below that limit (for example, a 50%, 66% or higher probability), and how successful we are in limiting emissions of other non-CO_2 forcing agents that affect the climate, such as methane or nitrous oxide. These choices can be informed by science but ultimately represent subjective value judgments. Once they have been made, knowledge about how much our planet has already warmed to date, of the amount of warming per cumulative tonne of CO_2, and about the amount of warming that is still expected once global net CO_2 emissions are brought down to zero can be combined to estimate how much of a carbon budget remains for a given temperature target.

The remaining carbon budget by definitions starts from today, but warming is also caused by historical emissions which are estimated by looking at the historical carbon budget. The historical carbon budget describes all past and present sources and sinks of CO_2. It thus describes how the CO_2 emissions that were emitted by human activities have redistributed across the various reservoirs of the Earth system. These are the ocean, the land biosphere, and the atmosphere, into which CO_2 emissions were released to start with. Whatever amount of carbon dioxide emissions that is not taken up by the ocean or the land biosphere results in an increase of atmospheric CO_2 concentrations, and therewith further drives global warming. CO_2 taken up by the ocean is not harmless, because it results in changing the chemistry of the ocean water, reducing its alkalinity. This process is known as ocean acidification. The study of the historical carbon budget teaches us that of the about 2440 billion tonnes of CO_2 that were released into the atmosphere by human activities between 1750 and 2017, about a quarter was absorbed by the ocean, and about a third by the land biosphere. About 40% of these emissions remains currently in the atmosphere. Adding these historical CO_2 emissions to estimates of remaining carbon budgets allows one to estimate the total budget consistent with a specific temperature goal.

[START FAQ 5.4, FIGURE 1 HERE]

FAQ 5.4, Figure 1: [Figure idea: visual combining the historical carbon budget, with straight lines going down from today's emissions to zero, and in line with the remaining carbon budget for 1.5°C or 2°C – coloured and labelled differently to make the difference clear.]

[END FAQ 5.4, FIGURE 1 HERE]



FAQ 5.1, Figure 1: Overview of the global carbon budget and the fraction of CO_2 remaining in atmosphere, land and ocean from 1960 to 2019. Estimates are derived from atmospheric observations, process-based models, data-driven ocean flux products, and atmospheric inversions (Le Quéré et al., 2018a). Dots denote yearly values, lines are the seven years running mean.

FAQ 5.2, Figure 1: [Figure Placeholder: Schematic of the processes that affect permafrost thawing (what speeds up or slows down the release of GHG emissions.)]

FAQ 5.3, Figure 1: [Figure suggestion – Time series of responses of climate system components with short to long response time scales (short term would include things like surface air temperature, long term would be warming, acidification and oxygen loss of the deep ocean, sea level etc.).]

FAQ 5.4, Figure 1: [Figure idea: visual combining the historical carbon budget, with straight lines going down from today's emissions to zero, and in line with the remaining carbon budget for 1.5°C or 2°C – coloured and labelled differently to make the difference clear.]

Frequently Asked Questions

FAQ 6.1: Why do we care about short-lived climate forcers?

The term short-lived climate forcers (SLCFs) refers to compounds such as methane and black carbon that affect Earth's climate over shorter time scales—from days to years—than greenhouse gases like carbon dioxide and nitrous dioxide, which can affect the climate for decades or more. Because they do not remain in the atmosphere very long, increases or decreases in emissions of SLCFs can have fairly rapid effects on the climate system. SLCFs also have adverse effects on air quality, human health, agricultural yield, and ecosystem vitality (cf FAQ 6.2). Measures to improve air quality have resulted in sharp reductions in emissions and concentrations of SLCFs in many regions over the last decades.

Short-lived climate forcers are those compounds whose impact on climate occurs primarily within the first decade after their emission. Just like the long-lived greenhouse gases, such as carbon dioxide or nitrous oxide, SLCFs like ozone and methane can affect Earth's energy balance by slowing down the loss of heat (as longwave radiation) to space and warm the lower atmosphere. Several of the SLCFs, particularly small particles called aerosols, also affect the energy balance by reflecting and/or absorbing incoming solar radiation, and by changing clouds. Increased reflection (cooling) is mainly by sulphate aerosols while black carbon (also known as soot) is the main absorbing component, and when deposited on snow and ice, it raises temperatures and increases melting rates. The sub-group of SLCFs causing warming are sometimes referred to as short-lived climate pollutants or SLCPs.

SLCFs are emitted by both natural and human sources. Emissions from human activities have increased since the start of industrialization and humans are now the dominant source for several SLCFs, including sulphur dioxide, black carbon and nitrogen oxides, even if there have been strong reductions in some regions to improve air quality.

Of all the SLCFs, methane and the short-lived halogenated species (such as hydrofluorcarbons) persist the longest in the atmosphere—about one decade, which is long enough to become mixed in the atmosphere at regional and global scales. Most other SLCFs only remain in the atmosphere for a few days to weeks, which is generally less than the time required for mixing in the atmosphere even at regional scales. This inhomogeneity implies that while the average global effect of the short-lived forcers is comparable in magnitude to that of the long-lived greenhouse gases, the local and regional forcings can far exceed those of the long-lived gases.

The observed climatic effects of short-lived forcers include large local effects on surface and near-surface temperatures and significant reductions in the lifetime of snow due to the melting induced by soot. Models of the current climate indicate that these agents have altered local and even hemispheric-scale circulation systems and regional patterns of precipitation. Recent observations show strong regional differences in the trends in aerosol concentrations, particularly over South and East Asia, which might influence regional weather systems. Aerosols also have direct impacts on clouds, affecting local precipitation mechanisms.

Because some short-lived forcers are co-emitted with long-lived greenhouse gases, and since several of these forcers offset some of the warming effect of the greenhouse gases, it is important to quantify the impacts of these SLCFs when considering strict mitigation scenarios aimed at keeping global warming below a specific temperature limit (e.g., 1.5°C above pre-industrial levels). Strict reductions in LLGHGs will lead to reductions also in cooling SLCFs, mainly SO_2. However, a large part of this warming can be mitigated by simultaneous reductions in methane and BC. Because reducing SLCF emissions can simultaneously reduce warming effects and adverse effects on air quality as well as help attaining Sustainable Development Goals, mitigation of SLCFs is often viewed as a favourable "win-win" policy option (see also FAQ 6.2).

Climate change mitigation policies depend on an accurate estimate of climate sensitivity since, among other things, it constrains the remaining carbon budget. This sensitivity can be determined by estimating the total forcing of the climate system since pre-industrial times, of which SLCFs are a significant part, and combine this with the observed global warming. Estimates of the historical forcing of SLFCs rely on how well we understand (1) historical emissions and chemical/physical removal processes of SLFCs, and (2) how they interact with clouds and radiation. By increasing the scientific understanding of the atmospheric lifecycle of SLFCs, models can be improved to more accurately simulate historical forcings. This leads to better estimates of climate sensitivity, which in turn can be used to develop climate change mitigation policies.

[START FAQ 6.1, FIGURE 1 HERE]

FAQ 6.1, Figure 1: Summary schematic of the main Short-lived climate forcers, how long they exist in the atmosphere, and their impacts.

[END FAQ 6.1, FIGURE 1 HERE]

FAQ 6.2: What are the links between climate change and air quality?

Climate change and air quality are intimately linked. Many of the human activities that produce long-lived greenhouse gases also emit air pollutants, and many of these air pollutants are also short-lived climate forcers that affect the climate. Indeed, many options for improving air quality may also serve to mitigate climate change and vice versa. However, some options for improving air quality cause additional climate warming.

Climate change and air pollution are both critical environmental issues that are already impacting humanity. In 2016, the World Health Organization attributed 4.2 million deaths worldwide every year to ambient (outdoor) air pollution, and climate change impacts water resources, food production, human health, extreme events, coastal erosion, wildfires, and many other phenomena.

Most human activities, including energy production, agriculture, transportation, industrial processes, waste management, and residential heating and cooling, result in emission of gaseous and particulate pollutants that modify the composition of the atmosphere, leading to degradation of air quality as well as climate change. While this means that air pollution and climate change are intimately connected issues, air pollutants and climate-forcing species are often defined, investigated, and regulated independently of one another both in the scientific and policy arenas.

When we drive our car or light a fire in the fireplace, it is not just CO_2 or air pollutants that are emitted, but always both. It is therefore not possible to unambiguously separate emissions into two distinct groups. Many other sources also emit both air pollutants and climate-forcing species. What is more, many emitted species are at the same time air pollutants and climate-forcing species. Therefore, policy options aiming at addressing climate change may have unintended benefits or trade-offs for air quality, and *vice versa*.

For example, some short-term "win-win" policies that simultaneously improve air quality and mitigate climate change include energy efficiency measures, the use of zero-emission vehicles, capturing and recovering methane from solid waste management and oil and gas industry, reducing emissions of soot (particulates) from diesel vehicles, eradicating of burning kerosene for lighting, implementing efficient and clean stoves for heating and cooking, improving brick kiln technology, reducing burning of agricultural waste. On a long-term perspective, decarbonization offer strong co-benefits for both air quality and climate.

There are, however, also "win-lose" policies or activities. For example, wood burning is defined as carbon neutral because a tree accumulates the same amount of CO_2 throughout its lifetime as is released when wood from that tree is burned. However, burning wood can also result in significant emissions of air pollutants, including carbon monoxide, nitrogen oxides, volatile organic compounds, and particulate matter that have local or regional impacts on climate, human health and ecosystems. On the opposite side, decreasing the amount of sulphate aerosols produced from exhaust of power and industrial plants improves air quality but unmasks warming, because those sulphate aerosols contribute to cooling the atmosphere by blocking incoming sunlight.

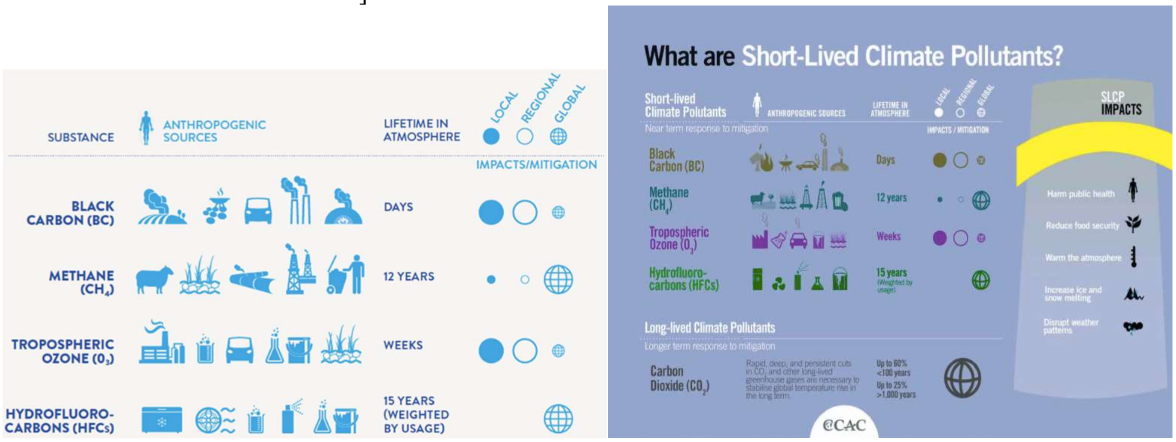
Air quality and climate change represent two sides of the same coin and addressing both issues together could lead to significant synergies and economic benefits while avoiding policy actions that mitigate one of the two issues but worsen the other.

[START FAQ 6.2, FIGURE 1 HERE] – being discussed with TSU

FAQ 6.2, Figure 1: Most common air pollutants and climate-forcing species and their impacts on climate, human health and ecosystems. These different species are often co-emitted by the same source and are impossible to consider separately. Anyone of the listed species can be an air pollutant, a climate-forcing specie or both (as in the case of e.g. particulate matter or ozone). *PM includes inorganic and organic particulates as well as black carbon.

[END FAQ 6.2, FIGURE 1 HERE]

[PLACEHOLDER FOR FIGURE]:



FAQ 6.1, Figure 1: Summary schematic of the main Short-lived climate forcers, how long they exist in the atmosphere, and their impacts.

[PLACEHOLDER TABLE]

Air pollutant/GHG	Climate effect: How it changes temperature	Air quality effect: Health/Ecosystem impacts
Carbon Dioxide (CO_2)	+	E
Fluorinated gases	+	-
Methane (CH_4)	+	H/E
Nitrous Oxide (N_2O)	+	-
Carbon Monoxide (CO)	+	H/E
Nitrogen Oxides (NO_X)	+/-	H/E
Ammonia (NH_3)	-	H/E
Sulphur Dioxide (SO_2)	-	H/E
Tropospheric Ozone (O_3)	+	H/E
Volatile Organic Compounds (VOCs)	+	H/E
Particulate Matter (PM)*	+/-	H/E

FAQ 6.2, Figure 1: Most common air pollutants and climate-forcing species and their impacts on climate, human health and ecosystems. These different species are often co-emitted by the same source and are impossible to consider separately. Anyone of the listed species can be an air pollutant, a climate-forcing specie or both (as in the case of e.g. particulate matter or ozone). *PM includes inorganic and organic particulates as well as black carbon.

Frequently Asked Questions

FAQ 7.1: Clouds – What have we learned since IPCC AR5?

One of the biggest challenges for climate science has been predicting how clouds will change in a warming world and whether those changes will amplify or partially offset the warming caused by increasing concentrations of greenhouse gases and other human activities. Scientists have made significant progress over the past few years and can now conclude that it is very likely that clouds will change in ways that will amplify, rather than offset, global warming in the future.

On average, clouds cover two thirds of the Earth's surface. They generally form when water vapour present in updrafts condenses around small particles known as aerosols (such as salt, dust, or smoke) to form water droplets. We see the reflections from these little droplets of water as clouds. When the droplets grow large enough or freeze to make ice crystals, they can fall to the surface as rain, snow, or other forms of precipitation. Clouds therefore play a key role in Earth's water cycle.

Clouds also play a critical role in Earth's energy budget—the balance between the amount of incoming solar radiation and the energy radiated back to space. Clouds reflect some of the incoming radiation, which has a cooling effect. But water vapour is a greenhouse gas, so clouds also trap (i.e., absorb and re-emit) some outgoing radiation, resulting in a warming effect. Over the last four decades, measurements from satellites and aircraft-based instruments have shown that high clouds tend to trap more radiation than they reflect, while low clouds reflect more than they trap. On average, the reflection of incoming radiation currently wins out, so that, overall, clouds have a cooling influence on the climate.

Scientists have known for decades that the radiative properties of clouds (that is, how much energy they reflect and trap) depend on the abundance of the aerosol particles upon which cloud droplets and ice crystals form. The atmosphere now contains more aerosols than in the pre-industrial period, and this increase has had two important effects on clouds. First, they are now more reflective because cloud droplets have become more numerous and smaller. There is broad agreement that the resulting cooling effect has counteracted a considerable portion of the warming caused by increases in greenhouse gas concentrations over the last century, though exact quantification has been a challenge. Second, it has also been proposed that the shift towards more numerous but smaller droplets acts to extend cloud lifetimes by delaying rain formation, although this effect remains controversial. While quantification is still a challenge, recent evidence suggests that increases in the lifetime and/or number of cloud droplets have amplified the cooling influence of clouds.

