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, in 1990, predicted that human-caused climate change would soon occur, but could not yet confirm that it was already happening. Today, evidence is abundant that the climate has already changed since the mid-20th century, and we know that human emissions of carbon dioxide, methane, and other gases are the principal cause of that change. With much more and much better data, we understand more about how the oceans and atmosphere interact, as well as about the ice and snow that cover large parts of the Earth. Compared with the computer climate simulations of 1990, today's Earth system models include many more physical processes, and they can make more specific projections of future changes in different places. Many early climate model predictions have been confirmed.

Since 1990, large numbers of new instruments have been deployed to collect data in the air, on land, at sea, and in 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, as well as decades of additional data from older observing systems, have provided a wealth of new, increasingly accurate data. 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. We also now know that most of the heat in the overall climate system is being retained in the oceans, and that even the deep ocean is warming up. In 1990, relatively little was known about exactly how the gigantic glaciers of Greenland and Antarctica would respond to warming. With much more data and better models of their behavior, evidence has emerged 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 the sun's heat. Today, data show us that the sun's heat has not changed much in the last century, and that major volcanic eruptions have occasionally cooled the planet for short periods of time (typically 1-3 years). The main human causes of climate change are heat-trapping gases emitted by burning fossil fuels, which warm the planet, and tiny particles in the air such as soot from burning coal, which have both warming and cooling effects depending on their size, color, and location. Since 1990 measurements of all these factors have become more accurate and precise, while older data have been recovered and integrated into the long-term record.

While most climate models in 1990 focused on the atmosphere, using only highly simplified oceans, today's Earth system models include detailed models of oceans, ice, snow, vegetation, and often many other variables as well. An important test of models is their ability to simulate past climates. Several rounds of such testing have taken place since 1990, and the testing itself has become more rigorous and extensive. As a group, in these tests models have predicted the actual changes reasonably well. Since there is no way to do a controlled laboratory experiment on the actual Earth, climate simulations can also provide a kind of "control Earth" to see what would have happened without human influences. These experiments show that without our influence, the observed post-1960s warming would not have occurred.

Finally, climate models make specific predictions of exactly how the climate should change if human influences and not natural causes are the reason, and many of those predictions have been confirmed by 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.

[*Figure proposal: 2-panel schematic of climate models then in 1990 (FAR) vs. climate models now in AR6. The figure below (from AR4) is an initial idea. FAR would have only solar radiation, GHGs, rain, clouds, land surface, prescribed ice, and swamp ocean. CMIP6 would add volcanoes, sulphates, aerosols, carbon cycle, rivers, overturning ocean circulation, interactive vegetation, air chemistry, ocean biogeochemistry, ocean eddies, "high-top" atmosphere (top level above stratopause), terrestrial nitrogen cycle, and dynamic sea ice at a minimum.]*

[START FAQ 1.1, FIGURE 1 HERE]

FAQ 1.1, Figure 1: [PLACEHOLDER]

[END FAQ 1.1, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 1 in the review comment sheet]

FAQ 1.2: At what point do we know it's climate change?

[PLACE HOLDER: This FAQ will be reshaped later to better coordinate with related FAQs in Chapters 2 and 3 (on detection and attribution)]

The signs of climate change are most obvious at the global scale, but they are increasingly clear on smaller spatial scales and in a range of climate variables. Regions which have a larger signal of change relative to the size of background climate variations will potentially face greater risks as they will see unusual or unprecedented climates earlier.

Observed and projected temperature change is often smaller in the tropics than at higher latitudes, but smaller variations means that tropical countries have potentially seen the effects of climate change earlier (see FAQ Figure 1.2). Often it is not necessarily the size of the change which is most important for climate-related risks, instead, it is the size of the change relative to the background fluctuations of the climate to which ecosystems or society is already adapted to.

[*Paragraph on projections and the implication of mitigation choices. A future where a strong mitigation strategy is in place will have different climate signal emerging compared to a projection where less mitigation occurs. Figure to be updated to include :*
- *Example of differences between climate signals*
- *Air temperature changes vs precip or sea level changes in the future*
- *How emergence depends on the GHG mitigation pathway / scenario chosen*]

[START FAQ 1.2, FIGURE 1 HERE]

FAQ 1.2, Figure 1: Observed variations in regional temperatures since 1920 from CRUTEM4. Europe has warmed by a larger amount than tropical Africa, but the background variations are also larger (shading represents 1 and 3 standard deviations of background interannual variations). The signal of observed temperature change emerged earlier in tropical Africa than in Europe.

[END FAQ 1.2, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 1 in the review comment sheet]

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. Careful observation of these past changes challenges our understanding of how our planet operates, and also allows us to test our latest models that are used for predicting future climate change. Of particular relevance, the "hothouse Earth" of ~50 million years ago represents the most recent time that atmospheric carbon dioxide concentrations were as high as those projected for the late 21st century if emission rates continue at present rates.

Although we have been taking measurements of the Earth's climate for centuries, the vast majority of instrumental observations began during the late 20th century, during a period already experiencing rapid human-made (anthropogenic) warming. Unlocking information spanning millions of years of the Earth's history, so-called 'paleoclimate records' are indirect climate measurements (from tree rings, ice cores, corals, and ocean and lake sediments, for example) that climate scientists use to understand current and future climate change.

The earth climate is a complex system in which the different components (atmosphere, ocean, cryosphere, etc) respond with very different paces to forcing. As a consequence of this, 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 causes of climate change (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 external drivers of global climate variability. During this time, global temperature variations amounted to 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 drought, El Niño/La Niña events, wildfires, and even tropical storms. Indeed, the last millennia provides a wealth of data that climate scientists use to probe the relationship between global climate state and the character of climate extremes. As such, it offers a "baseline" to which human-induced changes can be compared, and also 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 (with CO_2 concentrations of 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, vegetation and climate extremes accompanied these glacial-interglacial shifts. Intriguingly, glacial states are marked by examples of abrupt climate changes that 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 volcanic activity/crustal formation rates and weathering caused atmospheric CO_2 concentrations to climb to ~800ppm or higher – similar to levels expected in coming decades if emissions continue at present rates. During the Eocene period, roughly 50 million years ago, global temperatures were as much as 8°C warmer, sea level was 20-40m 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 many times higher than they were during past geologic intervals, these “hothouse” worlds hold key lessons for our climate future. In particular, they provide a window into how our planet may eventually end up like, if emissions of greenhouse gases continue unabated, and allow us to test how well our climate models perform under these extreme conditions. 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 boundary conditions than today. As such, past climate data allows us to test the general applicability of our models, and therefore the reliability of our future climate predictions

[*Figure concept:*

4 vertical panels, illustrating (from left to right):

- *i) the PETM,*
- *ii) the last millennium/pre-industrial,*
- *iii) present-day, and*
- *iv) 2100 projections (RCP8.5 or similar)*

with an infographic denoting changes in the following variables:

- *atmospheric CO_2 concentrations*
- *global temperature*
- *global sea level*
- *(other variables?)*]

[START FAQ 1.3, FIGURE 1 HERE]

FAQ 1.3, Figure 1: [PLACEHOLDER]

[END FAQ 1.3, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 1 in the review comment sheet]

FAQ 1.4: How do we calculate global temperature change?

We calculate global surface temperature change by analyzing the readings of thermometers all over the globe using statistical techniques to take into account areas like the poles where there are fewer measurements. Multiple independent groups of scientists work with an ever increasing number of readings and all have very similar results.

The surface temperature of the world has, on average, increased by around 1 °C since the pre-industrial period – hence the term 'global warming'. Making such a statement implies that we are confident in the ability of science to determine how surface temperatures change over time.

Multiple scientific organizations monitor global surface temperature and all datasets rely on long-term series of temperature measurements made of the air near the surface over land and of 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 can still give comparable changes. For that reason it is easier to measure temperature change, and not the absolute average temperature of the Earth's surface.

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

The second issue, which has recently seen a lot of discussion, is what type of measurement to use over the ocean regions. Traditionally, ship or buoy measurements of the temperature of surface water, have been combined with air temperature measurements (typically at 2 metres) over land. However, analyses with global climate models have tended to use simulated air temperatures everywhere. As air temperatures over the ocean can be expected to warm slightly faster than surface water, it is important to use the same methodology when comparing measurements to models.

The third issue is which time period to report the changes over. As global temperatures have a natural year-to-year variability, scientists normally average at least 20 years to obtain a representative value - but which years? For current temperatures, they naturally use the latest two decades. The period before significant human influence is more difficult to define, partly because measurements were much more sparse in the 18th and 19th centuries. Currently scientists use an 'early industrial' period from 1850 to 1900 as the starting point, though sometimes the 'pre-industrial' period around 1750 is also used.

While global temperatures have risen by about one degree over the last hundred years or so, the formal assessment, based on several independently produced data series, is that surface air temperatures changed by +0.87 °C between the average of 1850-1900 and 2006-2015.

[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 (eg, buoys, satellites, ships etc – could have icons for each?) Present placeholder is from Rennie et al. (2014).

[END FAQ 1.4, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 1 in the review comment sheet]

Frequently Asked Questions

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

Summary: *Climate is always changing but the rate and global synchronicity of recent warming appears to be without precedent in geological history. By looking into the past, we gain a long-term perspective on the unusualness of recent climate changes. Among the most prominent climate indicators is the Earth's surface temperature. The recent warming has reversed the long-term natural cooling trend and global temperature is likely higher now than it has been for millennia.*

A rich variety of geological evidence shows that climate has changed throughout Earth's history. Through information gathered from tree rings, or ocean and lake sediments, for example, we can see there were times when the planet was cooler, and times when it was warmer. While climate can be described by many variables, the temperature of the planet's surface is a basic indicator of climate and is fundamental to understanding climate change.

Inferring temperature changes of the past is challenging. Our confidence in quantifying large-scale temperature reconstructions generally decreases back in time, especially beyond the last millennium when the number of temperature records calculated from tree rings declines sharply. Despite this uncertainty, scientists can still identify several differences between recent warming and that of the distant past.

Firstly, it's currently warming when natural drivers of climate are acting to cool the Earth. Temperature over the Northern Hemisphere, and possibility both hemispheres, was decreasing over thousands of years. The cooling trend was reversed by the end of the 19th Century, and warming prevailed throughout the 20th Century. During recent decades, temperatures have continued to rise despite a slight downturn in the output of the Sun, which is known to alter temperatures over short time frames (~10 years).

It's been a very long time since global temperature has been this high. The past 50 years are probably the warmest over the last 1400 years, and possibly much longer. Although there is ongoing discussion on whether the world was warmer before the long cooling trend (that begun ~6000 years ago), the last time global temperature was similar to today could well have been during the peak of the last inter-glaciation - about 125,000 years ago - when global temperatures might have been up to a degree higher than present warming and sea level was about 5 m higher than now.

It's warming quickly. Most of the rapid temperature shifts in Earth's climate history have occurred as ice sheets collapsed, giving way to interglacial periods like the present (Holocene Epoch). The shift from glacial to interglacial climate corresponded to a temperature change of about 5°C and took about 5000 years. Within this transition, the maximum temperature change during any thousand-year period was likely about 1.5°C. Compare this to the present temperature increase of 1°C in just 170 years. The shift from the mid-19th Century to date is likely the single most extreme temperature shift since the last deglaciation.

Finally, it's warming almost everywhere. When temperatures changed in the past, some regions warmed while others did not. For example, the North Atlantic region warmed more than other places during the Medieval Climate Anomaly. 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 global than has been reconstructed for any previous rapid global change.

Not only is warming unprecedented, it is occurring at a time when human activity creates stresses that compound the effects of warming. So much that some scientists coin this era to be the beginning of a new geological period: the Anthropocene, a time where human activity is the most dominant influence on the world.

[START FAQ 2.1, FIGURE 1 HERE]

FAQ 2.1, Figure 1: Approximate average global surface temperature (y-axis) over the past two million years, combined from multiple sources and shown at five different time scales (x-axis). Temperature is relative to 1850-1900 (pre-industrial reference); 2,000,000 to 300,000 years ago and 200,000 to 30,000 years ago from marine oxygen isotopes; 20,000 to 10,000 years ago from multi-proxy records; 10,000 to 3,000 years ago from multi-proxy records; 2,000 to 300 years ago from multi-proxy records, mainly tree rings; 1800 to 2015 CE from instrumental temperature records.