Clouds are also expected to change as the planet continues to warm as a result of increasing concentrations of greenhouse gases, and these changes could act to amplify or offset some of the warming by altering the radiative fluxes, the effect called the cloud feedback. Exactly how various cloud properties, including the amount, altitude, and reflectivity of clouds will change in a warmer world, and how these changes will affect the energy budget of the Earth (FAQ7.1, Figure 1) constitutes the largest component of uncertainty in projections of global warming for a given emission pathway. The key question is whether cloud changes will have a net warming effect, amplifying the greenhouse warming (a positive cloud feedback) or a net cooling effect, offsetting some of the warming (a negative cloud feedback). In particular, the response of subtropical marine boundary layer clouds to surface warming has been the largest source of uncertainty in assessing the net cloud feedback.

The problem stems from the fact that clouds can change in many ways and their processes occur on much smaller scales than can be represented by global climate models. The latest generation of climate models do a better job of modelling cloud behaviour thanks to increases in spatial resolution and more sophisticated representations of processes that occur at even finer scales (Section 1.4.3). Yet, this improvement is incremental, and the representation of cloud processes even in the latest climate models remains a challenge.

Since the AR5, observational and modelling efforts have been further developed and integrated to build a more complete understanding of cloud processes. For example, the interaction between aerosols and clouds are now routinely included in model simulations. Furthermore, extensive analyses of the latest climate model simulations have enabled scientists to propose a number of emergent constraints on the magnitude of the overall cloud feedback. Combined with a coordinated set of fine-scale process modelling for stratocumulus and trade cumulus clouds, these studies have revealed how low clouds over the subtropical oceans are reduced and thinned in response to surface warming, providing evidence that this cloud feedback is positive (Section 7.4.2.4). Namely, the low-cloud feedback is no longer the biggest issue of climate feedback assessments. While uncertainties in feedbacks associated with other cloud regimes, such as tropical anvil clouds and extratropical mixed-phase clouds, have emerged instead, this reflects the fact that new problems arise when old problems are resolved as our understanding of clouds and their feedbacks improves.

In summary, cloud processes are now better understood and can be simulated more accurately, enabling us to narrow the range of possible cloud feedback and responses to aerosol changes. Also, the magnitude of the cooling effect of clouds enhanced by emissions of polluting gases such as sulphur dioxide and particles can now be better understood (Section 7.3).

[START FIGURE FAQ7.1, Figure 1 HERE]

FAQ7.1, Figure 1: Schematic illustration of different types of clouds in the present climate (grey) and their response to surface warming (red). From the left to right: high-level thick clouds, low-level thin clouds, and mixed-phase clouds over the high latitudes. Arrows represent radiative fluxes. Physical processes associated with the changes in cloud property and the resultant sign of the feedback are described at the bottom.

[END FIGURE FAQ7.1, Figure 1 HERE]

FAQ 7.2: How does climate sensitivity relate to climate projections and the latest climate models?

For a given future emission scenario, climate models give a range of future global surface temperature projections. This range is strongly related to the models' equilibrium climate sensitivity, where high climate sensitivity models give stronger future warming. The new models have higher average climate sensitivity than the best estimate of climate sensitivity from other lines of evidence. This leads to end of century temperature changes up to 2°C stronger in some simulations of the latest generation of models, compared to the earlier model generation. The high warming levels in these high sensitivity models are useful as representations of high risk, low-probability futures.

The equilibrium climate sensitivity is an idealised measure of climate response, defined as the equilibrium globally averaged surface temperature change caused by a doubling of carbon dioxide from its preindustrial concentration (Box 7.1). Even though an idealised quantity, it is found to strongly relate to future projections of surface temperature within climate models. Around 90% of the globally averaged projected surface temperature range in 2100 can be explained by the model range of equilibrium climate sensitivity (Section 7.5.7).

Equilibrium climate sensitivity estimates have been persistently uncertain across previous IPCC reports. A primary cause of this uncertainty is the way clouds respond to warming, which is difficult to estimate (see FAQ 7.1). This report makes considerable progress in quantifying equilibrium climate sensitivity by examining four different lines of evidence. 1) Process based evidence quantifies how the underlying physical processes such as how changes in clouds, water vapour, and surface reflectance contribute to climate sensitivity. 2) Historical evidence infers climate sensitivity from observed changes in the global energy budget and surface temperature over recent centuries. 3) Paleoclimate evidence infers climate sensitivity from what we know about ancient climates, particularly from the height of the last ice age (20,000 years ago). 4) Emergent constraint evidence looks at how a factor in climate models that can be observed (such as the warming rate in recent decades) varies with equilibrium climate sensitivity, and then uses observations of this factor to bound plausible sensitivity estimates (Section 7.5.1).

Simulations from previous and current generations of climate models are employed to some extent in each of these four lines of evidence but the climate models are not considered as a line of evidence in their own right. This is because they are already used as part of the other lines of evidence, and treating them again as a separate line would be circular. Additionally, it is possible to construct a physically plausible model with a wide variety of climate sensitivity values and the available model range is derived from a limited sample that is not expected to be statistically representative of the real-world value (Section 7.5.6).

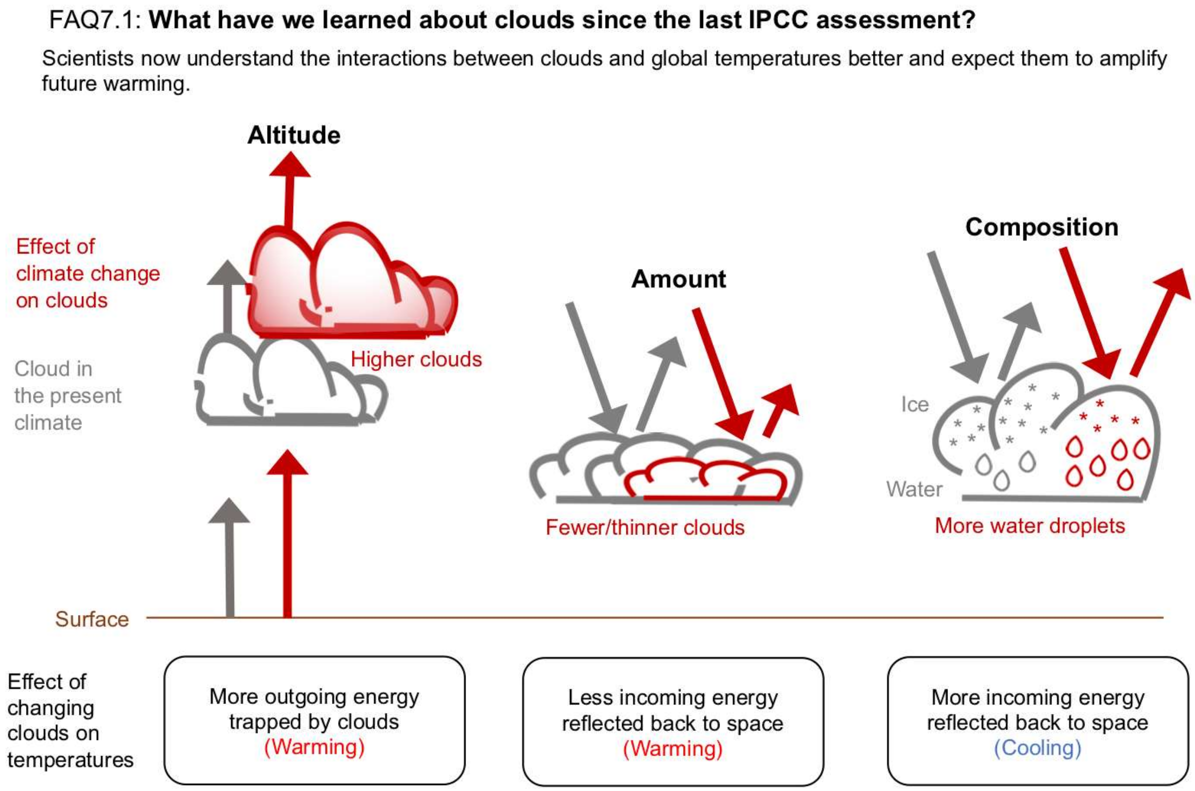
Chapter 7 uses the four lines of evidence to make a probabilistic estimate of equilibrium climate sensitivity, giving a best estimate of 3°C. Although this sensitivity is *likely* between 2.5 °C and 4 °C, there remains a 5% chance it could be larger than 5°C and a 5% chance it could be smaller than 2°C. Nevertheless, this reduction of uncertainty represents considerable progress over the broader range of possible values given in the AR5.

The equilibrium climate sensitivity across the latest climate models is, on average, both higher than that in the previous generation of models and higher than the best estimate of climate sensitivity estimated within Chapter 7 (see Figure FAQ7.2, Figure 1 left panel). Around 20% of the models have an equilibrium climate sensitivity larger than 5°C. Their high climate sensitivity values can be traced to cloud feedbacks. Yet, some of the cloud feedback changes are directly traceable to improved representations of clouds as compared to satellite observations. Furthermore, increased understanding of how climate feedbacks may change over time implies that models could display medium sensitivity in historical simulations, but transition to a higher sensitivity state under sustained warming. Therefore, an individual model cannot be ruled out as implausible solely based on their high equilibrium climate sensitivity. The overall shift towards higher sensitivity leads to generally higher projected warming compared to earlier generations of models, by up to 2°C in some simulations (see Figure FAQ7.2, Figure 1 right panel). Individual high sensitivity models provide important insights into low-probability, high-risk futures, but the best estimate of future warming does not rely on the latest models alone but factors in other lines of evidence that are included in the assessed climate sensitivity range. (Chapter 4, Box 4.1).

[START FIGURE FAQ 7.2, Figure 1 HERE]

FAQ7.2, Figure 1: The left panel shows equilibrium climate sensitivity estimated from the latest generation of climate models (CMIP6), the previous generation used in the AR5 assessment report (CMIP5) and the assessed *very likely* range from Chapter 7. The right panel shows the projected temperature change for a future high emission scenario over 2090-2100 for CMIP6, CMIP5, and from the assessed range in Chapter 4.

[END FIGURE FAQ 7.2, Figure 1 HERE]



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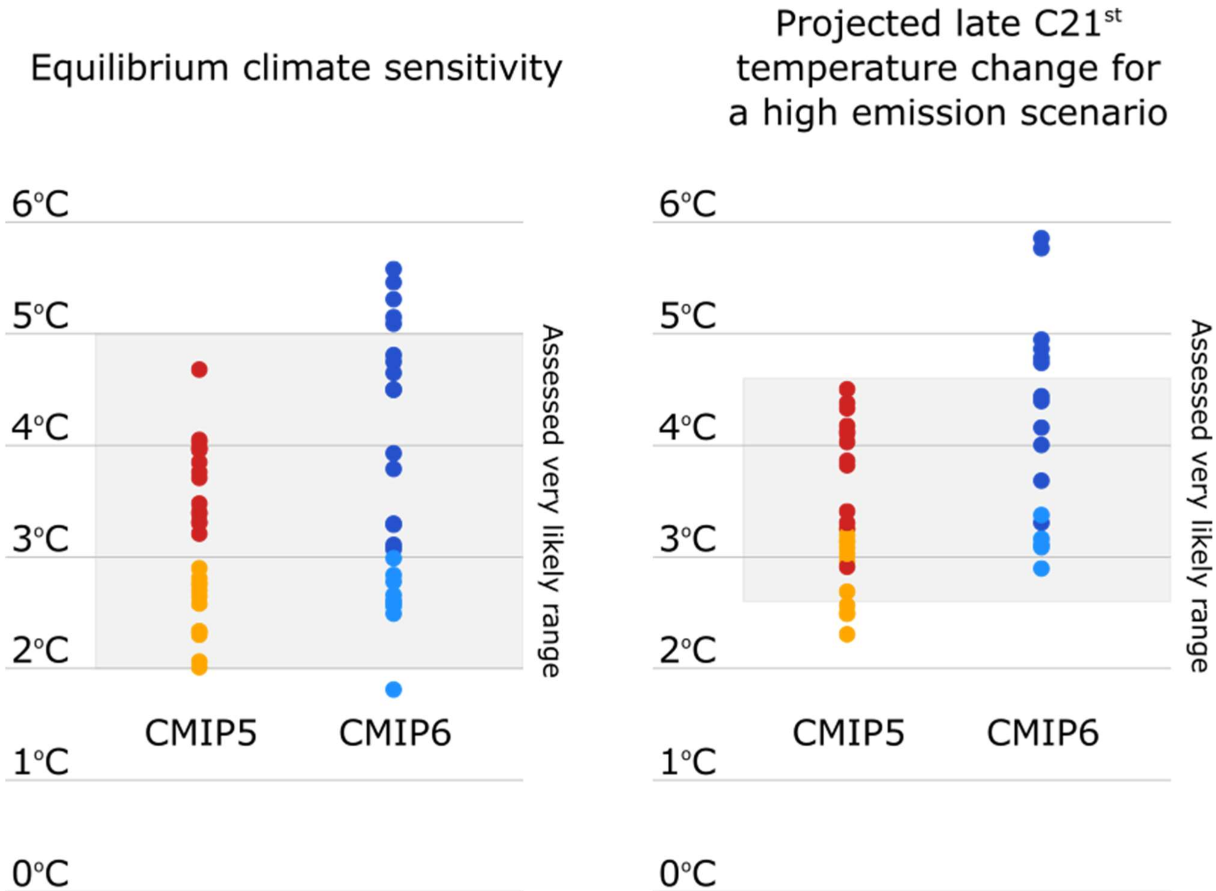

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Frequently Asked Questions

FAQ 8.1: How does land use change alter the water cycle?

Changes in how land is used by societies can affect the regional climate. In particular, altering land use can lead to changes in precipitation, evapotranspiration and the exchanges of water between the atmosphere, the soil and the sub-surface thereby modifying the water cycle and freshwater availability.

Land use changes can directly and indirectly alter the water cycle. Changes of land cover, for example from vegetation to an urban cover, modify the *surface albedo* (the propensity of the surface, or any object, to reflect sunlight). Changing the amount of reflected sunlight alters the *surface energy balance* (the difference between incoming and outgoing heat fluxes). Reducing the capacity of the surface to reflect sunlight will mean there is more energy arriving, and therefore warming the surface. Changes in surface land cover can also alter the porosity of the soil, and in turn, affect the ability of soils to soak up surface water (*infiltration*), altering the *surface water balance* (the difference between precipitation and the total amount of evaporation, ground storage and surface runoff). When the soil loses its capacity to soak up water, more precipitation can become runoff. Water that would normally infiltrate and contribute to groundwater recharge will now overflow, increasing surface water and the risk of flooding.

Changes in soil moisture content can also influence how quickly the ground heats up and cools down. Water retained in tiny gaps in the soil (pores) increases heat storage during daytime, which is gradually released during nighttime, reducing nocturnal ground cooling. If soil moisture is reduced, the ground can heat up and cool down more rapidly. This alters the energy budget due to changes of *sensible heat* (the loss of heat from the surface by conduction and convection) and *latent heat* (the loss of heat due to a phase change in water from liquid or ice to vapour). Warming induces more evaporation which cools the surface. By cooling down the surface, the *boundary layer* becomes more stable. This stabilization contribute to slow upward plumes of air, decreasing the occurrence of precipitation that in turn can further modify the water balance of the surface.

Changes in land use can also modify the amount of tiny *aerosol* particles in the air. *Aerosols* play a rather complex role in weather and climate. They scatter and absorb sunlight and are also *condensation nuclei* on which water molecules can stick and grow until reaching a weight large enough to precipitate. More aerosol particles can cause the water in clouds to be spread out over more numerous, but smaller droplets which make clouds reflect away more sunlight and reduce the efficiency at which clouds can convert droplets to precipitation. Therefore changes in aerosol pollution can alter the surface energy and water budgets.

The extraction of water from the ground and river systems for irrigation, industry and consumption also modifies the water cycle. On one hand, this extraction depletes ground water but on the other hand it also can increase surface evaporation which cools the surface (as observed over extensive irrigation areas), altering the surface energy balance and in turn indirectly modifying the water cycle.

Lastly but not least, the water balance is also affected by changes in vegetation, which plays an important role in soaking up groundwater and evaporating water into the air through tiny holes (*stomata*) used to take in CO_2. The ratio of transpiration to CO_2 uptake varies with plant type, and therefore land use change can affect ecosystem water-use efficiency. In return, higher atmospheric concentrations of CO_2 due to human activities can also make plants more efficient at retaining water since the stomata do not need to open so widely.

Due to the complexity of the interaction between the different land surface processes, there are large uncertainties when determining the overall effect of land use change on the water cycle. However, there is abundant evidence showing that land use change can alter both the surface energy balance and the water balance, potentially jeopardizing the availability of freshwater in some regions. This can impact water security (for example, increased water scarcity in arid regions) when combined with the effects of global warming.

[START FAQ 8.1, FIGURE 1 HERE]

FAQ 8.1, Figure 1: Schematic summarizing the influence of land cover and land use change on regional water cycle.

[END FAQ 8.1, FIGURE 1 HERE]

FAQ 8.2: Should we expect floods to be more severe or more frequent as a result of climate change?

A warmer climate increases the amount and intensity of rainfall during wet events, and this is expected to contribute to an increased severity of flooding. However, the link between rainfall and flooding is complex, so while the most severe flooding events are expected to worsen, the frequency of flood occurrences may decrease in some regions. Other human activities – primarily changes in land use – can also alter flood frequency and severity.

Flooding can result from rivers overtopping their banks or from a local accumulation of water where the influx exceeds outflow and drainage. This natural and important part of the water cycle causes harm where it affects human activities and infrastructure. As climate changes, the location, occurrence and severity of flooding alters. Sea level rise will also increasingly cause more frequent and severe coastal flooding, and the severity of these floods will be exacerbated when combined with heavier rainfall.

Inland flooding is most often caused by heavy and often sustained rainfall events, which are becoming more frequent and severe as the climate warms. Air near Earth's surface can carry around 7% more water in its gas phase (vapour) for each 1°C of warming. This extra moisture is drawn in to weather systems, fueling heavier rainfall. Rainfall can further intensify as extra heat released through greater condensation rates energize storm systems. On the other hand, this energy release can inhibit the uplift required for cloud development, while pollution can delay rainfall but invigorate storms. This means that the character of precipitation events (how often, how long lasting and how heavy they are) is expected to alter as the climate warms.

A warming climate affects wind patterns, how storms form and evolve, and the pathway those storms usually travel. However, natural variations also result in some regions being unusually wet or dry for months, years, or even decades. These fluctuations make it difficult to determine whether heavy rainfall events are changing locally as a result of global warming. However, an increased intensity and frequency of record-breaking daily rainfall has been detected for much of the land surface where good observations exist, and this can only be explained by human-caused increases in atmospheric greenhouse gas concentrations. Model simulations show an intensification of heavy rainfall in the future for most places. It is therefore *very likely* that where unusually wet events or seasons occur, the rainfall amounts will be greater, contributing to more serious flooding.

The link between heavy rainfall and flooding is, however, not simple. Heavier rainfall does not always lead to greater flooding because flooding also depends upon the type of river basin, the surface landscape, the extent and duration of the rainfall, and how wet the ground is before the rainfall event. There have been increases and decreases in flooding observed in different countries due to multiple causes, including changes in snowmelt, soil moisture and rainfall. However, flooding is projected to double in frequency over 40% of the globe by 2050, with the largest increase expected in Asia, but a decrease is also projected in many regions.

Some regions may experience a drying in the soil as the climate warms, particularly in sub-tropical climates, which could make floods from a rainfall event less probable because the ground can potentially soak up more of the rain. On the other hand, more intense but less frequent downpours can lead to dry, hard ground that is less able to soak up heavy rainfall, resulting in more runoff into lakes, rivers and hollows. Earlier spring snowmelt with more precipitation falling as rain rather than snow can trigger flood events in cold regions. Reduced winter snow cover can, in contrast, decrease the chance of flooding arising from the combination of rainfall and rapid snowmelt. Rapid melting of glaciers and snow in a warming climate is already increasing river flow in some regions, but as the areas of ice diminish, flows will peak and then decline in the future.

Flooding is also affected by changes in the management of the land and river systems, and the damage caused is affected by the location of where people live and work. For example, clearing forests for agriculture or building cities can make rain water flow more rapidly into rivers or depressions in the ground. Observed regional increases and decreases in flooding have been explained by multiple causes. Accounting for these many factors, there is an overall expectation that when weather patterns cause flood events, these floods will become more severe as the climate warms. However, in some regions the weather conditions and properties of the land surface that can lead to flooding will become less common.

[START FAQ 8.2, FIGURE 1 HERE]

FAQ 8.2, Figure 1: Schematic illustrating factors important in determining changes in heavy precipitation and flooding.

[END FAQ 8.2, FIGURE 1 HERE]

FAQ 8.3: What causes droughts, and will climate change make them worse?

Droughts are initially caused by a lack of precipitation, but then propagate to other parts of the water cycle (soils, rivers, and reservoirs). They can also be influenced by factors like temperatures, vegetation, and human management responses. In a warmer world, droughts will get worse in some regions and seasons, particularly in the arid subtropics. Other places may receive more precipitation, reducing the risk of drought.

A drought is broadly defined as drier than normal conditions; that is, a moisture deficit relative to the average water availability at a given location. Since they are locally defined, a drought in a wet place (like Brazil) will not have the same amount of water loss as a drought in a drier region (like Israel). Droughts are divided into different categories based on where in the water cycle the moisture deficit occurs: meteorological drought (precipitation), agricultural drought (soil moisture), and hydrological drought (runoff, streamflow, and reservoir storage). Special categories of drought also exist. For example, a snow drought occurs when snowpack levels over the winter are below average, leading to abnormally low streamflow in the spring. And while many drought events develop slowly over months or years, some events, called flash droughts, can intensify over the course of days or weeks. One such event occurred in 2012 in the Midwest region of the United States and had a severe impact on agricultural production, with losses exceeding $30 billion dollars. Droughts typically only become a concern when they adversely affect people (reducing water available for municipal and industrial needs) and/or ecosystems (inhibiting growth of crops and natural vegetation). When a drought lasts for a very long time (more than two decades) it is sometimes called a megadrought. The opposite of a drought – a period of wetter than normal conditions – is called a pluvial.

Most droughts begin when precipitation is below normal for an extended period of time (meteorological drought). This typically occurs when high pressure in the atmosphere sets up over a region, inhibiting clouds and local precipitation and deflecting away storms. The lack of rainfall then propagates across the water cycle to create agricultural drought in soils and hydrological drought in waterways. Other processes act to amplify or ameliorate droughts. For example, if temperatures are abnormally high, evaporation increases, drying out soils and streams beyond what would have occurred just from the lack of precipitation. Vegetation can play a critical role because it modulates many important hydrologic processes (soil water, evapotranspiration, runoff). Human modifications also determine how severe a drought is. For example, irrigating croplands can reduce the impact of a drought; conversely, depletion of groundwater in aquifers can make a drought worse.

The impact of climate change on drought varies across regions. In the subtropics (e.g., the Mediterranean, western North America, Central America, southern Africa, and southern Australia; FAQ 8.3, Figure 1), precipitation is expected to decline as the world warms, increasing the possibility that drought will occur throughout the year. Some studies suggest that megadroughts in western North America will become more frequent. Warming will decrease snowpack, amplifying drought in regions where snowmelt is an important water resource (e.g. the western United States, and parts of south Asia and South America). Higher temperatures lead to increased evaporation, resulting in soil drying and agricultural drought, even in regions where large changes in precipitation are not expected (e.g., the central United States, and central and northern Europe). If emissions are not curtailed, about a third of global land areas are projected to suffer from at least moderate drought by 2100. On the other hand, some areas and seasons may experience increases in precipitation as a result of climate change (such as high latitude regions in North America and Asia, and the Indian monsoon region, FAQ 8.3, Figure 1) which will decrease the possibility of droughts. FAQ 8.3, Figure 1 illustrates the projected effect of climate change on drought in different places; these patterns are similar regardless of the future emissions scenario.

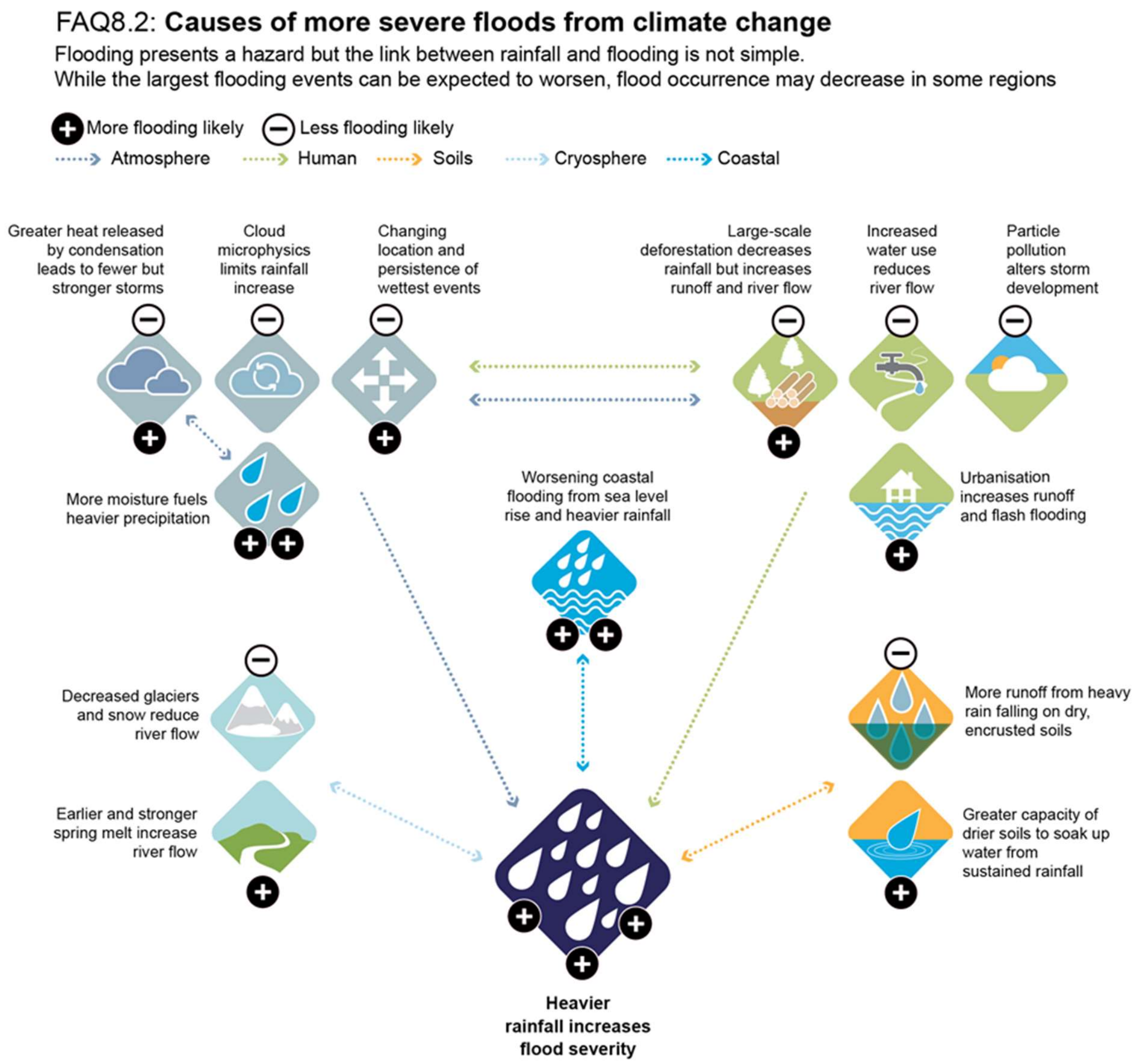
[START FAQ 8.3, FIGURE 1 HERE]

FAQ 8.3, Figure 1: Global map of soil moisture (left) and surface runoff (right) with regions expected to experience more or less drought labeled in brown (more) and blue-green (less) (use colors from precipitation diverging palette). Keep figure qualitative to avoid choosing a particular emissions scenario.