[END FAQ 2.1, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 2 in the review comment sheet]

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 our global climate. We are seeing changes in the atmosphere and oceans, in our glaciers and ice-regions, 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 imbetween that has occurred since the late 19th century.*

We have long observed our changing climate. From the earliest amateur 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. We truly live in a golden age of earth observation capabilities. 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. Change is not limited to the surface. The temperature of the lowest few kilometers of the atmosphere has risen, with associated increases in atmospheric water vapor and rainfall. 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 gained in the climate system being stored in the oceans. This warming has caused ocean water itself to expand, which in turn has contributed to the observed increase in global sea level in the past century.

Significant changes are also evident over the Cryosphere, the portion of the Earth where water is seasonally or continuously in solid form. There have been decreases in Arctic sea ice extent and thickness since the mid-1970s, with the Antarctic sea ice extent remaining quasi-stable. Spring snow cover in the Northern Hemisphere has fallen since the late-1970s. In addition, there is an observed warming of permafrost and evidence of thawing in many permafrost regions. The planet’s two largest ice sheets (Greenland and Antarctica) are shrinking, as are the vast majority of glaciers worldwide, further contributing to the observed sea level rise. Confidence in our understanding of melting glaciers and ice sheets and increasing ocean temperatures is increased because when their contributions to sea-level rise are added together they match very well the directly observed sea-level changes. Such closure highlights robust understanding.

Many aspects of the biosphere are also changing. Over the last century, long-term ecological surveys encompassing mammals, birds, invertebrates, and plants show that rates of change are increasing across a broad array of ecosystems. A broad array of species have 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. The global ocean has become more acidic as a result of increased carbon dioxide concentrations, and there have also been changes in marine ecosystems.

Change is ubiquitous 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: Independent analyses of many components of the climate system that would be expected to change in a warming world exhibit trends consistent with warming.

[START FAQ 2.1, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 2 in the review comment sheet]

Frequently Asked Questions

FAQ 3.1: How much of 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, as well as variations in climate driven by changes in solar brightness and by aerosol from large volcanic eruptions. Natural variability influences all aspects of the climate system, but compared to human-induced climate change, it plays a smaller role in long-term variations in globally-averaged temperatures in the oceans and atmosphere, and a relatively larger role in shorter-term, and smaller-scale fluctuations in climate, particularly in other variables such as precipitation and winds. Compared to human-induced changes, natural variability has a large impact on global mean temperature variations on inter-annual time scales. However, if you consider changes avareged over longer and longer time periods, the relative importance of natural variability in global mean temperatures decreases. Changes due to natural variability are small compared to human-induced change on centennial time scales. On decadal to inter-decadal time scales, there is a middle ground in which natural variability can have similar magnitudes to human-induced change. On this temporal range, natural variability can substantially enhance or diminish global warming; creating periods of faster warming or periods with little to no global warming at all.

Observational, 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 the changes generated within the climate system that are not connected to human-induced changes in atmospheric forcing.

The El Nino-Southern Oscillation is a phenomena that is a large source of natural climate variability, causing winds and sea surface temperatures over the tropical eastern Pacific Ocean to change. ENSO, as it sometimes referred to, lasts several years and can change ocean temperatures and rainfall patterns for that region as well as alter global mean temperatures. The Northern Annular Mode is another example of natural variability, which can effect weather in the high northern latitudes.

To understand which aspects of observed climate change have been caused by natural variability, scientists seperate the forcings of climate model simulations due to there anthropogenic or natural origins. When the latter are used as forcing the resulting simulations are generally called natural forced similations, and these can be used to assess the range of variations expects due to natural climate variability alone. Use of these simulations will allow us to assess which aspects of observed climate change are consistent with the expected response to human influences, which are consistent with natural variability.

It is clear that natural variability on inter-annual time scales can have a much larger impact on global mean temperatures than has been observed over the entire 100yr period (FAQ 3.1, Figure 1). As the temporal window increases, it is also clear that the influence of natural variability on global mean temperatures decreases, such that at decadal to inter-decadal time scales natural variability can have similar magnitudes to the observed trend over the last 100-years (FAQ 3.1, Figure 1, black line). This suggests that natural variability can lead to decadal periods of enhanced global warming and periods with little to no global warming. As we move to temporal windows between 50-100 years in length, the impact of natural forcing is so small that it is dwarfed by the mean warming rate observed over the last 100 years (FAQ 3.1, Figure 1).

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: Box and whisker plots displaying the magnitude of global mean surface temperature trends calculated in various temporal windows (x-axis) from observations and pre-industrial control simulations. The horizontal line within the box indicates the median, boundaries of the box indicate the 25th- and 75th -percentile, and the whiskers indicate the highest and lowest values of the results (note whiskers not displayed in this schematic illustration). The horizontal black line indicates the observed global mean surface temperature trend value calculated over the 1910-2010 period. *[Schematic illustration – will be updated with CMIP6 data for SOD]*

[END FAQ 3.1, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 3 in the review comment sheet]

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 they compare better with observations for key climate variables. For decades, models have shown that changes to the climate comes 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 allows for greater sophistication and more complex computer simulations, resulting in models that compare more closely with real-world observations of climate change.

[Paragraph introducing a climate model: its key parts – how they model the world, which processes/aspects are always included, which additional ones are only included in more sophisticated models etc.]

The internal make-up of climate models is evolving to make them more suitable for simulating a variety of climate processes, driven both by improved understanding of the climate system and scientists' ability to represent their understanding of processes by computer code and calculations, as well as the availability of ever-bigger high-performance computing resources needed to run such code. The most recent generation of models often has improved resolution 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, the latest generation of models, in many cases now simulate higher atmospheric altitudes (often extending to above 50 km in altitude), meaning that coupling processes between the upper atmosphere and the lower atmosphere are now more realistic. Models are also increasingly able to simulate changes in the concentrations of greenhouse gases and aerosols in response to changes in emissions, rather than having these changes prescribed. For carbon dioxide, this means that such models include interactive representations of the absorption of carbon dioxide by plants on land and by the ocean and its response to climate and environmental change.

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.

Key aspects of climate are now better simulated than in previous model evaluations. We know this through comparisons against observational estimates, often using many multiple climate variables. For example, [*key physical fields, TBD*] compare better against their observational references for recent decades (that are best covered by observations; 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 did not substantially improve in the current generation of models. Reflection of sunlight by clouds and precipitation, two key aspects of climate which in previous evaluations were problematic, are improved compared to the previous generation of models. However, these improvements are gradual, partly because climate models still do not operate at the resolution of about 1 km needed to realistically represent clouds. In several diagnostics, it appears that the top-performing models of the previous generation have not substantially improved but more poorly performing models have, meaning the CMIP6 ensemble as a whole is more suitable for simulating climate than the CMIP5 ensemble.

[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 four different variables: tas (surface air temperature), pr (precipitation), rlut (outgoing longwave radiation), and swcre (shortwave cloud radiative effect). Note the different scales. Results are shown for individual CMIP5 (black) and CMIP6 (blue) models as thin lines, along with the corresponding ensemble average (thick line) and median (open circle). 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 green circles). To ensure a fair comparison across a range of model resolutions, the pattern correlations are computed at a resolution of 4º in longitude and 5º in latitude. Only one realization is used from each model from the CMIP5 and CMIP6 historical simulations. Figure produced with ESMValTool v2.0a1. *[Update with CMIP3 and additional CMIP6 models in the SOD]*

[END FAQ 3.2, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 3 in the review comment sheet]

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 hundreds of thousands of years, and from computer models that can simulate past climate change, allows us to clearly identify the role of humans in driving 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. Results consistently show that such climate models can only reproduce the observed arming when including the effects of human activities, including the increasing concentrations of these greenhouse gases. These simulations show a dominant warming effect of greenhouse gas increases, which has been partly offset by the cooling effect of increases in atmospheric aerosols. By contrast, simulations that include only natural processes, including internal climate variability related to El Nino and other similar variations, as well as variations in solar brightness and emissions from large volcanoes, 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 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 continental land surface air temperatures (yellow panels), and upper ocean heat content (blue panel). Anomalies are given relative to 1880–1919 for surface temperatures and 1960–1980 for ocean heat content. All time-series are decadal averages, plotted at the centre of the decade. For temperature panels, observations are dashed lines if the spatial coverage of areas being examined is below 50%. For ocean heat content the solid line is where the coverage of data is good and higher in quality, and the dashed line is where the data coverage is only adequate, and thus, uncertainty is larger. Model results shown are Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble ranges, with shaded bands indicating the 5 to 95% confidence intervals. For further technical details see the Technical Summary Supplementary Material. {Figure 10.21; Figure TS.12}

[END FAQ 3.3, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 3 in the review comment sheet]

Frequently Asked Questions

FAQ 4.1: What Can We Say about Climate Change in the Next Twenty Years?

For most climate quantities that have shown a clear trend over the most recent decades, we expect this trend to continue in the next twenty years. Our confidence derives from the increase in radiative forcing due to the expected continued emissions of greenhouse gases and from our scientific understanding and confidence in model simulations of the global-scale changes caused by this increased radiative forcing. However, the magnitude of the changes is much more uncertain, mainly because over a period of twenty years, natural internal variability can mask and for some quantities overwhelm the climate response to the increased radiative forcing. While it is virtually certain that global sea level will continue to rise in the next twenty years, we cannot say much about the change in precipitation averaged over all land areas. We expect that globally averaged surface temperature will continue to rise over the next twenty years, although another slowdown caused by natural internal variability cannot be excluded.

There is a clearly recognized societal need for information about climate change in the next twenty years, defined here as the near term. But this information is difficult to provide robustly. The difficulty arises chiefly because over twenty years, natural internal variability plays a major role relative to the changes expected from the increased radiative forcing. Natural internal variability is caused by chaotic processes in the atmosphere and the ocean, such as the changing weather systems, and even after averaging in time over twenty years, the time averages or calculated trends contain a substantial chaotic element.

In analogy to weather forecasting, natural internal variability can be predicted to some extent, provided that the prediction simulations are started from the observed climate state. These 'decadal predictions' do not attempt to forecast individual weather events, but instead they 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 timescales. Current models have some skill in predicting these slow variations, such that useful statements about the future state of natural internal variability can be made.

The AR5 was the first IPCC Assessment Report to include information from decadal predictions, and substantial experience has been gained since. But it has also been confirmed that for most climate quantities of interest, natural internal variability cannot presently be skilfully predicted beyond at most ten years into the future. Looking ahead for twenty years, there are indications that natural internal variability will never be predictable over this time horizon, implying that natural internal variability causes some uncertainty that is irreducible.

However, climate simulation results for the next twenty years are less sensitive to which of the emissions scenarios they are based on – in stark contrast to simulation results for the end of the 21st century. The reason for this is well understood; all scenarios show further greenhouse-gas emissions over the next twenty years, leading to increased greenhouse-gas concentrations and hence increased radiative forcing. Hence the globally averaged surface temperature is expected to continue to rise over the next twenty (*high confidence*). If the current rate continues, a warming of 1.5°C above the pre-industrial level is expected to be reached by around 2040, as already stated by the SR1.5.

The area of the Arctic sea ice will continue to reduce in the next twenty years (*high confidence*), and globally averaged sea level is *virtually certain* to rise further. By contrast, we cannot say much about how precipitation averaged globally over all land areas will change over the next twenty years, and there are indications that such a statement cannot ever be made with confidence.

[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 four icons of global climate change, (a) globally averaged near-surface air temperature, (b) precipitation averaged globally over land, (c) the area of Arctic sea ice in September, and (d) globally averaged steric sea-level change, which arises purely from ocean warming. All quantities except the Arctic sea-ice area are shown as deviations from the average over the period 1995–2014. The black curves are for the historical period ending in 2014; the colours refer to various SSP scenarios as shown in the inlet. In (c), the dashed horizontal line is at 1 million km^2, the threshold conventionally used for designating an ice-free Arctic. [Placeholder figure, based on the CMIP6 model CanESM5. To be updated with other CMIP6 models and shading for indicating uncertainty. Sea-level change to be augmented by contributions from land-ice melt, something that is not included in the CMIP6 models.]