[END OF FAQ 8.3, FIGURE 1]

[Placeholder: To be developed for the FGD]

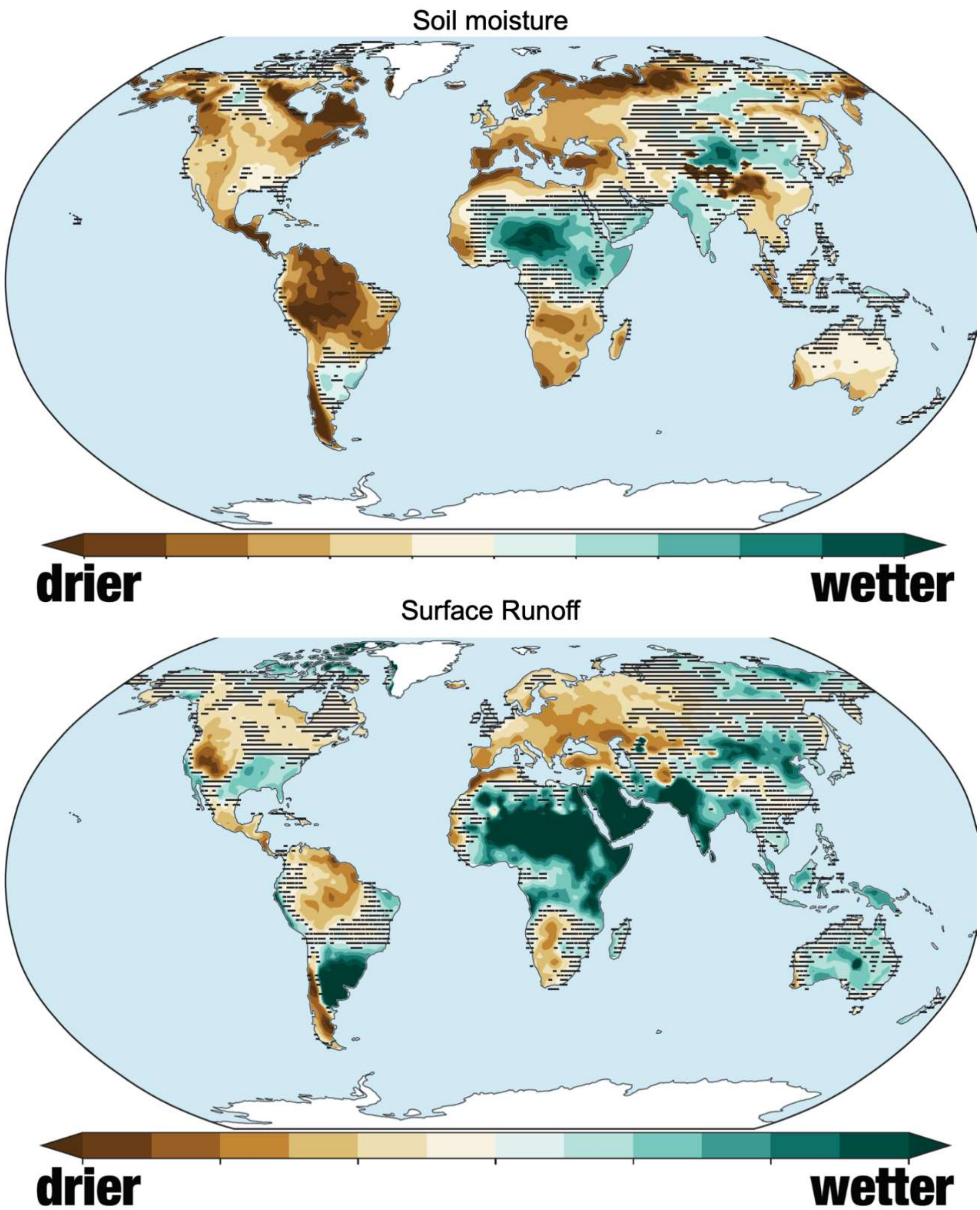
FAQ8.1, Figure 1: Schematic summarizing the influence of land cover and land use change on regional water cycle. To be prepared with TSU.



FAQ 8.2, Figure 1: Schematic illustrating factors important in determining changes in heavy precipitation and flooding.

FAQ8.3: **What causes droughts and will they worsen with climate change?**

The impact of climate change on droughts varies across regions. Droughts will get worse in the subtropics -- the Mediterranean, western North and Central America, southern Africa and southern Australia -- while other region will become wetter.



FAQ 8.3, Figure 1: (mock up). Global map of soil moisture (left) and surface runoff (right) with regions expected to experience more or less drought labeled in brown (more) and blue-green (less) (use colors from precipitation diverging palette). Keep figure qualitative to avoid choosing a particular emissions scenario.

Frequently Asked Question

FAQ 9.1: Will human-induced changes in the oceans and frozen environments be reversible?

Some of the processes we are currently witnessing, such as sea level rise, the release of carbon stores into the atmosphere from thawing permafrost and other natural sources, as well as changes in ocean chemistry, are effectively irreversible on human timescales. Evidence from the distant past shows that some parts of the planet might take hundreds to thousands of years to fully adjust to changes in climate. This means that some of the consequences of human-induced climate change will continue for a very long time, even if atmospheric greenhouse gas levels and temperatures are stabilised or reduced in future.

Humans are changing the climate, and although many of the consequences may take hundreds or thousands of years to be fully realised, a large part of the responses in the oceans and in frozen environments (the cryosphere) will occur over decades to centuries. An important question therefore is how long it will take for these changes to eventually reverse, once levels of greenhouse gases in the atmosphere are stabilized or reduced by humans and natural processes. Records from the past can help us answer this question.

For at least the last 800,000 years, the Earth has followed cycles of gradual cooling followed by rapid warming caused by natural processes. During each cycle, sea level slowly lowered as large ice sheets grew, and then rose much more quickly as ice sheets melted. Ice sheets retreat more quickly than they grow because growth relies on the steady accumulation of falling snow that eventually compacts into ice, whereas retreat can be affected by instability processes in which rapid loss can occur once a particular threshold is reached (Box 9.3). Under certain circumstances, several threshold or instability processes may combine, forming a self-reinforcing cycle, or positive feedback. For example, during a period of relatively rapid global warming 55 million years ago (the 'Paleocene–Eocene Thermal Maximum'), scientists think that warming was accelerated by the release of carbon dioxide or methane into the atmosphere from thawing of perennially frozen ground (permafrost) in Arctic and mountain regions (FAQ 5.2) or by the release of methane from frozen crystals (hydrates) in the deep ocean. If either were triggered in the future, global warming would increase rapidly, further melting permafrost areas, glaciers, and ice sheets, resulting in additional warming.

This kind of heightened response of the Earth system explains why relatively small increases in global average temperature have led to very large changes in the past, such as the collapse of the West Antarctic ice sheet and the loss of much of the Greenland ice sheet around three million years ago (the mid-Pliocene Warm Period) when global average temperature was only around 2ºC above present. At that time, carbon dioxide concentrations in the atmosphere were about the same as they are today, but collapse of the ice sheets meant that global sea level was 10 to 30 metres higher than now, changing coastlines around the world. Analysis of geological records from many different warm periods of the past show that this relationship is remarkably consistent.

The implications of these insights from the past are that future changes, for example in terms of thinning or retreat of the large ice sheets, sea level rise, or thawing of permafrost, may lead to environmental changes that take thousands of years to return to their present state, even if global temperatures decrease within this or the next century. Warming of the oceans as well as ocean acidification (in which carbon dioxide dissolves into seawater) would also take centuries to reverse because the heat and CO2 are transported down to the deep oceans, and take hundreds of years to circulate back to the atmosphere.

Changes in some elements of the cryosphere and oceans are more readily reversed, however. Mountain glaciers are much smaller than ice sheets, so they would regrow faster, taking centuries rather than millennia. Seasonal sea ice and snow cover in the northern hemisphere, once lost, would also probably return within a few years if air temperatures decreased to pre-industrial levels. Thawing of permafrost is expected to be reversible in most places, but the timescales to lock up the carbon again in permafrost and hydrates are very uncertain.

[START FIGURE FAQ9.1, FIGURE 1 HERE]

FAQ 9.1, Figure 1: Placeholder for figure with elements similar to above. Source: Nick Golledge

[END FIGURE FAQ9.1, FIGURE 1 HERE]

FAQ 9.2: How much will sea level rise in the next few decades?

Scientists estimate that, as of 2015, global average sea level was already about 20 cm higher than in 1900 and 5 cm higher than in 2000, and that sea level will rise by a further 7–25 cm by 2050. Two major reasons for this are the thermal expansion of water from increasing ocean temperatures and the melting of glaciers and ice sheets. Local sea level change can be higher or lower than the global mean, with the lowest rates of rise in formerly glaciated areas and the highest rates of rise in low-lying river delta regions.

Across the globe, sea level is rising. The rate of global mean sea level change was 3 millimetres per year from 1993 to 2017, which is about double the average rate observed during the 20th century. Scientists estimate the main causes of sea level rise for the earlier part of the last century were natural factors, such as the delayed response of mountain glaciers to northern hemisphere warming in the 19th century after the Little Ice Age. However, since at least 1970, human activities have been the dominant cause of global average sea level rise, and this will continue to be the case for centuries into the future.

Sea level rises when the oceans expand, either through warming of ocean waters, through the addition of water or ice previously stored on land, or through vertical movement of the land. The single largest source of current sea level rise is the expansion of ocean water due to global warming (39% of the rise observed since 1993), followed by melting of ice from mountain glaciers and ice caps around the world (24%). Melting of the two large ice sheets have played an increasing role since the 1990s, with average contributions of 16% from Greenland and 11% from Antarctica. Another source is changes in land water storage (5%), particularly due to extraction of water from groundwater reservoirs for consumption and irrigation.

The amount by which global mean sea level will rise over the next three decades will not depend much on whether or not greenhouse gas emissions are reduced. This is partly because the emissions are similar under all realistic scenarios in the near term and partly because oceans, glaciers and ice sheets mostly respond on slow timescales (decades, centuries and longer), so they will still be responding to warming that has occurred since the pre-industrial era. Scientists project there is a 90% or greater chance that global average sea level rise will be between 0.2 m and 1.1 m between the average level over 1995-2014 and the level in 2100 under all scenarios (SSP1-2.6 to SSP5-8.5). This means that the projected annual average rates of sea level rise range from the current rate of about 3 millimetres per year up to about four times faster than that.

Sea level change has large regional variations, so in many places local sea level change will be higher or lower than the global mean. Changes in ocean circulation and wind, which are the primary drivers of year-to-year local sea level variability, can lead to long-term local sea level change. In regions where large ice sheets covered the land during the last ice age, such as Scandinavia and North America, the land is still slowly rising up now that the downward pressure exerted by the extra weight of the ice sheets is gone. This local recovery is compensating global sea level rise in these regions and can even lead to a local fall in sea level. In regions just beyond where the former ice sheets reached, where the Earth bulged upwards, the land is now falling, and as a result local sea level rise is faster than the global rate. In many cities within low-lying delta regions, the land is rapidly subsiding (falling) because of human activities such as groundwater or fossil fuel extraction. In some cases, this subsidence reaches tens of millimetres per year, greatly amplifying local sea level rise. A further reason for local changes, which may sound counterintuitive, is that when an ice sheet melts, it has less gravitational pull on the ocean water. This causes sea level to fall close to the (now less massive) ice sheet while causing sea level to rise farther away because the melted ice sheet adds more water to the oceans overall. Melt from an ice sheet therefore affects sea level most in the opposite hemisphere from where the melting occurs.

Sea level rise will increase the frequency and severity of extreme sea level events at coasts. Scientists predict that in some regions, extreme sea level events that are currently expected once in 100 years will be experienced many times more frequently by 2050: they will occur every 2 to 50 years for most regions in high northern and southern latitudes, and they may occur multiple times per year in the tropics.

Beyond 2050, the amount by which sea level will rise is more uncertain. Some predictions show sea level rise continuing at a similar rate, while others show substantial acceleration. Present and future greenhouse gas emissions play a big role in determining how much rise there will be beyond 2050. Under SSP1-2.6, there is a 95 % chance that sea level rise will remain below 4.7 m by 2300. However, if the climate warms substantially due to sustained future emissions above this level, the Antarctic ice sheet may begin to lose ice much more quickly than today, leading to much higher sea levels.

[START FIGURE FAQ9.2, FIGURE 1 HERE]

FAQ 9.2, Figure 1: Placeholder for figure with elements similar to some of the above. Source: Sophie Berger & Nick Golledge & Aimée Slangen

[END FAQ9.2, FIGURE 1 HERE]

FAQ 9.3: Will the Gulf Stream shut down, and what happens if it does?

The Gulf Stream is part of a large ocean current in the North Atlantic called the Atlantic Meridional Overturning Circulation (AMOC). Scientists estimate that this current is slowing down and will slow more in the future. Most climate models project that the AMOC could slow or shut down in the 22nd century under most future emissions scenarios. As the Gulf Stream is a warm current, it affects the weather around the tropics where it begins and the North Atlantic where it ends. If it slows further or shuts down, North America will see higher sea levels and Europe will see changes in weather and reduced warming relative to other regions. Similar processes may also affect the Southern Hemisphere.

The Gulf Stream is the biggest current in the North Atlantic Ocean and one of the largest currents in the world in terms of water carried. Each second, it transports about 30 billion kilograms of water northward past any location along its path along the east coast of North America. It is a warm current, with temperatures typically 5° to 15°C warmer than surrounding waters. As it moves northward, it carries a large amount of thermal energy (i.e., energy stored in warmer water) from its southern origins, and as it travels it releases this thermal energy to the atmosphere and surrounding water. Thus, the Gulf Stream warms poleward latitudes and cools equatorward and southward latitudes.

The Gulf Stream is one of many currents in the world that flow along the western side of ocean basins. The Kuroshio is a similar current in the North Pacific Ocean that travels northward along the east coast of Asia. However, the Gulf Stream is special in that it serves a second role: supplying the source for cold, deep waters that circulate back towards the equator. Cold water is denser than warm water, and in the Labrador and Irminger Seas at the northern end of the Gulf Stream path, cold wintertime conditions tend to make surface waters cold enough to sink to a depth of about 1500 metres. This cold water returns southward, spilling over features on the ocean floor and mixing with other deep waters in the Atlantic to form North Atlantic Deep Water. This overturning flow, with the Gulf Stream in the upper kilometre flowing northward and the colder Deep Water flowing southward, is called the Atlantic Meridional Overturning Circulation. There is no comparable deep overturning circulation in the North Pacific. So, the Gulf Stream completes both the horizontal circulation of the North Atlantic surface waters, driven by the winds, and the vertical overturning circulation, resupplying the water that sinks and becomes North Atlantic Deep Water.

The Kuroshio and the part of the Gulf Stream that transports warm surface waters result primarily from wind patterns and are not expected to change much. These currents will continue to transport thermal energy poleward from the equator much as they do now, although there will be some changes as the atmosphere and surrounding waters continue to warm under climate change.

However, the Atlantic Meridional Overturning Circulation is slowing and is expected to slow even more by the end of this century. This is mainly due to freshening (reduction in salt content) of the ocean waters due to meltwater from the Greenland ice sheet and Arctic sea ice and increased precipitation in the North Atlantic. This is making waters in the Labrador and Irminger Seas warmer and fresher and thus less likely to sink in this region. Since 2005, an array of moorings across the Atlantic at 26.5°N has been monitoring the Gulf Stream. The slowdown is not yet apparent in the data from this new monitoring system, but there are other signs that the overturning is slowing—for example, the region where the Gulf Stream's surface waters sink is not warming up as fast as its surroundings with global warming. Climate models show that this pattern of relatively cooler waters is consistent with a slowing of the overturning. Models also agree that under all emissions scenarios, this slowdown is expected to intensify by 2100 and beyond, with some models projecting a shutdown in the 22nd century. Paleoclimate evidence shows that the overturning has weakened in the past, especially during the ends of ice ages as ice sheets were melting and temperatures were rising.

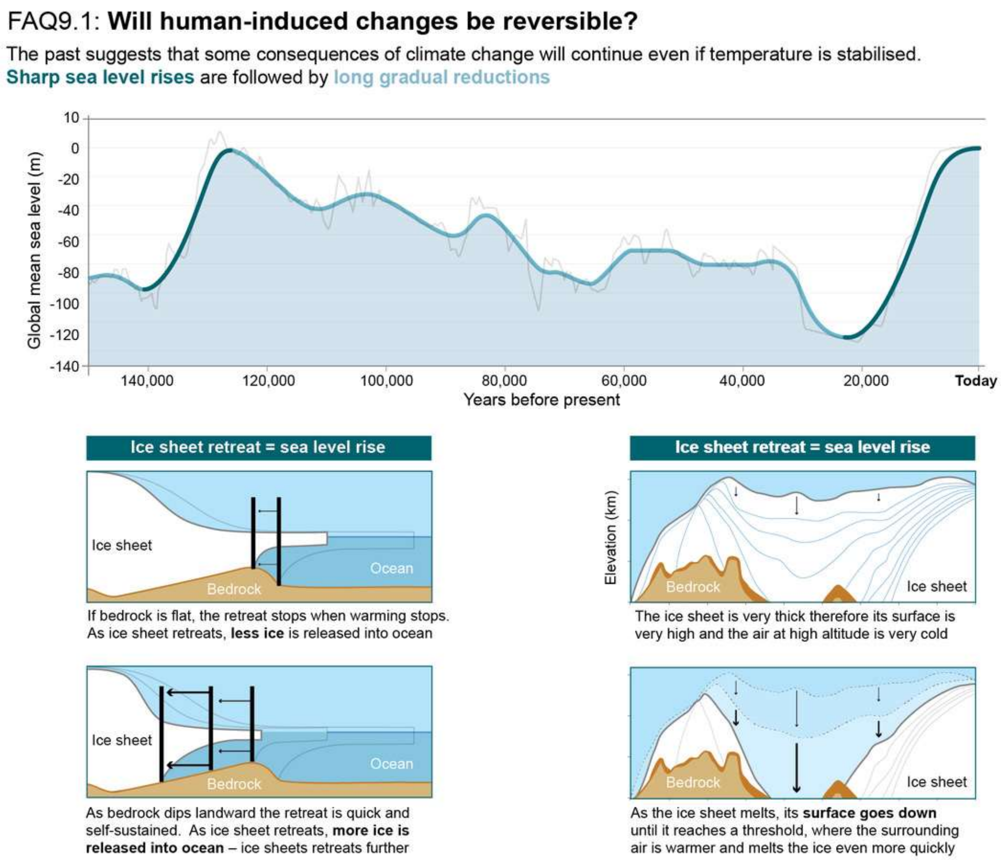
What happens as the overturning slows down? The atmosphere adjusts somewhat to compensate for the changes in the ocean overturning by transporting some of the missing heat transport. But the reduced oceanic poleward heat transport means the North Atlantic will warm more slowly than other regions, which in turn means that parts of Europe will warm more slowly than other regions. As a result of the additional heat accumulated in the Gulf Stream area and the slowing of this current, sea level along the coast of North America will rise more than it would without these changes. Models indicate that weather patterns around the Atlantic will be affected, with reduced precipitation in the mid-latitudes, changes to where strong precipitation occurs in the tropics and Europe, and stronger storms in the North Atlantic Storm Track. We have not been monitoring the changes in the AMOC long enough to be sure all of these model projections are accurate, and present variability of the AMOC do not yet indicate a long-term shutdown.

The North Atlantic is not the only site of meridional overturning. Around Antarctica, the densest water in the world is formed by freezing conditions that cool the water and form ice, adding salt to the remaining liquid water. Recent studies have shown that melting of the Antarctic Ice Sheet can reduce the salinity of this water, slowing the rate at which it sinks and thereby slowing a different, southern branch of the Meridional Overturning. This slowdown also results in a change in surface conditions near the sinking regions which in turn affects the weather locally and potentially across the Southern Ocean and the southern ends of South America, Australia, and Africa. As in the North Atlantic, as this shutdown has not begun in earnest these effects have not been observed, only projected by models. However, these changing weather patterns are not as well understood as those that would result from a shutdown of the overturning portion of the Gulf Stream.

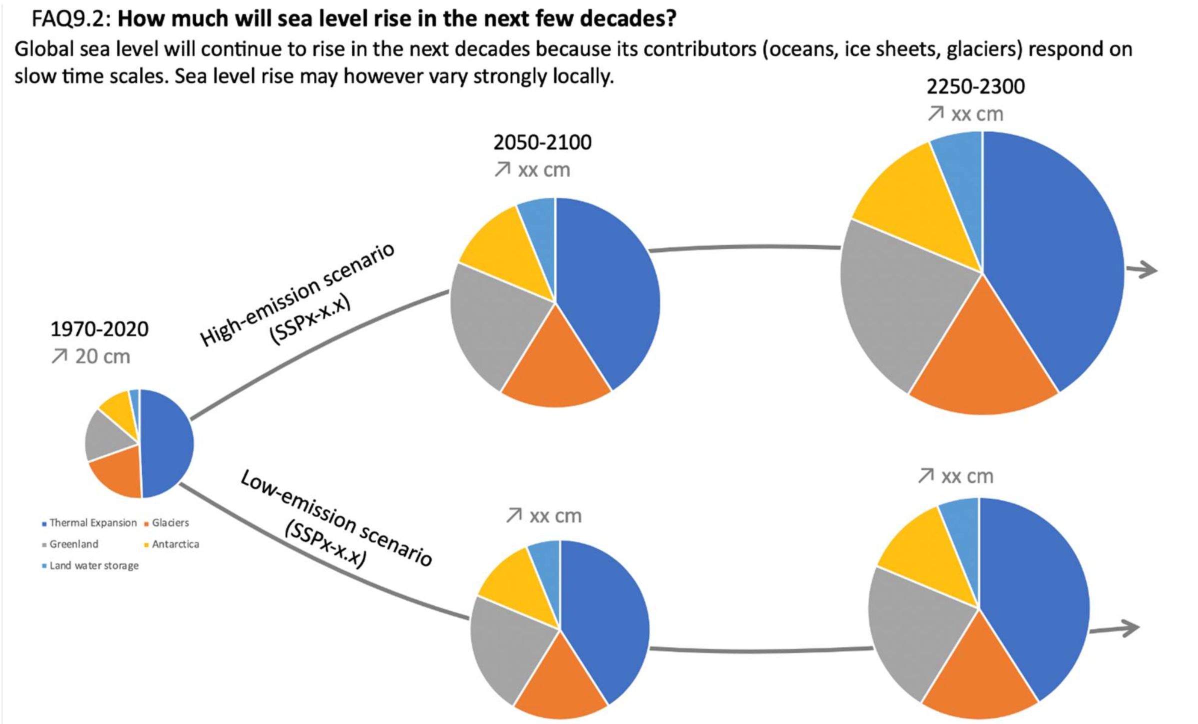
[START FIGURE FAQ9.3, FIGURE 1 HERE]

FAQ 9.3, Figure 1: [Placeholder for Gulf Stream Figure taken from RAPID/MOCHA website].

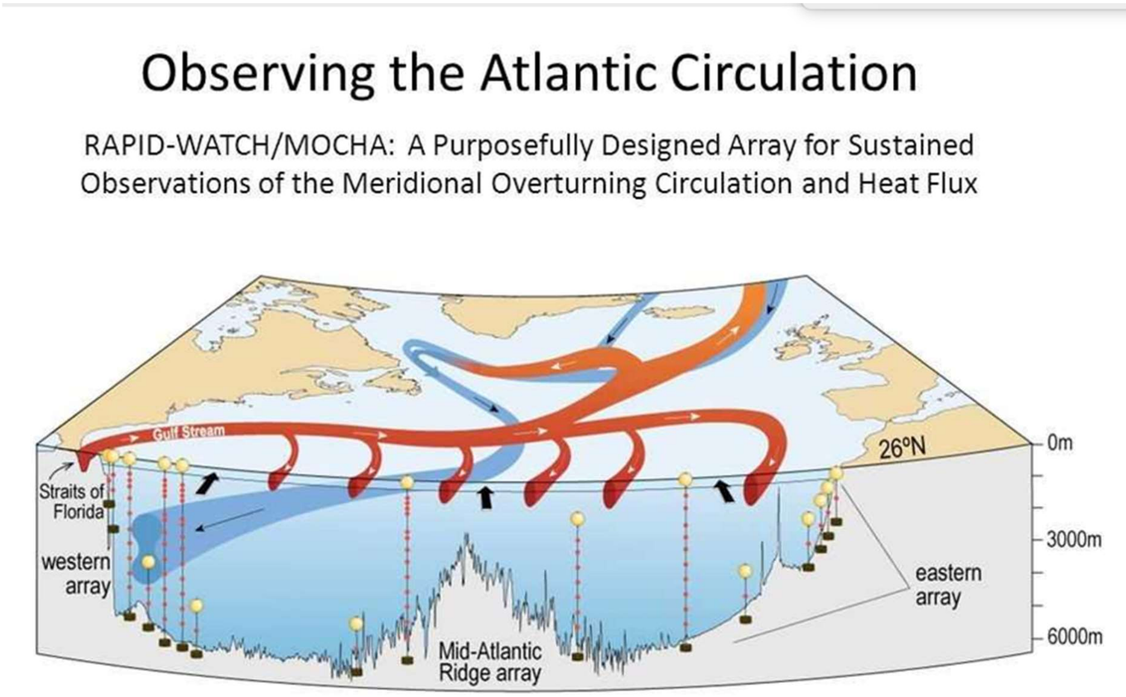
[END FIGURE FAQ9.2, FIGURE 1 HERE]



FAQ 9.1, Figure 1: [PLACEHOLDER FOR FIGURE WITH ELEMENTS SIMILAR TO ABOVE.] Source: Nick Golledge



FAQ 9.2, Figure 1: [PLACEHOLDER FOR FIGURE WITH ELEMENTS SIMILAR TO SOME OF THE ABOVE]. Source: Sophie Berger & Nick Golledge & Aimée Slangen



FAQ 9.3, Figure 1: [Placeholder for Gulf Stream Figure taken from RAPID/MOCHA website]

Frequently Asked Questions

FAQ 10.1: How can we provide useful climate information for regional stakeholders?

The world is physically and culturally diverse, and the challenges posed by climate change vary by region and location. Because climate change affects so many aspects of people's daily work and living, information about climate change can help with decision-making, but only when the information is relevant for the people involved in making those decisions. Users of climate information may be highly diverse, ranging from professionals in areas such as human health, agriculture or water management to a broader community that experiences the impacts of changing climate. Providing useful, actionable information thus requires an awareness of local contexts, agreement on the appropriate formulation of the information, and a mutual understanding of limitations and uncertainties.

The development, delivery, and use of climate change information are inherently influenced by the values of all parties involved: those providing the information, those communicating the information, those hearing the information, and those who need the information in order to make decisions or solve problems Consequently, partnerships between these participating communities, especially involving those for whom the information is intended, can help ensure that the appropriate information is delivered and provided in ways that are accessible and usable by decision-makers.

Effective partnerships recognize and respond to the values of all parties involved, especially when they involve culturally diverse communities. This is particularly true for climate change – a global issue posing challenges that vary by region. Challenges like this require exchanging information between groups that may be culturally diverse and from different disciplines and domains of expertise. By recognizing this diversity, climate information can be made more relevant and credible, most notably when conveying the complexity of risks for human systems and ecosystems and for building resilience in developing nations, which may be more vulnerable to damaging impacts of climate change.

Useful climate information can come in many different forms and from many different sources. For example, climate scientists can provide information on future changes by extending historical trends forward into the future, using model simulations of the global and/or regional climate change, and inferring regional change by evaluating changes in the weather behaviour that influences a region. Constructing useful climate information requires considering all available sources in order to capture the fullest possible representation of projected changes and distil the information in a way that meets needs of the stakeholders and communities impacted by the changes. Ideally, the distillation process (FAQ 10.1, Figure 1) engages with the intended recipients of the information, especially stakeholders whose work involves non-climatic factors, such as human health, agriculture or water resources. The distillation should evaluate the accuracy of all information sources (observations, simulations, expert judgement), weigh the credibility of possible conflicting information, and arrive at climate information that also estimates the confidence a user should have the information. Information providers should further recognize that the geographic regions and time periods governing stakeholders' interest (for example, the growing season of an agricultural zone) may not align well with the time and space resolution of available climate data, and thus additional development may be required to extract useful climate information.

Successfully framing information on climate impacts and effective societal responses requires presenting information in the context of the local challenges posed by climate change. For example, the U.S. state of Arizona passed an initiative that responded to a specific, local impact of climate change—water-resource shortfalls in Arizona – even though some of the state's government leaders were unsure about global climate change. The success of this effort was the result of recognizing a serious impact while avoiding the central, but likely controversial, motivation of fighting global climate change. Similarly, city officials of Lusaka in Zambia engaged in a sustained dialogue with climate scientists. The result was a partnership that constructs and communicates climate information relevant to governing an African city vulnerable to climate change, such as changes in rain seasons.
Stakeholders often need information about complex, compound events—such as floods following a period of drought – and the information they need, such as data on heat-stress conditions or a drought index, may not

be a primary concern for scientists focused on projecting changes in the physical climate system

One way to link complex information to stakeholder applications is through stories. Storylines give climate change information in a form that connects with the recipients' experiences of existing weather and climate. These storylines can make climate information more accessible and physically comprehensible. For example, a storyline may take a common experience like the arrival and duration of a winter storm and show how the storm's snowfall and winds will change in the future. The development of storylines uses the experience and expertise of stakeholders who seek to develop appropriate response measures, such as water-resource managers and health professionals. With appropriate choices, storylines can engage nuances of the climate information in a meaningful way by building on common experiences, thus enhancing the information's usefulness.

[START FAQ 10.1, FIGURE 1 HERE]

FAQ 10.1, Figure 1: [Placeholder, the figure will be updated: Climate information for decision makers is more useful if the physical and cultural diversity across the world is considered. The figure illustrates schematically the broad range of knowledge that must be blended with the diversity of users to distil information that will have relevance and credibility.**]**

[END FAQ 10.1, FIGURE 1 HERE]

FAQ 10.2: How does the growth of cities interact with climate change?

Urban areas with buildings in close proximity to each other "trap" heat, reduce the natural ventilation and modify the local radiation and energy balance. Combined with less vegetation and heat released by human activities, cities are creating the so-called "urban heat island" (UHI), which causes cities to experience higher than average temperatures than their surrounding areas. Urbanization and the increasing severity of heat waves under climate change further amplify this effect.

Cities are on front line in both the causes and the effects of climate change. On one hand, cities are responsible for up to 70% of current emissions of GHGs yet occupy less than 1% of global land mass. By 2030, almost 60% of the world's population will live in urban areas and every year sees the addition of 67 million new urban dwellers, 90% of these is added to cities in developing countries. On the other hand, cities and their inhabitants are highly vulnerable to climate extremes, including more frequent, longer and more intense heat waves. Urban areas are already vulnerable to increased thermal stress during heat-waves and projected rates of urban growth means that vulnerability will increase. This became apparent in 2003 in Paris, France, when daily mortality tripled during a heat wave in early August (around 30,000 causalities), or in 2010, in Ahmedabad, India, when a heatwave killed more than 1,100 people.
Due to the low albedo (reflectivity) of impervious surfaces, such as rooftops and asphalt roadways, differential heat storage (big heat capacity of building materials), anthropogenic heat, reduced wind speed (greater surface roughness), and light trapping within the canyons formed by taller structures, cities 'trap' heat (see FAQ10.2 Figure 1). They are therefore often associated with elevated surface air temperature, a phenomenon referred to as the urban heat island, where night-time urban air temperature is substantially higher (several degrees) than corresponding temperatures in the surrounding rural areas. In different cities around the world with different background climate, it has been found that during heat waves episodes, the urban heat islands gets intensified compared to its climatological mean values.