[END FIGURE FAQ 4.1, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 4 in the review comment sheet]

FAQ 4.2: When Greenhouse-Gas Emissions Reduce, What Changes Will We See?

In the long run, reductions in greenhouse-gas (GHG) emissions will limit the surface warming and changes in many climate indicators. In the first few decades after emissions reductions begin, however, their effects on the climate system will be difficult to diagnose, because the combination of climate inertia and 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 around 10 years, on global surface temperature after around 30 years, and on regional temperatures after around 40 years. An effect of mitigation on regional precipitation trends is expected only later in the 21st century.

Emissions reductions in long-lived GHG, especially in CO_2, will slow down the increase in atmospheric CO_2 concentrations but will over the first few decades not yet lead to a decrease in concentrations. This is a manifestation of one fundamental element of inertia in the climate system. As a consequence, the radiative forcing will also continue to increase, although after around 10 years at a detectably smaller rate. 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 changing weather systems. Natural internal variability will thus make it difficult to detect in the next two decades whether surface warming has indeed slowed down as a response to the emissions reductions.

There has been some recent research on this difficult detection problem, but not enough for a broad quantitative consensus to have emerged. The difficulties arise at multiple levels. First, we are asking a question about something that will arise at some point in an assumed future, namely whether putative emissions reductions have shown an effect on the climate system. At present we thus have no direct observations to guide us in this juxtaposition of emissions reduction and climate response. Second, there is no unambiguous definition of a no-mitigation emissions pathway against which emissions reductions can be defined. Third, any quantitative answer must rely on climate models simulating the correct ratio of response to emissions reductions on the one hand and the magnitude of natural internal variability on the other hand. Fourth, this detection problem – in analogy to detecting anthropogenic climate change in the observed record of the past – becomes more difficult on the regional scale and for many quantities other than temperature. And fifth, even if a response has been detected through some advanced statistical method, there remains the communications challenge if detection has not yet been possible for one of the icons of global climate change. But despite the difficulty of detecting climate responses in the decades immediately after emissions reductions begin, there his *high confidence* that such a response will emerge clearly in the second half of this century in many quantities of interest.

[START FIGURE FAQ 4.2, FIGURE 1 HERE]

FAQ 4.2, Figure 1: Illustrating the difficulty of discerning mitigation benefit in the near term: Shown are results from 100 simulations with the same climate model that all assume the same reduction in greenhouse-gas emissions from 2020 onward. The difference between individual simulations arises solely through different manifestations of natural internal variability and represents an irreducible uncertainty. We want to assess quantitatively to what extent emissions reductions lead to a reduction in warming trend. Thus we compare, in each simulation separately, how the warming trend differs between the periods 2021–2035 and 2005–2020 (left), and between the periods 2036–2050 and 2005–2020 (right). The length of each bar indicates how often a trend difference of a certain size occurs among the 100 simulations. In the near term (left), we already see a preponderance of a slowdown in surface warming, occurring in two-thirds of the simulations. But as many as one-third of the simulations show faster warming in the near term, despite emissions reductions. By the mid-term (right), almost 90% of the simulations show a slowdown in warming compared to 2005–2020. [Placeholder figure, based on (Marotzke, 2019). Suggest replacing by 20-year trends and using the AR6 WGI definitions of near term and mid-term, as well as by CMIP6 results.]

[END FIGURE FAQ 4.2, FIGURE 1 HERE]

FAQ 4.3: At a Given Level of Warming, What Can We Say about Climate Change in the World's Regions?

Climate change does not unfold uniformly across the globe, and yet there are patterns of change that are robust. 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. When such a robust pattern exists, we can infer the expected change in a region for each assumed level of global mean warming. Confidence in pattern robustness is highest for temperature-change patterns and for moderate levels of warming. By contrast, precipitation changes tend to show less robust patterns, because precipitation changes are more strongly influenced by regional forcing agents such as aerosol emissions and by natural internal climate variability; these influences are more pronounced under low levels of warming. 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.

Identifying a robust pattern of change for a given level of global warming offers two main advantages. First, it enables us to make statements about expected regional change that are largely independent of the forcing scenario. 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 resulting from this warming. And second, we can reliably interpolate and, with due caution, extrapolate to warming levels that have not been analysed or even simulated explicitly. Ideally a change pattern can be identified for every °C of global surface warming, and the expected regional change is readily found for every global warming level by simple multiplication ('scaling') of the pattern with this warming level. This approach can be highly efficient for studies of climate impacts at regional scales. When patterns of changes are robust, all 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 has been demonstrated to yield robust estimates for temperature changes at a given level of global warming. Limitations exist over 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 are not only a response to globally averaged surface warming, but also depend on the forcing agents such as anthropogenic aerosol emissions or 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 patterns of precipitation change. Nevertheless, pattern scaling can 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. Sea-level change, for example, is expected to be more closely related to the entire past history of warming, rather than to the warming level at any given time. And changes in bounded variables such as sea-ice and snow cover are better described by whether a threshold is crossed or not, the threshold determining whether a region experiences a complete melt. Once the melt is complete, there can be no further melting, and the simple proportionality lying behind pattern scaling no longer applies.

[START FAQ 4.3 FIGURE 1 HERE]

FAQ 4.3, Figure 1: Example for a robust warming pattern, which is presented here for the CMIP6 model MRI-ESM2 and calculated from the scenario SSP3-7.0. Surface warming relative to 1850–1900 is shown here for time periods over which the globally averaged surface warming is 2°C. We recognise the strong warming over the Arctic, generally stronger warming over land than over the ocean, and a slight cooling over the central subpolar North Atlantic. [Placeholder figure, to be replaced by the average over more CMIP6 models.]

[END FIGURE FAQ 4.3, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 4 in the review comment sheet]

Frequently Asked Questions

FAQ 5.1: Are the ways 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. These processes have thus roughly halved the rate at which atmospheric CO_2 concentrations have increased, and therefore slowdown 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 scientists began measuring CO_2 concentrations in the atmosphere in 1959, only about half of all emissions from the combustion of fossil fuels and land-use change (e.g. deforestation) has remained in the atmosphere, the so-called air-borne fraction. 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. Longer growing seasons in cold places due to global warming might also contribute to increased land CO_2 uptake. A large part of the CO_2 captured is lost back to the atmosphere through respiration, fires, other disturbances, and the net balance among all these processes constitutes the net land carbon sink.

The processes involved in the land CO_2 uptake are affected by many factors, and as climate and other biophysical properties changes, the land CO_2 uptake will change too. For instance, higher temperatures and droughts reduce the land sink, a process that is, often observed during El Nino years, a frequent climate event when the Earth surface has well above average temperatures. Other natural factors and human activities also influence the net removal of carbon by the land biosphere, either causing an increase in carbon storage (e.g. reforestation, nitrogen deposition) or a decrease (e.g. deforestation and land degradation, disturbances such as fire or windthrow, air pollution). 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 primarily driven by three physical and chemical factors: the difference in CO_2 concentration between the atmosphere and the surface ocean (approximately the upper 50m, but with important variations across seasons), the chemical capacity of seawater to take up CO_2 (or buffering capacity), and wind speeds at the ocean surface. Surface ocean water with elevated CO_2 is transported to the deep ocean in specific deep-water formation zones around the globe (like the Northern Atlantic and the Southern Ocean), effectively storing it away from the surface ocean and 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 CO_2 emissions staying in the atmosphere, to remain on average unchanged over the last five decades despite continuously increasing CO_2 emissions from human activities. There is currently no evidence that the land or ocean sinks are slowing down, and also no evidence that the way these sinks respond to the excess of anthropogenic CO_2 in the atmosphere is fundamentally changing (see Figure).

The fact that both the land and ocean sink respond to excess anthropogenic CO_2 in the atmosphere, suggests that the absolute sink strength of land and ocean will vary in proportion to future anthropogenic emissions. Hence this implies that if countries manage to strongly reduce global CO_2 emissions or even reach net zero or negative emission levels, these sinks will in all likelihood also again become smaller. Also, if emissions are not reduced that strongly, the ocean sink is expected to become smaller. For the land sink, model simulations suggest that if emissions are not reduced sufficiently strongly so as to cap warming at 2°C the combined effect of increasing atmospheric CO_2 and climate change may weaken the land sink in the second half of this century. In summary, CO_2 sinks will change in the future and understanding the directions of change will be fundamental to design mitigation pathways.

[START FAQ 5.1, FIGURE 1 HERE]

FAQ 5.1, Figure 1: Growth rate of the CO_2 inventory in the atmosphere, ocean and land, as well as the air-borne fraction of anthropogenic CO_2 emissions, and the efficiency of the ocean and land carbon sinks (defined as the size of the sink divided by the excess of anthropogenic CO_2 in the atmosphere). Estimates are derived from atmospheric observations, process-based models, data-driven ocean flux products, and atmospheric inversions (Le Quéré et al., 2018a). Dots and arrow bars denote the year-to-year variability as ±1 standard deviation. Uncertainties in the estimates will be added for the SOD.

[END FAQ 5.1, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 5 in the review comment sheet]

FAQ 5.2: Can thawing permafrost or ocean warming 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 amount 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 throughout the arctic would thaw under moderate to high amounts of global warming, and thus the carbon stored in this ecosystem is at risk.

Thawing of permafrost carbon has already began due to the rapid warming experienced in the Arctic, 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. The same warming also releases nutrients from the decomposing soils, and warmer and longer growing seasons favours plants to grow and store carbon as it 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, but the general results are: (a) that 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, but (b) not so strong that they would lead to warming that is greater than the warming from fossil fuel burning itself at any level of warming, and (c) that 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.

Current understanding shows that the global marine hydrate reserve is probably smaller than initially thought, now at 2000 PgC. Global warming also 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.

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

FAQ 5.3: Can negative emissions reverse climate change?

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. If CO_2 removal from the atmosphere is greater than CO_2 release, emissions are said to be net negative. The effect of negative emissions on atmospheric CO_2 depends on the balance between CO_2 releases, deliberate removals and removals by natural carbon sinks. Generally, net negative emissions results 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 will not result in immediate reversal of climate changes. While some parts of the Earth's climate system such as surface air temperature will follow a decline in atmospheric CO_2 quite rapidly, others will take decades to millennia to reverse.

[Concept of negative and net negative emissions] 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 emission can compensate release of CO_2 into the atmosphere. If CO_2 removal from the atmosphere is greater than CO_2 release, emissions are said to be *net* negative.

[Carbon bathtub] 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 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 will increase; if CO_2 release equals removal the, atmospheric CO_2 concentration will stabilise; and if CO_2 removal exceeds release, the CO_2 concentration will decline. In the same way, if *net* emissions (i.e. the sum of releases and deliberate removals) exceed removals by natural carbon sinks, atmospheric CO_2 will go up; if net emissions equal removals by sinks, atmospheric CO_2 will not change; and if removals exceed net emissions, or emissions are net negative, atmospheric CO_2 will go down.

[Climate system inertia, reversibility] If the CO_2 concentration in the atmosphere starts to go down, the Earth's climate will 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 reversal 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 reversal 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.

[Overshoot scenarios] A class of future scenarios that is receiving increasing attention, particularly in the context of ambitious climate targets, such as the 1.5°C and 2°C targets 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 target level will result in additional climate changes (compared to a scenario that reaches the target level without overshoot) that will take decades to many centuries to reverse.

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 will follow a decline in atmospheric CO_2 quite rapidly, while others such as sea level rise will take multiple centuries to reverse.

[[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.).]]

[If you want to comment on this FAQ, please select Chapter 5 in the review comment sheet]

FAQ 5.4: What is a carbon budget?