Although the urban heat island phenomenon is well documented and better understood, important measurements of meteorological and external climatic drivers across urban areas remain are lacking, due to the scarcity of high-density, in-situ measurement networks. Especially, long-term datasets (a year or more) are very scarce but invaluable because they allow more in-depth research on the seasonal evolution of the urban climate. In many cities, especially in the developing world, the historical record is too short, discontinuous, or the quality too uncertain to support trend analysis and climate change attribution.

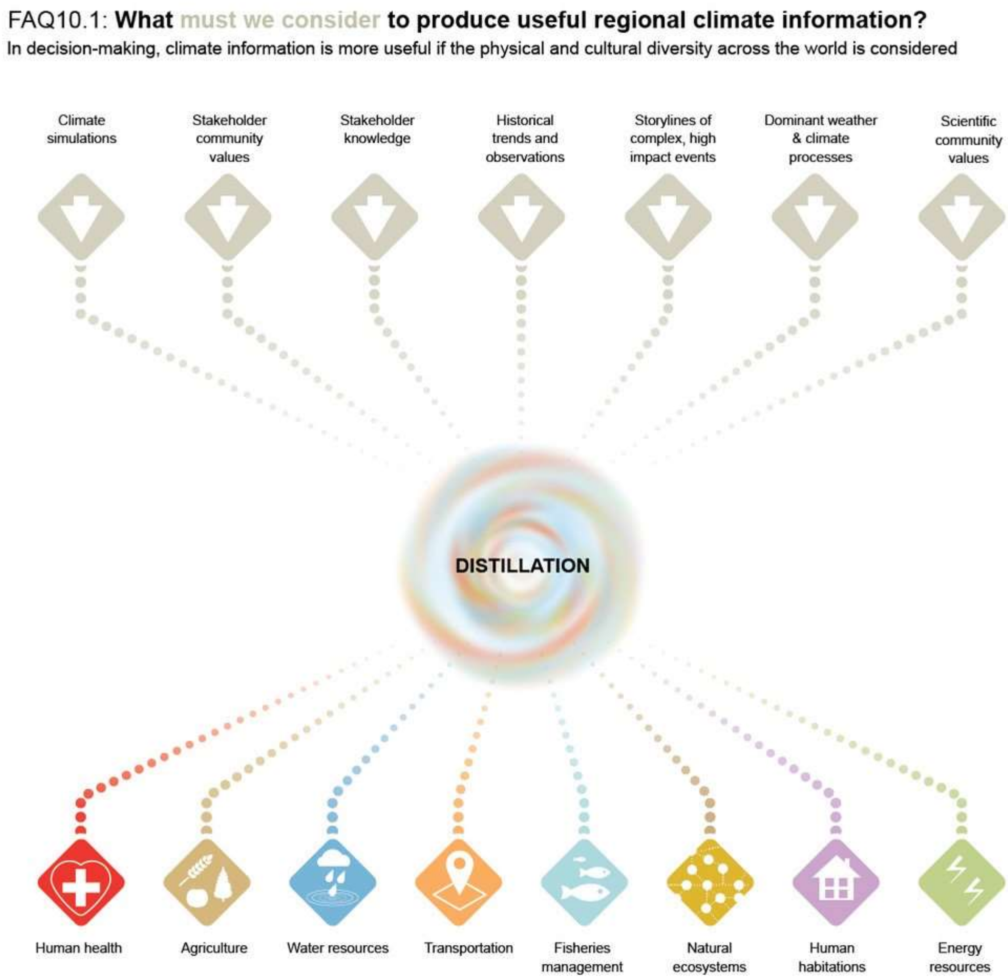
Estimating how the urban heat island will evolve under climate change conditions is uncertain because several studies, which use a variety of methods, report contrasting results. However, there is *clear evidence* that future urbanization amplifies the projected air temperature under different background climate *with a strong impact on minimum temperatures that could be comparable in magnitude to the global warming*.

Climate change will, on average, have a limited impact on the magnitude of the urban heat island but urbanization together with more frequent extreme climatic events (e.g. heat waves) will strongly affect cities.

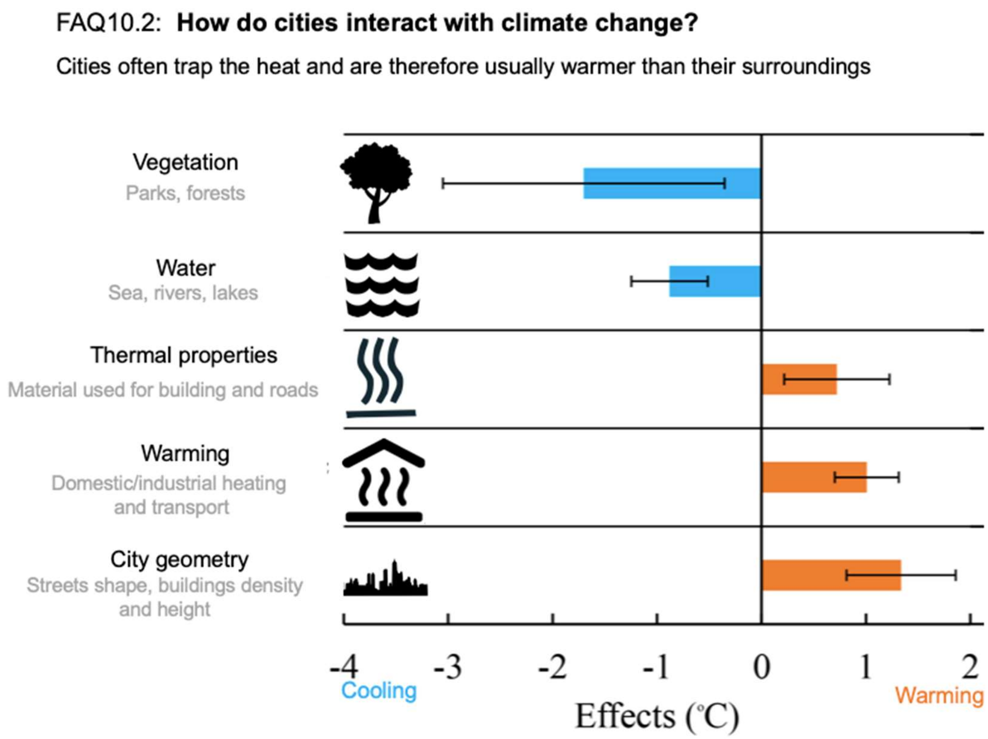
[START FAQ 10.2, FIGURE 1 HERE]

FAQ 10.2, Figure 1: [Placeholder, the figure will be updated: Various factors contribute to either warm up or cool down urban areas, compared to their surroundings. Overall, cities tend to be warmer than their surroundings. This is called the "urban heat island" effect. Values are taken from the recent literature.**]**

[START FAQ 10.2, FIGURE 1 HERE]



FAQ 10.1, Figure 1: Climate information for decision makers is more useful if the physical and cultural diversity across the world is considered. The figure illustrates schematically the broad range of knowledge that must be blended with the diversity of users to distil information that will have relevance and credibility.



FAQ 10.1, Figure 2: Various factors contribute to either warm up or cool down urban areas, compared to their surroundings. Overall, cities tend to be warmer than their surroundings. This is called the "urban heat island" effect. Values are taken from the recent literature.

Frequently Asked Questions

FAQ 11.1: How do changes in climate extremes compare with changes in climate averages?

Climate extremes, such as heat waves and extreme precipitation events, can significantly impact ecosystems and societies, so it is important to understand how global warming may alter the frequency and severity of such events. For near-surface temperature, increases in extreme heat events are expected to be larger in magnitude extremes will occur on the backdrop of global mean warming.

One way to illustrate both averages and extremes for a given aspect of climate or weather (e.g., extreme heat relative to average temperature) is by showing a probability density function (PDF), which approximates the relative frequency of occurrence of the full range of possible values for a given variable, such as daily maximum temperatures. The extreme values at either end of the PDF may have much lower probabilities, and would thus be rare events. In the case of near-surface temperature, the distribution of observed temperatures is commonly approximated by the familiar bell curve, or Gaussian PDF—this is a symmetric distribution where both low and high extreme values are equally likely (FAQ 11.1, Figure 1.a). Precipitation, however, is usually better approximated by a distribution with a skewed shape—one that is asymmetrical, where extremes with low precipitation amounts occur with a greater probability than high-precipitation extremes (FAQ 11.1, Figure 1.b).

In this context, changes can be viewed in terms of how the shape and average values of a PDF for a given aspect of climate change as a result of global warming. For example, Figure 1 illustrates hypothetical PDFs for temperature and rainfall and how those distributions might change in the future compared to historical conditions. As shown in the figure, the probability of a historical extreme may change as a result of a simple shift in the average, but it is also possible that the variability or shape of the distribution may change in more complex ways

Climate model simulations show that, at local scales, changes in the daily temperature PDF are dominated by a shift in which all values, including the mean and the extremes, are displaced towards warmer temperatures. In most places, land regions warm more than global average. These changes arise due to both the increase of greenhouse gases and local processes that can either amplify or offset the overall warming influence of increasing greenhouse gase concentrations. As a result, changes in local mean temperatures can vary greatly across regions and throughout the year, though most land regions warm more than the global average. In some cases, local processes may have little effect on changes in average conditions but can influence extreme events when they are moderated or exacerbated by specific weather conditions. For example, daily hot extremes can be more likely or more severe in situations where there is limited availability of soil moisture. Also changes in surface albedo (the fraction of incoming solar energy reflected by the surface) have been shown to have more effect on hot extremes than on average temperatures. This is because there tends to be more incident shortwave radiation on hot days, so an increased surface reflectivity associated with higher albedo will result in a stronger net cooling.

Likewise, the absence of increases in the maximum temperatures observed on hot days may be explained by processes affecting extremes rather than averages. Notably, the absence of warming in India has been ascribed to cooling from increased concentrations of aerosols (small particles in the atmosphere) as a result of burning fossil fuels and in the U.S. Midwest to local land management practices, including irrigation and cropland intensification.

Rainfall changes are generally more complicated than a simple shift in the distribution and also result from the combined effects of various processes occurring at different temporal and spatial scales. FAQ 11.1, Figure 1.b illustrates a case where the future PDF is more skewed (that is, more asymmetrical) than the historical PDF, with a larger mean value together with a higher probability of heavy precipitation events and a lower probability of light precipitation events. Heavy precipitation events are expected to increase in severity and frequency in a warming climate because water vapour increases 7% for every degree Celsius increase in surface temperature, meaning there is more water available to fall as precipitation.

However, at regional scales, changes in the dynamics of the climate system, including atmospheric circulation, can modulate, or even reverse the increases in extreme precipitation. Annual average precipitation amounts will only increase at rates of about 2–3% per degree Celsius of warming due to limitations from the rate at which the associated energy dissipates in the atmosphere, mostly at global scales.

[START FAQ 11.1, FIGURE 1 HERE]

FAQ 11.1, Figure 1: *Schematic representations of the probability density function of (a) daily temperature, which tends to be approximately Gaussian, and (b) daily precipitation, which has a skewed distribution. Solid lines represent a previous (historical) distribution and dashed lines a changed (future) distribution. The probability of occurrence, or frequency, of extremes is denoted by the shaded areas. In the case of temperature (red and blue shade), changes in the frequencies of extremes can be affected either by changes only in the mean, or average (shift) or in both the mean and the variance, or shape (shift+var). For example, the wider distribution of the shift+var case means that both cold and warm extremes are more common relative to the average than in the historical or future (shift) cases. But combined with the increase in average, this increase in variability means a higher probability of extremely warm temperatures compared to the future (shift) case, where the variability does not increase. Similarly, in a skewed distribution such as that of precipitation (green shaded), a change in the mean of the distribution generally affects its variability or spread, and thus an increase in mean precipitation would also imply an increase in heavy precipitation extremes, and vice-versa. In addition, the shape of the right-hand tail could also change, affecting extremes. Furthermore, climate change may alter the frequency of precipitation and the duration of dry spells between precipitation events. (Parts a–c modified from Folland et al., 2001, and modified from Peterson et al., 2008, as in Zhang and Zwiers, 2012.)*

[END FAQ 11.1, FIGURE 1 HERE]

FAQ 11.2: Could unprecedented extremes occur as a result of human-induced climate change?

As the climate changes, associated unusual or extreme events will also change. Future extreme events will be similar to those experienced in the past, but some will occur with much larger magnitudes than before and some events will occur much more frequently, possibly resulting in events or impacts that are unprecendented. Some locations may experience events (such as wildfires) not previously observed in those areas, with possible concerns for impacts on human and natural systems. The occurrence of multiple extreme events simultaneously or in close succession may also change the severity of events and impacts relative to what has been experienced in the past.

Human and natural systems have generally adapated to the climate of the last few decades and centuries, where extreme and rare events occured. As human-induced changes shift the climates of the future, the climate moves away from the state to which local human and natural systems are currently adapated. Extreme events already test, and sometimes exceed, the limits of those human and natural systems, so changes in the frequency or severity of some types of extreme events may result in different impacts than in the past.

In a warmer climate, extreme events may occur with differing characteristics to what we have experienced in the past. Characteristics of the same events types (e.g., heatwaves, floods or droughts) may change: future extremes may be more severe, may occur more frequently or may occur for differing durations.
We have experienced heatwaves in the past and we will experience heatwaves in the future, but in a warmer climate, the heatwaves will generally have hotter temperatures and last longer than past heatwaves. For example, the 2013 severe heatwave event in China today is projected to occur, of be exceeded, in 50% of future summers in even the moderate RCP4.5 scenario.

Human-induced changes could result in extreme events that have unprecedented impacts. However, the impact of an event depends not just on its physical attributes but also on the exposure and vulnerability of systems, and these may also change. Changes in heat extremes in the future, for example, could lead to unprecedented severity or duration of heat events and coral reef bleaching in novel locations. Coral reef heat stress depends on the magnitude and duration of temperatures above a certain threshold. Either a short-duration, high-magnitude event or a long-duration, lower-magnitude event can cause bleaching. Such impact thresholds also exist for human and animal physiologies, suggesting that some new climates may lead to serious health concerns. While these extreme events types (e.g., heatwaves) are similar to those already experienced, future extreme events may be considered a new type of event because of their unprecedented impacts.