The term carbon budget refers to two major concepts depending on how it is used. It can refer to how emissions of carbon dioxide from human activities get redistributed in the Earth system: how much of those emissions accumulate in the atmosphere and how much are taken up by the ocean or the land biosphere. It is then referred to as the "human perturbation carbon budget" or the 'historical/contemporary carbon budget'. However, carbon budget can also refer 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. It is then called the 'remaining carbon budget'.

The term carbon budget is a widely used term but refers to different concepts depending on its context. First, the term is used when describing the historical carbon budget. The historical carbon budget describes all past and present sources and sinks of carbon dioxide. It thus describes how the carbon dioxide 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 carbon dioxide emissions were emitted 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 carbon dioxide concentrations, and therewith further drives global warming. Carbon dioxide 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 carbon dioxide 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.

The term carbon budget is also used when describing 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 preindustrial levels. In this context it is referred to as the 'remaining carbon budget'. 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 stay 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 exact size of the remaining carbon budget depends on the global warming level that we set as a limit, the probability with which we want to ensure that warming is held below that limit, and how successful we are in limiting emissions of other emissions that affect the climate, like methane or nitrous oxide. [[Sentence on the AR6 WG1 remaining carbon budget assessment.]]

[[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.]]

[If you want to comment on this FAQ, please select Chapter 5 in the review comment sheet]

Frequently Asked Questions

FAQ 6.1: Why do we care about Short-Lived Climate Forcers?

Short-lived climate forcers can alter the Earth's climate by changing the flows of sunlight and heat in the Earth's atmosphere and land surface. The climatic effects include changes in temperature, snow cover, atmospheric circulation, and precipitation. These agents also have adverse effects on air quality, human health, agricultural yield, and ecosystem vitality. Due to chemical sinks and other removal mechanisms, short-lived climate forcers have much shorter characteristic residence times in the Earth's atmosphere than those of long-lived greenhouse gases. For this reason, the impact of mitigation (or increased emissions) of these agents occurs quickly. Due to widespread introduction of measures to improve air quality, sharp reductions in emissions and concentrations of SLCFs have been observed in many regions.

As their name indicates, short-lived climate forcers don't stay around for long, but their presence in the atmosphere still impacts climate and the environment. Of all the SLCFs, methane 'lives' the longest in the atmosphere, at around one decade, but most others only stay there for a few days to weeks. Black carbon (or soot as it's also known), tropospheric ozone and sulfur dioxide (the substance that causes acid rain) are other types of SLCFs. Emitted by natural and anthropogenic (man-made) sources, SLCFs emissions have increased since the start of industrialization and now several of the anthropogenic sources, for example the production of sulfur dioxide, the have become the dominant worldwide sources.

Just like long-lived greenhouse gases like carbon-dioxide or nitrous oxide, SLCFs can affect climate by altering the Earth's energy balance through their effects on sunlight and heat in the Earth's atmosphere and land surface. As well as altering the Earth's energy balance, SLCFs impact the Earth and its inhabitants in other ways.

The observed climatic effects of short-lived forcers include large local perturbations in surface and near-surface temperatures and significant reductions in the lifetime of snow due to the melting induced by soot. It is *expected* that these agents have altered local and even hemispheric scale circulation systems and regional patterns of precipitation. Recent trends in observed aerosol burdens show strong regional differences, in particular over south and east Asia that might influence regional weather systems. Short-lived forcers also have direct impacts on clouds, affecting local precipitation mechanisms.

Short-lived climate forcers can also have negative impact on air quality. Ozone is a powerful oxidant that can irritate the airways, reduce lung function, and can harm lung tissue. It can also trigger a variety of health problems including chest pain, coughing, throat irritation, and airway inflammation, and it can worsen bronchitis, emphysema, and asthma. Microscopic particles such as soot and sulphate particles can penetrate deep into the lungs and have been linked to a wide range of serious health effects, including premature death, heart attacks, and strokes, as well as acute bronchitis and aggravated asthma among children. Short-lived climate forcers can also reduce agricultural yield and affect economic vitality through the effects of smog on visibility.

Due to the rapid chemical sinks and removal mechanisms such as precipitation, which can scavenge (remove) hydrophilic aerosols, these agents have much shorter characteristic residence times in the Earth's atmosphere than those of long-lived greenhouse gases. For many species, the residence times are appreciably shorter than the characteristic timescales for mixing of the atmosphere at synoptic and global scales. As a result, these agents are very inhomogeneously distributed in the Earth's atmosphere. Particles affect the properties of clouds regionally, generally enhancing the direct forcing of the particles. This inhomogeneity implies that while the global forcing by the short-lived forcers is comparable in magnitude to that of the long-lived greenhouse gases, the local forcings by these forcing agents can far exceed those of the long-lived gases.

Because some short-lived forcers are co-emitted with long-lived greenhouse gases, and since several of these agents offset some of the forcing by these gases, these agents are important under strict mitigation scenarios (e.g. a temperature limit of 1.5°C). But, the adverse effects of SLCFs on air quality make mitigation of SLCFs a favourable policy option as a win-win strategy. In fact, the strong reduction in emissions of SLCFs that is and has been observed in many regions, and predicted in future scenarios, are mainly a result of policies to improve air quality.

[*PLACEHOLDER Figure suggestion: Short-lived climate forcers – where do they come from and where do they go? Schematic showing the main sources of CH4, SO2, O3, BC, HFCS (?) and their impacts: health, crop yields, precipitation / clouds, and main removals: rain, atmospheric chemical reactions.]*

[If you want to comment on this FAQ, please select Chapter 6 in the review comment sheet]

FAQ 6.2: What is the link between air quality and climate change?

Air quality and climate change are intimately linked, since many air pollutant sources are also sources of long-lived greenhouse gases and the pollutants themselves influence climate and are also altered by climate change. Anthropogenic activities are responsible for the emission of gaseous and particulate chemical species that modify atmospheric composition. Such changes are, in turn, responsible for the degradation of air quality at the regional/local scale as well as for climate change. Indeed, many mitigation options offer the possibility to both improve air quality and mitigate climate change but, in some cases, mitigation options that may provide benefits to one aspect, may worsen the situation in the other.

Critical environmental issues, climate change and air pollution are already impacting humanity. The World Health Organisation attributes 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 essential for our life.

All anthropogenic activities (e.g., energy production, agriculture, transportation, industrial processes, waste management, residential heating, etc.) are responsible for the emission of gaseous and particulate pollutants that modify atmospheric composition, leading to degradation of air quality as well as climate change.

All anthropogenic emission sources emit air pollutants and climate-forcing species at the same time, making air pollution and climate change two intimately connected issues. Yet in the scientific and the policy arena, air pollutants and climate-forcing species are often defined, investigated, and regulated independently of one another and their impacts on climate, human health, and ecosystems are also often considered independently, in spite of the scientific evidence, now well established, linking emissions of air pollutants and climate-forcing species and their associated impacts.

The chemical composition of the emission from any given source determines the actual effect on air quality and climate change. 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 anthropogenic emissions in two distinct groups: atmospheric pollutants and climate-forcing species, and many of the same sources emit both climate-forcing species and air pollutants. What is more, many emitted species are at the same time air pollutants and climate-forcing species.

Therefore, policy options aiming at addressing e.g. climate change, may have unintended benefits or trade-offs for air quality and *vice-versa*.

Win-win policies that benefit at the same time air quality while mitigating climate change are e.g. energy efficiency measures, zero-emission vehicles, capturing and recovering methane from solid waste management and oil and gas industry, reducing emissions of soot (particulates) from diesel vehicles, etc.

There are, however, also win-lose policy options. For example, wood burning is defined as carbon neutral, because trees accumulate the same amount of CO_2 throughout their lifetime as that released when wood is burned. However, burning wood can also result in significant emissions of air pollutants (carbon monoxide, nitrogen oxides, volatile organic compounds, particulate matter) that have local/regional impacts on climate, human health and ecosystems, offsetting the CO_2 benefit. On the opposite side, mitigation options to improve air quality, such as such as exhaust gas desulphurization in power and industrial plants, unmasks some warming since sulphate aerosols contribute to cooling the atmosphere.

Two sides of the same coin, addressing air quality and climate change together could lead to significant synergies and economic benefits, avoiding policy actions intended to mitigate one of the two issues that could worsen the situation in the other.

[START FAQ 6.2, FIGURE 1 HERE]

Air pollutant/GHG	Climate impact	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.

[END FAQ 6.2, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 6 in the review comment sheet]

Frequently Asked Questions

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

In often seems we are making little progress on understanding clouds and their role in climate change. We in fact have made a tonne of progress and can now quantify their amplifying effect on global warming from greenhouse gases, but details remain to be worked out.

Clouds cover two thirds of the Earth's surface. They generally form when the water vapour that is present in updrafts of air condenses out of the air to form water drops. We see the reflections from these little drops of water as clouds. When the drops grow large enough, they can fall to the surface as rain. If they get cold enough, they can freeze to make ice crystals that can grow and fall to the surface as snow. Clouds play a key role in the Earth's water cycle and also in the Earth's energy budget. Over the last four decades, numerous satellites have measured the role that clouds play in reflecting sunlight and trapping thermal radiation. High clouds tend to trap more radiation than they reflect, and low clouds reflect more than they trap. On average, their reflection wins out and overall clouds cool the climate.

The temperature structure as well as the moisture structure of the atmosphere controls the occurrence of clouds, and clouds themselves shape the atmospheric circulation by releasing condensation heat and altering the radiative balance. For decades it has also been known that the radiative properties of clouds depend on the abundance of aerosol particles upon which cloud droplets and ice crystals must form. Since atmospheric aerosol concentrations have increased considerably since pre-industrial times due to fossil fuel and biomass burning, today's atmosphere contains more such particles than at pre-industrial times. This has made clouds more reflective, because cloud droplets have predictably become more numerous and smaller. There is broad agreement that this cooling effect has counteracted a considerable portion of the greenhouse warming over the last century, though exact quantification has been a challenge. It has also been proposed that the more numerous but smaller droplets act to extend cloud lifetime and/or increase cloud water content by delaying rain formation, but this effect remains controversial. While some studies using satellite observations find evidence in strong support of it, others find a negligible impact. Climate models also disagree on the matter, simulating everything from negligible to very strong cooling due to aerosol effects on cloud temporal and spatial extent. On balance, the evidence points to an amplification of cloud-mediated aerosol cooling through increased cloud lifetimes and/or amounts, but the magnitude of this amplification remains poorly quantified.

When the global radiation balance is perturbed by increasing atmospheric greenhouse gases clouds also change as the climate state warms. Climate scientists often refer to the 'cloud feedback'. This feedback relates to how clouds will change in a warmer world, and how these changes will affect the radiation balance of the Earth. It is the largest component of uncertainty in global warming projections for a given emission pathway and has proved a tricky nut to crack. The problem stems from the fact that clouds can change in a myriad of ways and their processes tend to occur on much smaller scales than represented by current global climate models. The latest generation of climate models have improved their representation of clouds by both increasing their resolutions and sophisticating their representation of processes that occur at still finer scales, so-called sub-grid parameterisations (Chapter 1). Yet, this improvement is incremental, and the representation of cloud processes even in the world's best climate models remains a challenge.

Over the past decade, new detailed numerical simulation and measurement efforts have allowed us to accelerate our understanding of how the clouds interact with circulation, and how their changes affect climate. Analyses in IPCC AR5 were able to make use of cloud measurements by radar and LiDAR on a series of satellites. These active sensors gave information on vertical profiles of cloud occurrence and cloud water, overcoming earlier limitations. Increase in computer power also made very large area simulations possible at horizontal resolutions of a few kilometres where convective cloud systems could be explicitly resolved (FAQ7.1, Figure 1). Such simulations complemented large-eddy simulations that simulate particular cloud systems over a few days and have the resolutions of 100m or less.

Since IPCC AR5, these observations and modelling efforts have been further developed and integrated to

build a more complete understanding of cloud processes. For example, aerosol-cloud processes are routinely represented in fine detail. Furthermore, extensive analyses of the latest climate model simulations have enabled scientists to propose a number of constraints on the overall cloud feedback.
A coordinated set of simulations for stratocumulus and trade cumulus cloud regions has revealed how low clouds are reduced and thinned in response to increasing surface temperature, providing evidence that the cloud feedback amplifies global warming (Section 7.4.2).

[START FIGURE FAQ7.1, Figure 1 HERE]

FAQ7.1, Figure 1: Global view of infrared brightness temperature (T_{bb}) on 6 August, 2016, and monthly- and zonal-mean cross section of cloud liquid (blue) and ice (purple) contents. T_{bb} has a low value where cloud covers surface and is used as a measure of cloud distribution from space. (Top) Satellite observations and (bottom) a global cloud-resolving simulation using 3.5 km NICAM. Colours are the same between the two panels. Thin purple curves in the top panel show the satellite paths along which the zonal mean is calculated.

[END FIGURE FAQ7.1, Figure 1 HERE]

Verification of cloud vertical structure in climate models using recent satellite products identified a common error in their simulations, particularly in representing mixed-phase clouds (clouds that may contain both liquid and ice) for the present climate over the Southern Ocean. Recent studies have also revisited the problem of how deep tropical clouds will change with warming from a new perspective. If tropical high clouds, called anvil clouds, decrease in size in a warmer climate, that will have a cooling effect, reducing the amount of expected warming from greenhouse gas increases. Climate scientists now believe that a reduction of anvil cloud area will occur in association with a greater clustering of convective storms with warming. To date, observational analyses, detailed simulations, and theory have helped climate scientists understand these processes in greater detail, but they have yet to accurately determine their role in cloud feedback.

In summary, more and more cloud processes are being understood and simulated well enough to enable us to narrow the range of possible cloud feedbacks and cloud responses to aerosol changes, which will ultimately help us better constrain future projections of climate. The assessment in Section 7.4 halves the uncertainty range in cloud feedback compared to IPCC AR5 and assesses that it is now *very likely* that cloud changes will amplify the global warming effect of greenhouse gases. In contrast our emissions of polluting gases such as sulphur dioxide and particles enhance the cooling effect of cloud, and this cooling effect can now be better constrained (Section 7.3). The nut is still firmly in its shell but scientists are hungry and we have much better nutcrackers than 10 years ago so it shouldn't take long!

[If you want to comment on this FAQ, please select Chapter 7 in the review comment sheet]

FAQ 7.2: Which emission metric should I use?

Emission metrics are used in climate policy to compare greenhouse gases, but there is a debate over which to use. Science can help inform appropriate metrics for specific policy targets but societal values and judgements about what is important are the deciding factor.

Emission metrics provide a summary of the comparative effects, over some time horizon, of different emissions, as assessed against some specific climate or socioeconomic measure. They provide a short-hand for comparing emissions. It has been customary to use one such metric, the global warming potential or GWP, in carbon accounting approaches. However, while they are potentially useful, metrics can be misleading if used inappropriately, and they are not essential. Gases and other forcing agents could be treated separately by a climate policy, without the need for comparison between them. The Montreal Protocol used a multi-basket approach which allowed trading within a basket of similarly behaving gases, but not between different baskets of gases. Climate policies, starting with the Kyoto Protocol, have adopted a single-basket approach based on GWP evaluated over a 100-year time horizon. However, the focus on a single metric to trade gases has received substantial criticism from the scientific and research community since Kyoto's inception. Partly in response to this criticism, a range of alternatives have been proposed. GWP100 compares the integrated radiative forcing over 100 years of a gas to carbon dioxide. Some of the alternatives have attempted to instead compare the damages from different emissions. Others have made different choices over whether to compare the effects of emissions at a point in time, integrated over time or their transient effects. Some arguments regarding metrics have focused on choosing different time-horizons or on avoiding trade-offs that are rational under GWP100 but which would leave the world warmer overall.

Because emission metrics have, so far, attempted to compare the effects of different gases against some function of a single climate or socioeconomic measure, and because policy is multi-faceted, there is no universally-applicable metric. This does not mean that all metrics are equally valuable, or evidentially supported, or intellectually defensible. Some emission metrics probably are better than others, because some choices are either better-supported, scientifically, or more compatible with widely-shared normative judgements (e.g. about time horizons).

In Box 7.3 the performance of different metrics against different climate variables is shown. Here we discuss metric performance against the scientific goals articulated in the Paris Agreement. The global climate change regime complex contains many elements, but temperature and greenhouse gas stabilization have central roles. Article 2 of the Convention states "The ultimate objective of this Convention [is] stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." The Paris Agreement commits countries to "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels[.]" Article 4 states: "In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty." The only explicit climate targets expressed numerically in the Paris Agreement are the temperature targets in Article 2. Neither the greenhouse gas stabilization (UNFCCC) nor the "balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases" nor the early peaking targets in Article 4 are enumerated.

It has been shown repeatedly that the temperature targets (Paris Agreement) are poorly-matched with integrated metrics such as GWP100 as traditionally used. It is a general property of integrating metrics that they cannot shadow the temperature effects of a trajectory of long-lived and short-lived greenhouse gases. They are better suited for comparing other climate measures, such as sea-level rise or the accumulation of energy in the climate system.

Trajectory-based approaches to the comparison of gases and other forcing agents better capture the temperature effects of short-lived and long-lived emissions. The warming signal implied by a portfolio of gases under such metrics is much less ambiguous than that of the same portfolio of gases reported under GWP20 or GWP100. This does not mean that trajectory-based approaches have universal applicability as it is still inherent within them that short-lived greenhouse gases and long-lived gases should be treated differently: a one-off emission of a long-lived gas needs to be compared to an indefinitely sustained emission change in a short-lived gas. If policy goals are focused instead on things other than temperature targets, such as integrated measures of change, then an integrated metric would be a better choice for those goals.

As identified by previous reports, metric choice should be informed by policy goals. On the presumption that policymakers will care about many different measures over many different timescales, considering short and long-lived greenhouse gases separately may be advantageous. However, the choice of how – or whether – to compare the effects of different gases within either a single-basket approach or a two- or multi-basket approach, relies on choices that science alone cannot determine.

[If you want to comment on this FAQ, please select Chapter 7 in the review comment sheet]

Frequently Asked Questions

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

Components of the surface energy balance and surface water balance are altered with land use change. In particular, land use changes lead to changes of precipitation, evapotranspiration, infiltration, and groundwater recharge, modifying the water cycle and freshwater availability.

Land use changes induce alterations in the water cycle. For example, when changing the surface from any type of vegetation cover to an urban cover, also changes the *surfacealbedo* (i.e., the property of the surface, or any object, to reflect solar radiation). By changing the amount of reflected solar radiation, we alter the *surface energy balance* (i.e., the difference between incoming radiation and outgoing radiation). Hence if the capacity of the surface to reflect solar incoming radiation decreases, the energy balance becomes positive, warming the surface. Changes in surface cover also induce modifications in soil infiltration, altering the *surface water balance* (i.e., the difference between precipitation and the total amount of evaporation, ground storage and surface runoff). When soil losses its capacity to infiltrate water, more precipitation can become in runoff. This implies that the water that would normally contribute to groundwater recharge will now overflow, enhancing the probability of flash floodings.

Changes in soil moisture content can also modify the surface thermal contrast. Water retained in the porous of the soil layers allows for heat to be stored during the day, which is gradually released during the night, inducing warming. Whereas if soil moisture is lower than normal or null then the heat stored will be less and it will also be released much quicker. This alters the energy budget, as the *sensible heat* (i.e. a conductive flux of heat) and *latent heat* (i.e. turbulent flux associated with a phase change of water: evaporation or condensation) changes. Warming induces evaporation and therefore cooling of the surface. By cooling down the surface, there is a stabilization of the *surface boundary layer*. This stabilization prevents deep convective activity, altering the occurrence of precipitation, which may, in turn, modify the water surface balance, reducing precipitation.

There is another factor to be considered in land use change: it increases the amount of aerosols in the atmosphere. *Aerosols* play a rather complex role in weather and climate, but regarding water cycle, they have at least three important effects. First, aerosols modulate the rate of conversion of cloud water to precipitation; since aerosols serve as *condensation nuclei* on which water molecules can adhere and grow until reaching a weight large enough to precipitate, then aerosols can modify the water balance. Second, aerosols have a cooling effect by scattering and absorbing solar radiation. Third, aerosols can modify cloud optical properties, altering the surface energy balance.

Even when land use change implies shifting from one vegetation cover to another (for example, deforestation for agricultural uses), surface albedo is altered as each type of vegetation has a different albedo, modifying the surface energy balance. But not only surface albedo varies with vegetation changes. The water balance gets also modify as vegetation also play an important role by transpiration and capturing CO_2 (stomatal reaction). Recent studies over extensive irrigation areas exhibit a reduction on the surface temperature.

Due to the complexity of the interactions between the different land surface processes, there are large uncertainties when determining the net effect of land use change on the water cycle; however, there is abundant evidence that shows that land use change can alter both the surface energy and water balance, ultimately endangering the availability of freshwater.

[If you want to comment on this FAQ, please select Chapter 8 in the review comment sheet]

FAQ 8.2: Should we expect more severe floods from climate change, and why?

Flooding presents a hazard when it affects human activities and infrastructure. A warming climate will increase the amount and intensity of rainfall during wet events that is expected to contribute to an increased severity of flooding. However, the link between rainfall and flooding is not simple and so while the largest flooding events can be expected to worsen, flood occurrence may decrease in some regions.

Flooding describes a temporary accumulation of water on the land surface that may result from rivers overtopping their banks or a more local build-up where the influx of water exceeds outflow. 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 are likely to alter. Sea level rise due to expanding of the ocean and melting of ice sheets as climate warms worsens coastal flood risk and this can combine with flooding from heavy rainfall.

Flooding is usually caused by a rapid influx of water supplied by heavy and often sustained rainfall events that are expected to become more severe in a warming climate. As the air near Earth's surface warms it carries around 7% more water in its gas phase (vapour) for each ºC rise in temperature on average. This extra moisture is drawn in to weather systems, fueling heavier rainfall. Rainfall intensity can be further amplified by extra heat released through condensing of water vapour into droplets thus energizing storm systems. On the other hand, this energy release and also the effects of pollution can inhibit uplift required for cloud development over larger time and space scales. This means that the character of precipitation is expected to alter as the climate warms. More intense but less frequent downpours can cause less of the rainfall to be soaked up by the ground and more to runoff into lakes, rivers and hollows. Changing wind patterns and the pathway that storms usually travel are a less well understood aspect of climate change and also vary a lot from one year to the next. This makes it difficult to observe that heavy rainfall events are increasing over many regions. An intensification of heavy rainfall in the future is simulated for most places though. It is therefore very likely that when and where extremely wet events or seasons occur, the rainfall amount will be greater, potentially 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 but depends upon the type of river catchment or surface landscape, how extensive, long lasting and intense the rainfall event is and also how wet the ground is before the rainfall event. Some regions may experience a drying in the soil, particularly in sub-tropical climates, which could make floods from a rainfall event less likely as the ground can potentially soak up more of the rain. Earlier spring snowmelt and associated flood events are likely in a warmer climate while in some regions reduced winter snow cover can decrease the chance of flooding associated with rain combined with rapid snowmelt. Observations of how high river flows have changed remain inconclusive yet flooding is projected to double in frequency over 40% of the globe by 2050, with the largest increases expected in Asia with decreases also projected in many regions. Future flood risk is also affected by changes in the management of the land and river systems and the location of where people live and work. Accounting for these many factors, there is an overall expectation that when weather patterns cause flood events, these will become more severe as the climate warms yet some regions will experience decreased flooding.

[If you want to comment on this FAQ, please select Chapter 8 in the review comment sheet]

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) (see FAQ 8.3, Figure 1) 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 US Midwest 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.

[START FAQ 8.3, FIGURE 1 HERE]

FAQ 8.3, Figure 1: Clip-art style illustration of types of droughts.

[END FAQ 8.3, FIGURE 1 HERE]

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 will vary across regions and seasons. Across the subtropics (e.g., the Mediterranean, southern North America, Central America, southern Africa, and southern Australia), precipitation is expected to decline as the world warms, increasing drought risk throughout the year. Some studies suggest that the risk of megadroughts in western North America will increase substantially. 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 the humid mid- to high-latitudes, and the summer monsoon regions) which will decrease drought risk. FAQ 8.3, Figure 2 illustrates the projected effect of climate change on drought in different places.