Compound events – where multiple hazards combine to elevate risks and impacts – are also an important consideration for future extremes and unprecedented impacts (FAQ 11.2, Figure 1). For example, the occurrence of drought combined with extreme heat will increase the risk of wildfires and agriculture losses. Another example is a drought followed by extreme rainfall, which exacerbates the runoff as well as introducing multiple impacts. A changing climate may alter the interaction between hazards or result in the combination of multiple unprecedented events. It is possible that compound events will exceed the adaptive capacity or resilience of the human and natural systems more quickly than individual events. The result could include types or levels of impacts (societal, economic, ecological, etc.) not seen at all previously.

There is also the possibility of the future occurrence of extreme events that have not been anticipated. In many regions, observational data are limited to 50–60 years, which means that we may not have a complete understanding of what sort of extremes (such as the hottest maximum temperatures or the maximum amount of rainfall) are possible for some areas, even in a stable climate. The shortness of the observational record may mean that events that are very rare, but not impossible, are difficult to anticipate or plan for. When such rare or unprecedented extreme events occur, they may be suprising and have particularly large impacts. As warming continues, the climate moves further away from the historical state that we are familiar with, and unprecedented or suprising events, become more likely. Additionally, landscapes that are changing rapidly or at risk of crossing important thresholds, such as areas currently covered by perennial ice or permafrost, may be at higher risk of unique or locally unprecedented events.

[START FAQ 11.2, FIGURE 1 HERE]

FAQ 11.2, Figure 1: Illustration of enhanced risks associated with compound events (from Zscheischler et al., 2018b), The hypothetical present-day distribution of two climatic drivers and their potential future distribution, together with a critical region in which impacts are induced. Continuous lines depict the 50th and 80th percentiles, dashed lines denote the 95th percentiles. The coloured points denote different possibilities to generate potentially critical events. The critical region is shown in orange with a blurred border to illustrate uncertainty in the estimation of its extent. The critical region can only be known if enough critical events have occurred (or can be simulated) to characterize it. This figure illustrates that climate change is modifying the envelope of the distribution of climate extremes we have at the moment, which possibly could yield new unprecedented extremes which are within some "critical region" in which new impacts could happen.

[END FAQ 11.2, FIGURE 1 HERE]

FAQ 11.3: Did climate change cause that recent extreme event in my country?

The climate and weather we experience varies from day to day and from year to year. As a result, we have always experienced extreme weather and climate events. However, there is strong evidence that characteristics of many individual extreme events have already changed because of human driven changes to the climate system. Some types of highly impactful extreme weather events have occurred more often and have become more severe due to these human influences. As the climate continues to warm, the frequency or severity of some extreme weather events will continue to change as the human influences on these events increase.

Many factors contribute to the occurrence of complex, rare events. Attributing the causal influence of climate change on current extreme weather events requires considering both natural and human influences. Recent developments have allowed scientists to quantify the human influence on the magnitude or frequency of specific extreme weather events. For a wide variety of recent extreme weather events, an influence from global warming has been demonstrated. Borrowing methods from epidemiology, this influence is often expressed as a change in the likelihood of an extreme event of the observed magnitude and/or as a change in the magnitude of the event for a fixed estimated probability of occurrence.

[START FAQ 11.3, FIGURE 1 HERE]

FAQ 11.3, Figure 1: Examples of how temperature extremes differ in cooler and warmer climates. Changes in extreme events can be thought of as either changes in the frequency of events of a given magnitude or as changes in the magnitude of events that occur at the same frequency. These two concepts are closely related, as illustrated in this example for (a) hot extremes and (b) cold extremes. The vertical axis shows the range of extreme temperatures on a logarithmic scale, while the horizontal axis shows the estimated average time between events, referred to as the return period of an event. In a warmer climate, extreme hot events of the same magnitude occur more frequently (that is, the return period for a given temperature decreases) and cooler events occur less frequently (return period increases) as indicated by the horizontal arrows between curves. If we look at events of a fixed rarity (constant return period), we see that in a warmer climate, both hot and cold extreme temperature events of a given return period are warmer (vertical arrows), although not necessarily by the same amount.

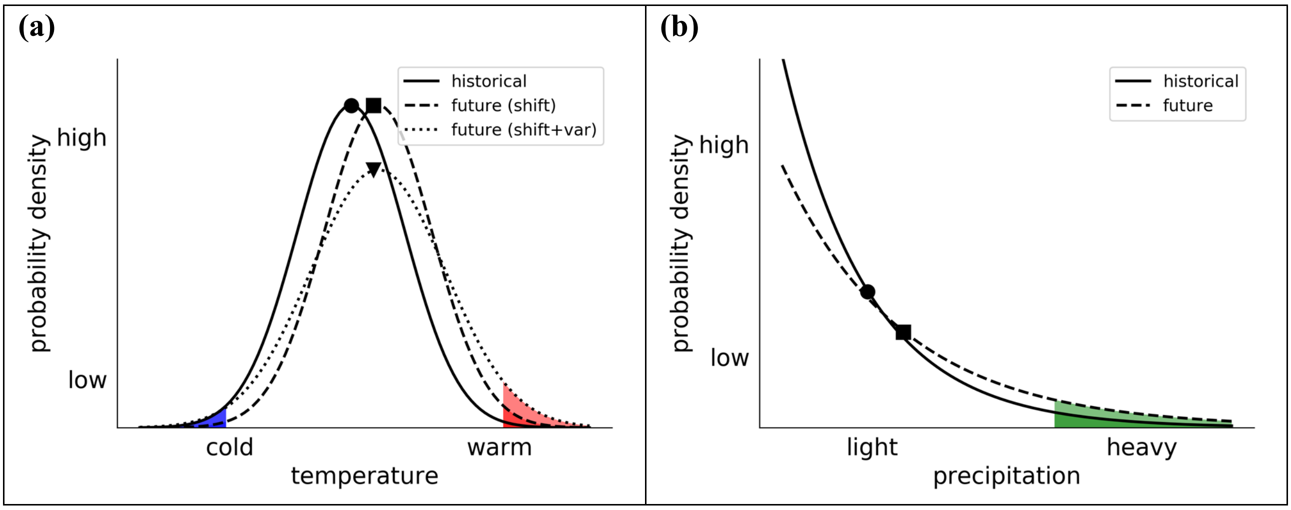
[END FAQ 11.3, Figure 1 HERE]

The change in temperature extremes as the climate warms is illustrated in FAQ 11.3, Figure 1: a depiction of the magnitude of extreme temperature events versus their frequency. Both cooler and warmer worlds experience hot and cold temperature extremes, but with different frequencies and magnitudes. In a warmer climate, the cold events of a given temperature occur less often than in the cooler climate, while hot events of a given temperature occur more frequently. For example, a “once every 50 years” cold event in the cooler climate is more rare in the warmer climate, while the “once every 50 years” hot event is less rare. Similarly, when comparing the magnitude of events of a constant rarity between these two worlds, both hot and cold temperature events are warmer in the warmer world.

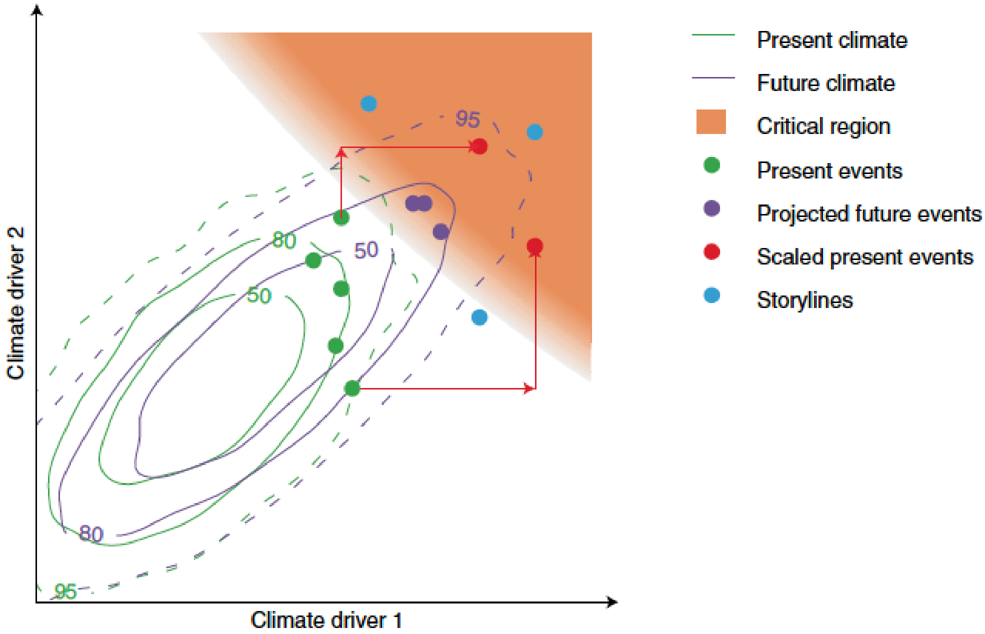
Many individual heat waves and extreme precipitation events have been intensified by human changes to the composition of the atmosphere. The causes of any specific extreme climate or weather event are complex mix of human and natural factors. The science of extreme event attribution quantifies the relative contributions of human and natural influences on these events. Hence, on a case by case basis, scientists can produce a quantitative estimate of the contribution of human influences to the severity or likelihood of an extreme event. However, other human activities also contribute to changes in some types of extreme weather events. For instance, urbanization can also lead to increased flood and heat wave risks, while high levels of air pollution can reduce observed high temperatures. In some cases, large natural variability in the climate system prevents making a conclusive attribution statement about the human influence on an extreme event.

Additionally, attribution of certain classes of extreme weather (e.g., tornadoes) is beyond our current modelling and theoretical capabilities.

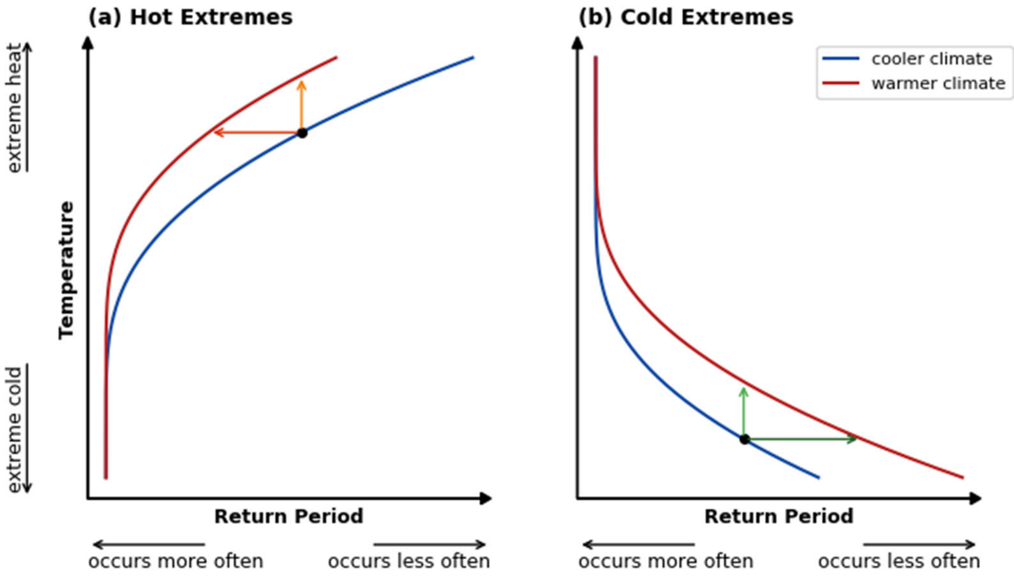
A related question is whether some recent extreme events would have actually been impossible had humans not altered the climate system. While we have seen climate and weather events that are unprecedented in the historical record, we do not yet have convincing evidence that any of these events would have actually been impossible in the absence of climate change. However, some events that would have been very rare are now relatively common place. As the climate continues to warm, high temperatures and precipitation accumulations that were impossible prior to human intervention in the climate system are expected to occur.



FAQ 11.1, Figure 1: Schematic representations of the probability density function of (a) daily temperature, which tends to be approximately Gaussian, and (b) daily precipitation, which has a skewed distribution. Solid lines represent a previous (historical) distribution and dashed lines a changed (future) distribution. The probability of occurrence, or frequency, of extremes is denoted by the shaded areas. In the case of temperature (red and blue shade), changes in the frequencies of extremes can be affected either by changes only in the mean, or average (shift) or in both the mean and the variance, or shape (shift+var). For example, the wider distribution of the shift+var case means that both cold and warm extremes are more common relative to the average than in the historical or future (shift) cases. But combined with the increase in average, this increase in variability means a higher probability of extremely warm temperatures compared to the future (shift) case, where the variability does not increase. Similarly, in a skewed distribution such as that of precipitation (green shaded), a change in the mean of the distribution generally affects its variability or spread, and thus an increase in mean precipitation would also imply an increase in heavy precipitation extremes, and vice-versa. In addition, the shape of the right-hand tail could also change, affecting extremes. Furthermore, climate change may alter the frequency of precipitation and the duration of dry spells between precipitation events. (Parts a–c modified from Folland et al., 2001, and modified from Peterson et al., 2008, as in Zhang and Zwiers, 2012.)



FAQ 11.2, Figure 1.: Illustration of enhanced risks associated with compound events (from Zscheischler et al., 2018b), The hypothetical present-day distribution of two climatic drivers and their potential future distribution, together with a critical region in which impacts are induced. Continuous lines depict the 50th and 80th percentiles, dashed lines denote the 95th percentiles. The coloured points denote different possibilities to generate potentially critical events. The critical region is shown in orange with a blurred border to illustrate uncertainty in the estimation of its extent. The critical region can only be known if enough critical events have occurred (or can be simulated) to characterize it. This figure illustrates that climate change is modifying the envelope of the distribution of climate extremes we have at the moment, which possibly could yield new unprecedented extremes which are within some "critical region" in which new impacts could happen.



FAQ 11.3, Figure 1: Examples of how temperature extremes differ in cooler and warmer climates. Changes in extreme events can be thought of as either changes in the frequency of events of a given magnitude or as changes in the magnitude of events that occur at the same frequency. These two concepts are closely related, as illustrated in this example for (a) hot extremes and (b) cold extremes. The vertical axis shows the range of extreme temperatures on a logarithmic scale, while the horizontal axis shows the estimated average time between events, referred to as the return period of an event. In a warmer climate, extreme hot events of the same magnitude occur more frequently (that is, the return period for a given temperature decreases) and cooler events occur less frequently (return period increases) as indicated by the horizontal arrows between curves. If we look at events of a fixed rarity (constant return period), we see that in a warmer climate, both hot and cold extreme temperature events of a given return period are warmer (vertical arrows), although not necessarily by the same amount.

Frequently Asked Questions

FAQ 12.1: What makes an extreme event or trend a climate hazard?

Climate change can alter many aspects of the climate system, but efforts to identify impacts and risks usually focus on a smaller set of changes known to affect, or potentially affect, things that society cares about. The term 'climate hazard' refers to a level of change in a specific aspect of the climate system (such as temperature, rainfall, or humidity) that is directly associated with potential impacts on one or more sectoral assets (such as farms, roads, wildlife, human health, or reservoirs). Furthermore, a climate risk exists only when a climate hazard has the potential to affect an asset that is both exposed to and vulnerable to that hazard.