[START FAQ 8.3, FIGURE 2 HERE]

FAQ 8.3, Figure 2: Global map with regions expected to experience more or less drought labeled in brown (more) and blue-green (less) (use colors from precipitation diverging palette). Recommend contour-hugging shading; mock up below is just for the general idea. Would need to ensure accuracy w/r/t both CMIP5 and CMIP6 results.

[END FAQ 8.3, FIGURE 2 HERE]

[If you want to comment on this FAQ, please select Chapter 8 in the review comment sheet]

Frequently Asked Questions

FAQ 9.1: Can the long-term effects of climate change be reversed?

Some impacts of current climate change will take hundreds to thousands of years. Evidence from climates of the distant past shows that if greenhouse gas levels in the atmosphere were reduced, many of these impacts would take similar lengths of time to reverse. This means that sea level rise, release of carbon stores into the atmosphere, and ocean pH changes are expected to last for centuries to millennia to come.

Humans are changing the climate, and many of the effects will be very slow to take place. An important question is whether these long-term effects will reverse once levels of greenhouse gases in the atmosphere are reduced by humans or natural processes.

The Earth has changed between warmer and cooler climates many times in the past. For example, geological archives indicate that around three million years ago, during the mid-Pliocene Warm Period, a global average temperature of around 2°C above present sustained over many thousands of years lead to collapse of the West AIS (FAQ 9.3). The warmer temperatures probably also melted part of the East AIS and much of the GrIS, eventually leading to a global sea level around ten to thirty metres higher than today. Analysis of geological records from many different warm periods of the past show this relationship is remarkably consistent: that is, prolonged warming of the ocean and atmosphere tends to lead to ice sheet losses that may contribute many metres to global sea level, even under atmospheric carbon dioxide levels similar to today. In other words, the GrISs and AISs are highly sensitive to sustained warming.

During the ice age cycles of the past few milion years, the polar ice sheets and mountain glaciers have waxed and waned in volume. Ice sheets grow through snow falling on the surface that eventually compacts into ice, but this process is very slow, so it would take thousands of years to restore the GrIS and West AISs if they were lost. Melting of mountain glaciers and warming of the oceans, which also cause seas to rise (FAQ 9.2), would take centuries to reverse. This means that long-term sea level rise is effectively irreversible on human timescales, and will affect coastal regions for centuries to millennia to come. However, frozen water elsewhere on Earth will be easier to restore. Seasonal sea ice and snow cover in the northern hemisphere, once lost, would return if air temperatures decreased to pre-industrial climate.

Many changes to the carbon cycle also act over long timescales, affecting the movement of carbon between its natural reservoirs on the planet. During a period of relatively rapid global warming 55 million years ago (the Palaeocene-Eocene Thermal Maximum), scientists estimate the warming was accelerated by release of carbon dioxide or methane into the atmosphere from thawing of perennially frozen ground (permafrost) in the Arctic and mountains (FAQ 5.2) or release of methane from frozen crystals ('hydrates') in the deep ocean. If either were triggered in future it would increase global warming. 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. However, release of hydrates is predicted to be *very unlikely*, as it would take thousands of years of warming.

About one third of carbon dioxide emitted by human activities has dissolved into the oceans, reducing the pH by about 0.1 units since the pre-industrial period, which is lower than the past 65 million years. This 'ocean acidification' makes it more difficult for some marine life to grow, such as coral and organisms with shells. Once the carbon dioxide is taken into the deep ocean by circulation, it would take hundreds to thousands of years to be removed by natural processes or to return to the surface and be released into the atmosphere.

[START FAQ 9.1, FIGURE 1 HERE]

FAQ 9.1, Figure 1: Placeholder for new diagram of some of the elements shown: Antarctic and Greenland ice sheets, glaciers, oceans. Remove other elements and add representation of Arctic/mountain permafrost, ocean acidification, and hydrates.

[END FAQ9.1, FIGURE 1 HERE]

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

Scientists estimate that global average sea level – in 2015 already about 20 cm higher than in 1900 and 5 cm higher than in 2000 – will rise by a further 7–43 cm by 2050. Thermal expansion of water from increasing temperatures is a major reason for this, but the melting of ice-caps, glaciers and ice sheets all contribute. Local sea level change will be higher or lower than the global average in many locations, with the lowest rates 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 has increased from an average of 1.4 ± 0.1 millimetres per year over the 20th century to 3.1 ± 0.3 millimetres per year from 1993 to 2017. 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 mean sea-level rise, and they will continue to be for centuries into the future.

The main source of current sea level rise is the expansion of ocean water due to global warming (42% since 1993), followed by melting of ice from mountain glaciers and ice caps around the world (21%). Melting of the two large ice sheets have played an increasing role since the 1990s, with average contributions of 15% from Greenland and 8% from Antarctica. Another source is changes in land water storage, such as groundwater extraction.

The amount by which global average sea level will rise over the next three decades will not yet depend much on the level of greenhouse gas emissions. This is because oceans, glaciers and ice sheets mostly respond on slow timescales (decades, centuries and longer), so they will still be responding to past climate changes caused by both natural factors and greenhouse gas emissions in the twentieth century. Scientists predict there is a 90% or greater chance that global mean sea level rise will be between 12 cm and 48 cm in the period 2000 to 2050. This means that the average rate of sea level rise ranges from keeping the rate at the start of the century to about three times faster.

In many places, local sea level change will be higher or lower than the global average. 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 Siberia, the land is still recovering and rising up after the ice sheets melted. This is compensating global sea level rise and can even lead to a local sea level fall. In regions near the former ice sheets, where the Earth bulged upwards, the land is now falling, contributing to a local sea level rise. In many cities within low-lying delta regions, the land is rapidly subsiding, because of human activities such as extracting groundwater or fossil fuels. In some cases this happens at tens of millimetres per year, so this is amplifying 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 ice sheet and the sea level to rise far away. Melt from an ice sheet therefore affects sea level most in the opposite hemisphere.

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: every 2 to 50 years for most regions in high northern and southern latitudes, and up to multiple times a year in the tropics.

Beyond 2050, sea level rise is much more uncertain. This is not only because it will depend on greenhouse gas emissions but also because it is difficult to predict how the AIS will respond to large temperature changes.

[START FIGURE FAQ9.2, FIGURE 1 HERE]

FAQ 9.2, Figure 1: Placeholder for figure with elements similar to some of the above. Source: Aimée Slangen.
[END FAQ9.2, FIGURE 1 HERE]

FAQ 9.3: What happens if the Greenland or Antarctic ice sheet collapse?

[PLACEHOLDER]

The Antarctic and Greenland ice sheets are the largest parts of the cryosphere, containing the vast majority of fresh water on earth's surface as ice.

What prevents them from melting now? Temperatures, accumulation, buffering, etc.

How are they changing now?

How are they expected to change this century?

How much is sea level expected to change? Globally? Regionally? What are the changes in the solid earth & gravity?

How much will polar climate change? Will this affect weather elsewhere?

[If you want to comment on this FAQ, please select Chapter 9 in the review comment sheet]

FAQ 9.4: What happens if the Gulf Stream shuts down?

Scientists estimate that the Atlantic Meridional Overturning Circulation (AMOC) is slowing down and will slow more in the future. The Gulf Stream is a part of this circulation. 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 shuts down, North America will see higher sea levels and Europe will see changes in weather and cooling relative to other regions.

The Gulf Stream is the biggest current in the North Atlantic Ocean and one of the largest currents in the world. 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 toward the north it carries a large amount of thermal energy (i.e., energy stored as warmer temperatures) from its southern origins, and as it travels it releases this thermal energy to the atmosphere and surrounding water. Thus, the poleward latitudes are warmed by the Gulf Stream, while the equatorward ones are cooled.

The Gulf Stream is one of many Western Boundary Currents in the world. The Kuroshio is a similar current in the North Pacific Ocean that travels northward along the east coast of Asia. The pattern of Westerlies and Trade Winds tend to drive the upper ocean between about 10N and 40N toward the equator. Western Boundary Currents, like the Gulf Stream and Kuroshio return this water poleward, resulting in circulating counterclockwise flow patterns, called subtropical gyres, in the N. Pacific and N. Atlantic.

However, the Gulf Stream is special in that it serves a second role. 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 about 1500m depth. This cold water returns southward, spilling over features in the bathymetry and mixing with other deep waters in the Atlantic to form North Atlantic Deep Water (NADW). This overturning flow, with the Gulf Stream in the upper kilometre flowing northward and the colder NADW flowing southward, is called the AMOC. There is no comparable deep overturning circulation in the N. Pacific. So, while the Kuroshio completes the circuit of N. Pacific water driven by the winds, the Gulf Stream completes the circuit of both the N. Atlantic surface waters driven by the winds and resupplies the water that sinks and becomes NADW.

Although the winds do change somewhat with climate change, it is not expected that the Westerlies and the Trade Winds will stop altogether. Thus, the Kuroshio and the part of the Gulf Stream that complete the circuit of the subtropical gyres are not expected to change much. The thermal energy carried by these currents will continue much as they do now, except they will differ a little as the atmosphere and surrounding waters warm under climate change.

On the other hand, the AMOC is slowing and is expected to slow even more by the end of this century. Thus, this part of the Gulf Stream is expected to slow down. Since 2005, at 26.5N an array of moorings across the Atlantic is monitoring these changes in the Gulf Stream. The slowdown is not yet apparent in the data from this new monitoring system. However, 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 slowing of the overturning. They also agree that under strong greenhouse gas emissions, this slowdown is expected to intensify by 2100 and beyond. 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? It is not quite as simple as Northern Europe gets colder, because the atmosphere adjusts somewhat to compensate the changes in the ocean overturning. Also, the slowdown is occurring at the same time that the rest of the planet is warming, so rather than cooling it is perhaps easier to describe the effect as the N. Atlantic warms more slowly than other regions. However, models indicate that weather patterns are affected, typically reducing precipitation in the midlatitudes, strong changes to precipitation in the tropics, and stronger storms in the N. Atlantic Storm Track. European weather and seasonal precipitation patterns are strongly affected. Furthermore, sea level in the Western N.

Atlantic will rise.

[PLACEHOLDER for a more detailed description].

[If you want to comment on this FAQ, please select Chapter 9 in the review comment sheet]

Frequently Asked Questions

FAQ 10.1: To produce useful regional climate information, what must we consider?

Both physically and culturally, the world is diverse. Providing citizens useful information on how climate is changing can help with decision-making but only when relevant for the people involved. Useful climate information, when relevant, robust and well understood makes a difference to the decision. To achieve this requires awareness of the context where the information will be used, and establishing a common ground of understanding by all involved as to the robustness and appropriate formulation of the needed information.

The development and use of climate change information are inherently influenced by the values of all parties: those constructing the information, those communicating the information, those hearing the information, and critically those who identify a problem that the climate information seeks to inform. Consequently, partnerships between these participating communities, and most especially with those for whom the information is intended, can substantially enhance the usefulness of the climate information in addressing the problem.

Effective partnerships recognize and respond to the values of all parties involved, especially when taking into account that the world and regions within it are culturally heterogeneous. By recognizing this heterogeneity, the information can be made more relevant and credible, most notably when informing the complexity of risks for human systems and ecosystems and resilience in developing nations, which may be more vulnerable to damaging impacts of climate change.

Many sources can provide useful descriptions of climate. These can include 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 needs to consider all sources, in order to capture the fullest possible representation of projected changes, and then distil from them the information that links to the needs and concerns of the stakeholders and members of the community impacted by the changes. The distillation process (FAQ 10.1, Figure 1) ideally engages with the intended recipients of the climate information and, especially those stakeholders whose work involves non-climatic factors, such as in issues of human health, agriculture or water resources. Distilling climate information should further recognize that the geographic regions and time periods governing stakeholders' interest (for example, the growing season of an agricultural zone) may not be well aligned with the time and space resolution of available climate data, and thus may require additional development to extract useful climate information.

Successful framing of climate information and effective societal response have occurred when climate information is presented in the context of the local challenge 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 the climate information came from recognizing a serious impact and avoiding the central, but likely controversial, motivation of fighting global climate change. Similarly, the city officials of Lusaka in Zambia engaged in sustained collaboration with climate scientists and effectively changed the city's approach to changing climate through a partnership that constructs and communicates climate information relevant to governing an African city vulnerable to climate change.

Stakeholders often need information from complex, compound events (e.g. floods after a drought) and in terms of quantities that, for those simulating climate, may not be primary concerns, such as receiving heat-stress conditions or a drought index. One way that complex information can be linked to the application is by stories. Storylines give climate change information that links with the recipients' experiences of existing weather and climate. This makes the climate information more accessible and physically comprehensible. The development of storylines uses the experience and expertise of stakeholders who seek to develop appropriate response measures (e.g., water-resource managers, health professionals, etc.). With appropriate choices, storylines can engage nuances of the climate information in a meaningful way by linking them to familiar details of a region's weather, thus enhancing the information's usefulness.

[START FAQ 10.1, FIGURE 1 HERE]

FAQ 10.1, Figure 1: [Placeholder: Schematic of possible figure showing the distillation of multiple factors into useful climate information. Underlying figure of the distillation flask found at http://www.clker.com/clipart-23858.html]

[END FAQ 10.1, FIGURE 1 HERE]

[If you want to comment on this FAQ, please select Chapter 10 in the review comment sheet]

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

Cities feel the impact of climate change in a unique way. Tall buildings in close proximity to each other 'trap' heat, creating a so-called 'urban heat island', which causes cities to experience higher than average temperatures than their surrounding areas. Urbanization and the increasing severity of climate change further aggravate this effect.

Cities are on front line in both cause and effect of climate change. On one hand, cities are responsible for up to 70% of current emissions of greenhouse gases, 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 people who live in them 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, 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. They are therefore often associated with elevated surface air temperature, a phenomenon referred to as the urban heat island (UHI) 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, it has been found that during heat waves episodes, the UHI gets intensified compared to its climatological mean values.

Although the urban heat island phenomenon is well documented, and studies have increased our understanding, important measurements of meteorological and external climatic drivers across urban areas remain very limited 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. For example, it is very important to know whether, and to what extent, estimates of global warming trends are influenced by the growth of the urban heat island (UHI) in cities around the world due to the urban sprawl. In fact, if observations of near-surface air temperatures in growing cities are used in the assessment of global warming trends, these trends may be overestimated. For this reason, computations of global warming trends either avoid using measurements from cities or else adjust urban measurements to account for UHI influences.

Estimating how the UHI will evolve under climate change conditions is uncertain because several studies using a variety of methods report contrasting results. However, there is *clear evidence* that future urbanization may amplify the projected air temperature in different climatic regions *with a strong impact on minimum temperatures that could be comparable in magnitude to the global climate change warming.*

[START FAQ 10.2, FIGURE 1 HERE]?
Figure : [Placeholder: Infographic explaining the urban heat island effect and how urbanization aggravates this effect or schematic summarizing why cities are important to climate change.]
[START FAQ 10.2, FIGURE 1 HERE]?

[If you want to comment on this FAQ, please select Chapter 10 in the review comment sheet]

Frequently Asked Questions

FAQ 11.1: How do extreme changes compare with mean climate changes?

Changes in temperature and precipitation extremes are at times larger and spatially more robust than their average counterpart. Yet changes in means and extremes can be governed by different processes, thereby challenging their intercomparison.

When comparing extreme changes to mean changes in climate, the answer depends on the aspect of extremes, as well as on the questions being asked. One can, for instance, consider variations in (i) the magnitude of the change, (ii) the spatial scale, or (iii) the underlying processes driving the changes.

Magnitude. While changes in global mean temperature have been used as an important indicator of global climate change, changes in regional mean land temperature are often larger than changes in global mean temperature. This is due to the lower heat capacity of land compared to oceans, and because land absorbs energy at the surface, whereas solar radiation penetrates into the water column and oceans subsequently transport it further down through mixing and circulation. This leads to land warming – on average – faster than oceans, and hence faster than the global average. In addition, for several variables and regions, absolute changes in extremes are larger than changes in global – and sometimes even local – means. This is exemplified in Figure 1, showing that past and future warming during the hottest day in the Mediterranean is consistently larger than the rise in global mean temperature. In contrast, in a few regions observational records do not show a rise in extreme temperatures despite a mean warming. For instance, observations show no increase in warm temperature extremes in recent decades over most of India and the US Midwest. For precipitation, percentage changes in wet extremes are usually larger than that changes in annual mean amounts (see below).

[START FAQ 11.1, FIGURE 1 HERE]

FAQ 11.1, Figure 1: In the Mediterranean, warming of hot extremes is consistently larger than the rise in global mean temperature.

[END FAQ 11.1, FIGURE 1 HERE]

This is illustrated by the modelled relation between daily maximum temperature during warmest day of the year and global mean temperature change (red band) lying consistently above the 1:1 line (dashed line). Full lines represent the CMIP5 multi-model mean changes under past (black), moderate future (RCP4.5, blue) and business-as-usual future (RCP8.5, red) emissions, whereas the red band represents the multi-model envelope including uncertainties from emission scenarios, model deficiencies and natural variability. From Seneviratne et al. (2016), see ref for technical details.

Spatial scale. While local-scale changes in extreme may be subject to considerable uncertainty, spatial aggregation of temperature and precipitation extremes highlights a robust response to climate change with increased likelihood of both hot extremes and heavy precipitation. Moreover, a small change in the mean conditions shifts the entire distribution, resulting in a relatively large change in the probability of extremes.

Processes driving mean and extreme change. Some processes amplify extreme events rather than mean conditions, resulting in the tail of variable distributions showing a higher increase than the median values. This is for instance the case with hot extremes in regions that are projected to become drier during the warm season. Also changes in surface albedo have been shown to affect hot extremes more than median temperatures: because there tends to be more incident shortwave radiation on hot days, an increased surface reflectivity associated with higher albedo will induce a stronger net cooling. Likewise, also the absence of warming during hot days may be explained by processes affecting extremes rather than mean. Notably, the absence of warming in India and the US Midwest has been ascribed to cooling from aerosols and local land

management including irrigation and cropland intensification.
In case of precipitation, changes in wet extremes are largely constrained by moisture availability, leading to extreme precipitation changing consistent with the Clausius-Clapeyron relation in absence of a moisture limitation (that is, an increase by about 7% per degree of warming). In contrast to this thermodynamic control on extremes, changes in mean precipitation rather tend to be determined by changes in atmospheric circulation, moisture transport and the surface energy balance, generally leading to more complex patterns and rates of change. Additionally, there is evidence for dynamics to modulate such that larger change is associated with more extreme precipitation.

[If you want to comment on this FAQ, please select Chapter 11 in the review comment sheet]

FAQ 11.2: Could new types of extreme events develop from climate change?

As the climate changes, the associated unusual or extreme events will also change. Most future extreme events will be similar to past events, but some will occur with magnitudes much larger than experienced in the past and some events will occur much more frequently. The compound occurrence of multiple extreme events may change the type and severity of future impacts.

The climate we have experienced is one to which both human and natural systems have adapted. This climate state includes the occurrence of unusual and extreme events. As the climate changes, it moves away from that which the human and natural systems are accustomed. When extreme events occur in the new climate state, they have the potential to be different from those events experienced in the past. For example, we have seen an increased occurrence of record-breaking hot temperatures globally and throughout many regions. In addition, warming may have resulted in more precipitation brought by tropical cyclones and continued warming is projected to increase tropical cyclone rainfall even more. In this sense, new extremes that have never been experienced before may emerge.

In general, many extreme events in a warmer climate will be similar to what we have experienced in the past. This is because the projected changes in large-scale circulation and thus, the associated weather systems that generate extreme events, are relatively small. However, these extreme events will often be more severe or occur more frequently. For example, we have experienced heatwaves in the past and we will experience heatwaves in the future. However, under a warmer climate, the heatwaves will have hotter temperatures and last longer than past heatwaves. A severe heatwave event that occurs once in five years in China today is projected to become an annual event under a high level of global warming.

Compound events are also an important consideration for future extremes. They occur when multiple hazards combine to produce increased risks and impacts. For example, the occurrence of drought combined with extreme heat will increase the risk of wildfires and agriculture losses. A changing climate may alter the interaction between hazards or see 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 not seen previously.

[If you want to comment on this FAQ, please select Chapter 11 in the review comment sheet]

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, there will always be unusual or extreme weather and climate events. However, there is strong evidence that characteristics of many types of extreme events have already changed because of changes in the climate. These events are occurring more often and becoming more severe.

Many factors contributed to the occurrence of any specific extreme event. While some factors may include the built environment or human behavior (e.g., increased pavement in an urban area that contributed to increased flooding), many factors involve the local or global climate. These climate factors are driven by natural variability on the backdrop of a changing climate. While it is difficult to answer if climate change has caused particular extreme events, it is possible, through a process called event attribution, to quantify how climate change has altered the characteristics of some types of extreme events.

There is strong evidence that characteristics of extreme events, including their frequency or magnitude, may have changed as a result of climate change. Precipitation extremes have intensified over large scales and in some regions. Heatwaves around the globe have consistently increased in frequency, and many in magnitude as well. That is, heatwaves are occurring more often and with hotter temperatures. With warming, cold extremes are less frequent and less cold.

[START FAQ 11.3, FIGURE 1 HERE]

FAQ 11.3, Figure 1: Demonstration of changing temperature extremes with a warming climate. Return periods for hot (a) and cold (b) extremes are shown with a log scale for a natural only climate (dark blue) and a climate that includes human-driven climate change (light blue). A return period describes the average time between events of a certain magnitude; shorter return periods indicate more frequent occurrence. An extreme hot temperature in the natural climate increases in both frequency (red arrow) and magnitude (orange arrow) under climate change. Similarly, an extreme cold temperature in the natural climate decreases in frequency (dark green arrow) and increases in magnitude (light green arrow) with climate change.

[END FAQ 11.3, FIGURE 1 HERE]

The change in temperature extremes is illustrated in FAQ 11.3, figure 1. A climate that is influenced by only natural factors will still experience extreme hot and extreme cold events. However, including the effects of anthropogenic climate change results in a warmer climate. In this case, the cold events of the natural climate occur less often, while the hot events occur much more frequently. Similarly, the cold event that occurs once in 50 years, for example, will be much warmer under the influence of climate change. The same is true for hot events; an event that occurs with the same frequency in both climates will be warmer with climate change.

While a specific event may not be entirely attributable to human-driven changes in the climate, there is already evidence that climate change is resulting in certain extreme events occurring more frequently or becoming more intense. With continued warming, it is expected that many extreme events will continue to occur more often or become more severe in the future.

[If you want to comment on this FAQ, please select Chapter 11 in the review comment sheet]

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 and shift conditions for many climate variables, but impact and risk applications focus on a smaller set of changes and climate phenomena known to affect things that society cares about. These climate 'hazards' are distinguished because they connect essential climate variables (such as temperature, rainfall, or humidity) to the vulnerability and/or exposure of a sectoral asset (farms, roads, wildlife, human health, or a reservoir, for example). Sectoral decision makers have long identified that certain weather and climate conditions can be problematic (or 'hazardous') for their assets. These may include the occurence of extreme weather and climate phenomena (e.g., a tornado, hail storm, or flood) that directly impacts an asset, critical climate thresholds (e.g., an extreme temperature, a low soil moisture content) beyond which systems start to experience elevated stress or breakdown, or even 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 mean temperatures climb. The connection to an asset's vulnerability underscores that a changing climate variable is not hazardous when below biophysical or engineered tolerance, for example heavy rainfall events are not hazardous to city wastewater systems until rates exceed drainage limits. Likewise, connection to an asset's exposure recognizes that extreme conditions are not hazardous if they occur in a location that does not contain any assets to be affected.