Sectoral decision makers have long known that certain weather and climate conditions can be problematic, or hazardous, for their assets. These may include the occurrence of extreme weather events (e.g., tornadoes, hail storms, or floods) that directly impact an asset, critical climate thresholds (e.g., an extreme temperature, a low soil moisture content) beyond which systems start to break down, or long-term trends (e.g., warming trends or sea level rise) that change the suitability of an asset's day-to-day viability. For example, crops can be severely damaged by hail events, have increasingly negative biophysical responses when temperatures rise above successive thresholds, and may not be suitable for local cultivation as average temperatures climb.

The connection to an asset's vulnerability implied by the term climate hazard underscores that a change in the climate system is not considered hazardous when the results of that change do not exceed the biophysical or engineered tolerances of a particular asset. For example, increases in river flow are not directly hazardous to regional agriculture or settlements unless and until river levels exceed embankments.

[START FAQ12.1, FIGURE 1 HERE]

FAQ12.1, Figure 1: [Placeholder: A graphic illustration is under development here to show how successive stages of a river flooding illustrate the concept of a hazard threshold. (Panel a) river with level gauge showing normal flow well below embankments, with surrounding farms and a town. (Panel b) River at higher flow but still below embankments, surrounding farms and town not affected – not yet at hazard level. (Panel c) River overflows and surrounding farms and town are affected. The key is the distinction between panels b and c which defines a hazard level.]

[END FAQ12.1, FIGURE 1 HERE]

FAQ 12.2: In what ways can human-driven climate change cause climate hazards to shift?

Climate hazards have long been a challenge for natural ecosystems and society. Human-driven climate change can alter a region's climate hazard profile by changing the magnitude or intensity of a climate hazard, the frequency with which a hazard occurs, the duration that hazardous conditions persist, the timing when a hazard occurs, or the spatial extent threatened by a hazard.

Risk managers examine historical observations and future climate projections to identify changes to the characteristics of a regional hazard's:

<u>Magnitude or intensity</u>: The raw value of a climate hazard, such as a change in the maximum temperature on the hottest 1% of days, or in the depth of flooding that results from a once-in-100-year coastal storm.

<u>Frequency</u>: The number of times that a climate hazard occurs or surpasses a threshold over a given period, for example changes to the number of nuisance coastal floods, tornadoes, or droughts experienced in a year or a decade.

<u>Duration</u>: The length of time over which hazardous conditions persist beyond a threshold, such as changes in the number of consecutive days where maximum temperature exceeds 35°C, changes in the number of consecutive months of drought conditions, of the number of days that a tropical cyclone affects a location.

<u>Timing</u>: The occurrence of a hazardous event in relation to the course of a day, season, year, or other period in which sectoral assets are evolving or co-dependent (such as the time of year when migrating animals expect to find a seasonal food supply). Examples include the day of the year when the last spring frost occurs or when first seasonal rains arrive, the length of the wintertime period when the ground is typically covered by snow, the year in which the Arctic Ocean is effectively ice-free, or the rate at which soil moisture moves from normal to drought conditions.

<u>Spatial extent</u>: The region in which a hazardous condition is expected, such as the area currently threatened by tropical cyclones, geographical areas where the coldest day of the year restricts a particular pest or pathogen, terrain where permafrost is present, zones where climate conditions are conducive to outdoor labour, or the size of a coherent marine heatwave.

These changes are often intertwined or stem from related physical changes to the climate system. For example, changes in the frequency and magnitude of extreme events are often directly related (see FAQ 11.1).

[START FAQ12.2, FIGURE 1 HERE]

FAQ12.2, Figure 1: [*placeholder figure still under development.* Text embedded in figure: FAQ12.2: How can climate change cause hazards to shift? Climate change can alter the intensity and magnitude, frequency, duration, timing, and spatial extent of climate hazards.]

[END FAQ12.2, FIGURE 1 HERE]

FAQ 12.3: Can climate change be both hazardous and beneficial?

Climate changes are experienced differently across sectors, regions, and assets. In many cases the same climate change that exacerbates risks for a given asset can have beneficial effects for another. In some cases assets benefit from small changes even as larger changes become hazardous.

Climate hazards occur when climate conditions intersect with the vulnerability of sectoral assets and thus introduce the potential for adverse consequences. There is tremendous variety in the range of assets in natural and human systems, so precise levels for hazards can vary depending on biophysical and engineering limitations (e.g., genetics for biological systems or design criteria, materials specifications and construction quality for infrastructure) as well as a number of local conditions that alter hazard susceptibility (e.g., soils, topography, land use, management practices, resource competition).

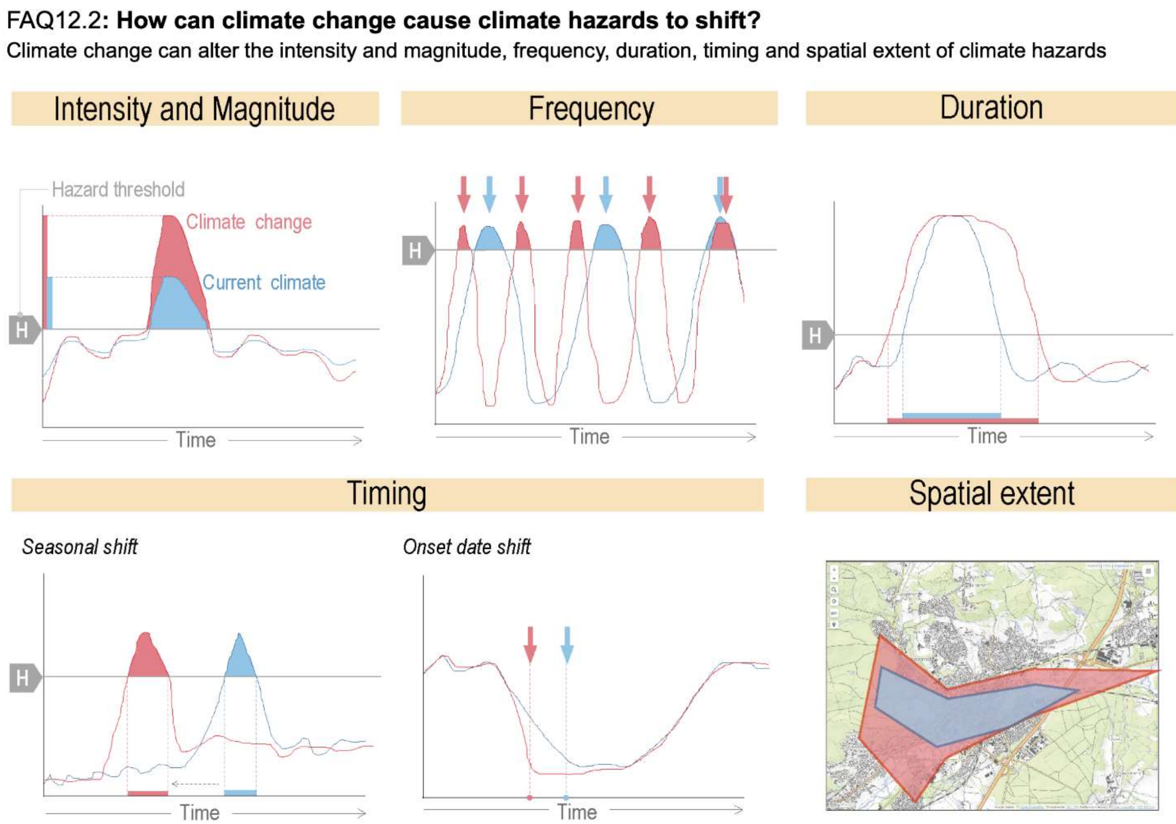
Scientists have identified thresholds where changing climate conditions are known to challenge natural and human systems in specific ways that are hazardous or beneficial. Many natural and human systems are well adapted to their climate setting and suffer as those conditions change, while others may thrive given climate changes that move toward a more optimal local climate. For example, warmer conditions may reduce the productivity of a region's traditional agricultural crop but also allow cultivation and investment in a high-value alternative crop that previously could not grow locally. The same warming that may increase a region's agricultural value may also be detrimental for natural ecosystems and increase human illness during heat waves. Under continued warming that high-value crop may also lose productivity to the point of no longer being locally viable. Decreasing cold spells provide another example, as they can be beneficial in cold regions and seasons where extreme cold weather is hazardous but in warm regions the reduction in cold spells eliminates important opportunities for communities to cool off at night, leading to health challenges.

[START FAQ12.3, FIGURE 1 HERE]

FAQ12.3, Figure 1: [*placeholder figure still under development.* Text embedded in figure: FAQ12.3: Can climate change be both hazardous and beneficial? Yes, climate change can cause increases or decreases in climate characteristics with outcomes that vary by sector, region, and asset.]

[END FAQ12.3, FIGURE 1 HERE]

FAQ12.1, Figure 1: [Placeholder: A graphic illustration is under development here to show how successive stages of a river flooding illustrate the concept of a hazard threshold. (Panel a) river with level gauge showing normal flow well below embankments, with surrounding farms and a town. (Panel b) River at higher flow but still below embankments, surrounding farms and town not affected – not yet at hazard level. (Panel c) River overflows and surrounding farms and town are affected. The key is the distinction between panels b and c which defines a hazard level.]



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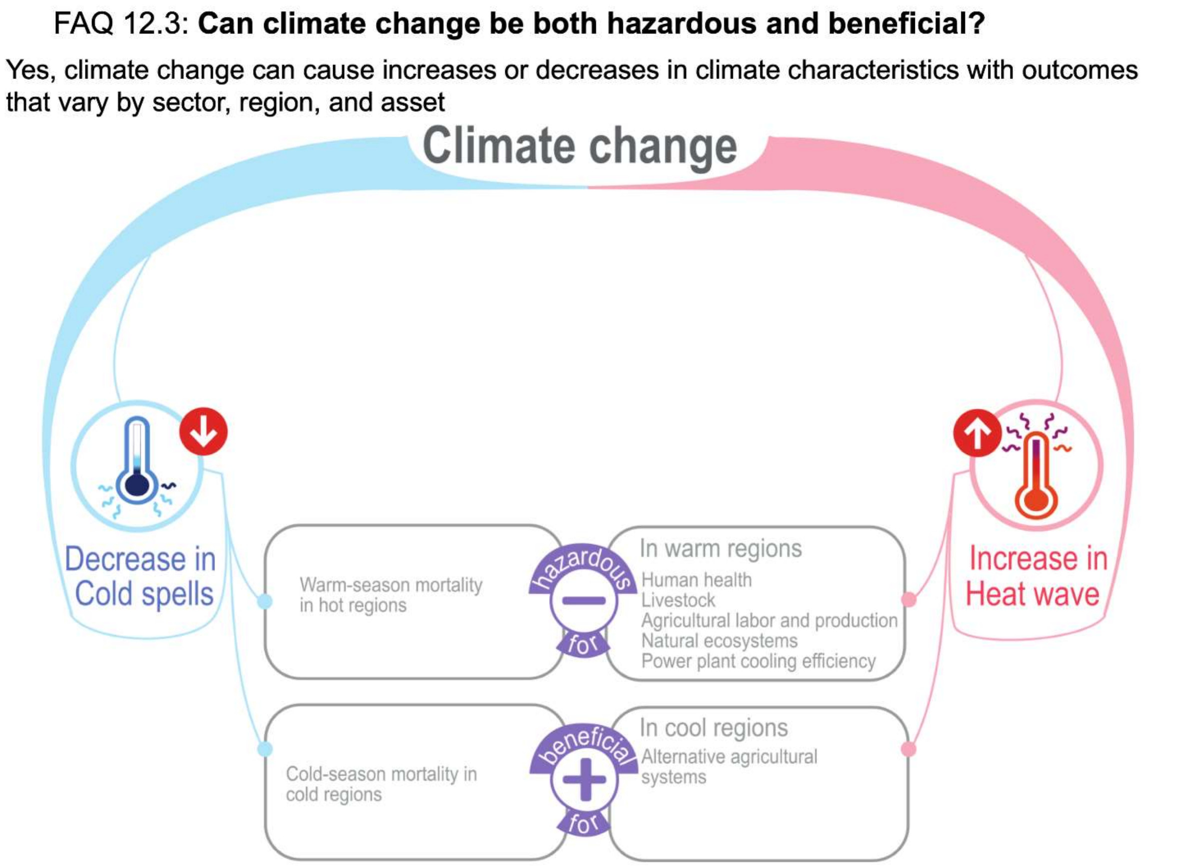

FAQ12.3, Figure 1: [*placeholder figure still under development.* Text embedded in figure: FAQ12.3: Can climate change be both hazardous and beneficial? Yes, climate change can cause increases or decreases in climate characteristics with outcomes that vary by sector, region, and asset.]

Frequently Asked Questions

[FAQs will be further developed in the final draft]

FAQ ATLAS.1: Why is there an AR6 WG I Interactive Atlas?

One of the main limitations of static (printed or electronic) climate products (e.g. maps or summary tables) is the limited options available to extract relevant information for regional analysis. For instance, the use of standard seasons limits the assessment in many cases (such as regions affected by monsoons or seasonal rainband migrations) and the limited number of variables prevents the inclusion of relevant indices and climate impact drivers. These factors limited the scope of the AR5 Atlas, which provided global and regional information only for temperature and precipitation for the standard seasons due to space limitation. The Interactive Atlas has been conceived as a tool for flexible regional and temporal analysis, but with limited predefined functionality and granularity to prevent misuse. Moreover, links have been established with other chapters in order to adopt their methodological recommendations and to support their assessment.

FAQ ATLAS.2: How can I use the Interactive Atlas for mitigation and adaptation studies?

FAQ ATLAS.3: How can I use the Interactive Atlas for climate risk assessment?

FAQ ATLAS.4: Where can I find the information that was used to produce the figures in the Interactive Atlas?

In order to ensure transparency and promote FAIR principles (findable, accessible, interoperable and reproducible results), the reproducibility of results has been a major concern when developing the Interactive Atlas. As a result, metadata is provided in the Interactive Atlas for the full workflow, from the data sources to the final products (only for spatial maps in the SOD) and the scripts used to generate the intermediated products (e.g. indices) as well as the figures are available online in a GitHub repository (Atlas GitHub, 2020). Moreover, in order to increase reusability, simple notebooks have been produced illustrating the different steps of the process (data collocation, transformation, etc.) using smaller subsets. These scripts are based on the climate4R open source framework (Iturbide et al., 2019). FAQ Atlas.4, Figure 1shows a screenshot of the repository for a particular topic (calculation of warming levels).

[START FAQ ATLAS.4, FIGURE 1 HERE]

FAQ Atlas 4, Figure 1: Screenshot of the GitHub repository containing the scripts and results of the warming level calculations for CMIP5 and CMIP6 models, together with some sensitivity studies to the effect of the length of the moving window.

[END FAQ ATLAS.4, FIGURE 1 HERE]