[*Placeholder*: *An info-graphic-like figure is envisioned here for the SOD showing two angles on hazards: (a) how the same climate hazard can affect multiple sectoral assets, for example heat wave hazards affecting human health, crops, ecosystems, and road pavement; and (b) how one sector can be vulnerable to multiple climate hazards, for example crops vulnerable to heat, frost, hail, drought, pluvial flooding, etc. This would be accompanied by additional text to encourage readers to consider the effect of multiple hazards on their systems, as well as to recognize that a given hazard can have broader system impacts.]*

[If you want to comment on this FAQ, please select Chapter 12 in the review comment sheet]

FAQ 12.2: How can hazard combinations be more dangerous than individual components?

When climate conditions become extreme they can be hazardous for sectoral assets like human health, ecosystem species, crops, infrastructure, and freshwater resources. The various impact sectors are each complex systems, however; and observational evidence makes it clear that sectoral assets respond to combinations of hazards and changing climate conditions in ways that can amplify the effects of the individual hazard components on their own. Hazard combinations can occur when hazards occur at the same time (concurrently), when hazardous trends exacerbate episodic hazards, and when a sequence of hazards builds to a larger threat.

Concurrent hazards: In many cases assets contain key biophysical or structural sensitivity to combinations of extreme conditions. For example, hot and humid conditions lead to heat stress for people, livestock, and many wild animals, while hot and dry conditions are particularly dangerous for crops and wild plants facing water stress. Coastal river deltas are particularly challenged by coastal surges and heavy rains associated with tropical storms when river levels are already high. Coral reef ecosystems are also threatened by marine heat waves that act on top of ocean acidification.

Trends exacerbating episodic hazards: Long-term trends are hazardous in their ability to change the overall regional climate, but they also alter the profile of extreme events affecting the same climate variables. For example, long-term regional warming trends raise the average temperature closer to assets' critical biophysical or engineering thresholds. This lowers the relative anomaly required to exceed episodic heat wave hazard conditions, leading to more frequent heat wave hazards or the apparent normalization of what was previously more extreme events. Additional examples include sea level rise lifting all coastal surges, and regions with a wet trend being closer to soil saturation such that heavy rainfall events lead to more surface runoff for pluvial flooding hazards.

Sequential hazards: Apparently minor events can lead to major hazards when they occur in a sequence leading to a cascading hazard. For example, a springtime heat wave may not be very hazardous in its own right, but when it leads to early leaf-out or flowering it can have devastating results if followed by a late-season frost (which may not even be out of the ordinary). Scientists have also identified longer sequences that can be problematic, such as a wet spell (which encourages forest undergrowth) followed be a drought (which dries out plant matter) followed by a wildfire (which then has plenty of fuel).

Dependent hazards: In several cases, two types of hazard may impact the same system with a joint probability that is much larger than the product of each separate probability. The occurrences of the hazards are not independent and should be studied in a combined way. For instance, combined river flood and storm surge in stormy conditions along coastal areas amplify coastal flooding, or a persistent larege-scale atmospheric flow can drive clusters of successive extratropical storms that can damage infrastructure.

[*Placeholder: Will add figure here for SOD illustrating an example of a concurrent hazard, trend/episodic hazard, and sequential hazard. This would be accompanied by additional text to encourage readers to recognize that hazards cannot be treated in isolation and that they may be able to identify particularly dangerous combinations.*]

[If you want to comment on this FAQ, please select Chapter 12 in the review comment sheet]

FAQ 12.3: In what ways can anthopogenic climate change cause climate hazards to shift?

Climate hazards have long been a challenge for natural ecosystems and society. Human-driven (anthropogenic) 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. These changes are often intertwined or stem from related physical changes to the climate system. Different sectors and sectoral assets may respond more acutely to one or more of these changes, so risk managers examine all of these change aspects in determining how climate change will shape the future hazard profile.

Magnitude or intensity: The raw value of a climate hazard, such as the change in the 99th percentile temperature, coastal surge, or flood event.

Frequency: The number of times that a climate hazard surpasses a threshold over a given period, for example changes to the number of nuisance floods, tornadoes, coastal surges, or droughts.

Duration: The length that hazardous conditions persist beyond a threshold, such as changes in the number of consecutive days where maximum temperature exceeds 35C or the number of consecutive months classified as drought.

Timing: The occurrence of a hazardous event over the course of a day, year, or other period in which sectoral assets are evolving or co-dependent (such as migrating animals expecting seasonal food supply). Examples include the day of the year when the last spring frost occurs, the date when first seasonal rains arrive, or the length of the wintertime period when the ground is typically covered by snow.

Spatial extent: 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, or zones where climate conditions are conducive to outdoor labour.

[*Placeholder: A two-panel figure is planned here for the SOD that will demonstrate all types of hazard changes. (a) will show a comparison of two hypothetical probability distributions for temperature (current and future), highlighting how the differences shed light on changing intensity (shift in 95th percentile or trend in mean), frequency (cumulative difference between probability distribution lines above a given threshold), and spatial extent (vanishing events at bottom of tail indicate no longer present in this location; unprecedented events at top of tail indicate hazards newly present in this location). (b) will show two hypothetical daily temperature time series over a year (current and future), highlighting shifts in magnitude (of hottest day of year), frequency (of events exceeding a threshold), duration (of temperatures above a threshold), timing (of last spring frost and first winter frost), and spatial extent (showing how coldest day of the current year no longer occurs in the future). Could also show integrated exceedance or deficit above a threshold to show things like growing degree days or heating degree days). This would be accompanied by additional text describing how the reader can interpret these changes and apply them more broadly beyond this example*.]

[If you want to comment on this FAQ, please select Chapter 12 in the review comment sheet]

FAQ 12.4: Can climate change be both hazardous and beneficial?

Climate hazards occur when climate conditions intersect with sectoral assets' vulnerability or exposure 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, materials specifications, construction quality) as well as number of local conditions that alter hazard susceptibility (e.g., soils, topography, land use, management practices, competition). Chapter 12 indicates many connections between hazards and sectoral assets with demonstrated detrimental responses and assesses how these hazards are projected to change from the available scientific literature.

Climate change can also alter some hazard profiles in ways that are both beneficial and detrimental to sectoral assets. Increases in atmospheric CO_2 concentrations are a primary cause of anthropogenic climate change, but beneficially enhance photosynthesis and water retention by crops and natural ecosystems at leaf level. Other hazardous events are important elements of natural growth cycles, for example wildfires and floods play a critical role in maintaining ecosystem biodiversity. Typical examples of beneficial changes include opportunities for agriculture to develop at higher latitudes as the warm season becomes longer, or a reduction of heating energy consumption in northern countries brought by a shorter cold season.

Even within the same region and hazard category there can be large differences in whether the response is hazardous or beneficial. For example, a warming trend may alter the suitability of customary crops in a given location, opening the opportunity for new high-value crops but potentially pushing out traditional cultivation without a viable option for replacement. The same warming that may increase a region's agricultural value may also be detrimental for natural ecosystems and increase human morbidity during heat waves. Even some apparent benefits and opportunities would require substantial investment and perhaps face secondary hazards, for instance many high-latitude regions considering agricultural expansion will face increased wet hazards.

It is noteworthy, however, that the scientific literature presentsmuch more scientific evidence of hazard increases than hazard decreasesin future climate projections. Despite a bias of the current literature towards studying hazard increases rather decreases cannot be ruled out, Chapter 12 reflects a general overall increase in many characteristics of hazards.

[*Placeholder: An info-graphic-like figure or table is envisioned here to illustrate (a) some examples of beneficial changes (intersections of particular hazard categories/sectoral assets); (b) examples when changes in the same hazard category is beneficial to one sector and hazardous to another; and (c) examples when changes in the same hazard category can be beneficial or hazardous to different assets in the same sector. This would be accompanied by additional text to encourage readers to look for these details rather than only considering aggregate hazard changes*.]

[If you want to comment on this FAQ, please select Chapter 12 in the review comment sheet]

Frequently Asked Questions

FAQ ATLAS.1: If results from models are uncertain, how can we trust them?

A model is a simplified representation of something more complicated. Children's play, for instance, often involves models of anything from machines to human social systems. For predicting weather and climate, models are built which are simplified representations of the complicated physical and chemical interactions which take place in the atmosphere, on land and in the oceans. These take the form of computer models which solve complex mathematical equations derived from these simplified representations. Clearly it is not possible to represent all the detail of the real world in a computer model and so the results it will generate will only approximate the real world, i.e. will contain a degree of uncertainty. However, if we compare these results with observations then we can quantify this uncertainty which can allow us to say how much trust we can have in them. In the case of climate change projections we can use an assessment of how well models have been able to reproduce recent climate changes, and the reasons for these, to estimate how much we can trust them to predict how the climate will continue to change in the future. In turn, this then allows us to explore with reasonable confidence the potential impacts of climate change under various scenarios of world evolution and to examine the robustness of a given adaptation option under a wide range of possible futures.

Climate models, global or regional, coupled or uncoupled, are numerical simulations of real-world systems; they solve complex mathematical equations based on well-established physical laws defining the behaviour of the weather and climate. It is not possible nevertheless to represent all the detail of the real world in a computer model, so approximations have to be made, such as the choice of the temporal and spatial resolution of the calculations or the processes included in the models. These approximations lead to some inherent uncertainty.

Since the first climate models with a simplified representation of the atmosphere, our knowledge of the real world has much improved and remarkable advances have been made in computer power. Models have incorporated more of the complexity of the climate system with its many potential interactions and feedbacks. Current state-of-the-art climate models now include fully interactive clouds, oceans, land surfaces and aerosols, with the latest models containing detailed atmospheric chemistry and the climate carbon cycle. Increasing numerical resources have allowed for an ever increasing of the spatial and temporal resolutions at which calculations are made, as well as for the incorporation of more complex parameterisations.

As a result, far more and far more detailed experiments are run with different versions of the models. We can quantify the uncertainty in our predictions and thereby increase confidence in the results. As models have evolved, the fundamental physical responses of the modelled climate systems have remained consistent with the early simpler models, and the coupling process has not uncovered any major errors in the pre-existing models.

The uncertainty of the models can be (and is) characterised. Models are tried and tested in a number of ways. They are used to reproduce the climate of the recent past and the present day, having considerable success at this, both in terms of the average and variations in space and time. They are also used to reproduce what we know about ancient climates. They are calibrated and validated using observations from experiments or analogies, and then run using input data representing future climate. This work gives confidence in the results of the models, or if need be, a representation of their weaknesses which can be in turn taken into account when assessing their results.

While explicitly discussing uncertainty is important for good climate science and the confidence assessment in model results, uncertainty about the future conflicts with individual needs for predictability and control. To address this, scenarios called Representative Concentration Pathways (RCPs) can be used to interpret scientific uncertainty regarding future climate conditions more meaningfully.

RCPs describe a range of plausible future concentrations of global greenhouse gases and aerosols in the atmosphere, which could come as a result of different combinations of future economic, demographic, policy, institutional and technological conditions. Through climate modelling, these RCPs are translated into projected changes in temperature and precipitation, among other climate variables, revealing a range of possible futures. These enable researchers to explore the potential impacts of climate change, and for decision makers to examine the robustness of a given adaptation option under a wide range of possible futures. Decision-makers should treat projections as indicators of possible future trends (and not absolute values) which can inform their pursuit of climate-resilient development pathways.

Thus, scientific uncertainty can here be interpreted as the opportunity to explore rigorously a range of possible future scenarios and to chart climate-resilient pathways, rather than as a lack of any reasonable view of what the future might look like.

[*Placeholder: A schematic of all processes represented in climate models, illustrating the complexity of the climate systems and its interaction with humans and nature*.]

[Other proposed FAQs

Given CMIP5, CMIP6, CORDEX, which model(s) is(are) best for our region?

How do you evaluate models when there is sparse observation?

How can I use the (interactive online) Atlas for mitigation and adaptation studies?

How can I use the (interactive online) Atlas for climate risk assessment?

Specifics FAQs on the Atlas tools regarding the use of the tool in the direction of providing guidance

- *Where can I find the information to produce the figure(s)?*
- *Where are the metadata?]*

[If you want to comment on this FAQ, please select Atlas in the review comment sheet]