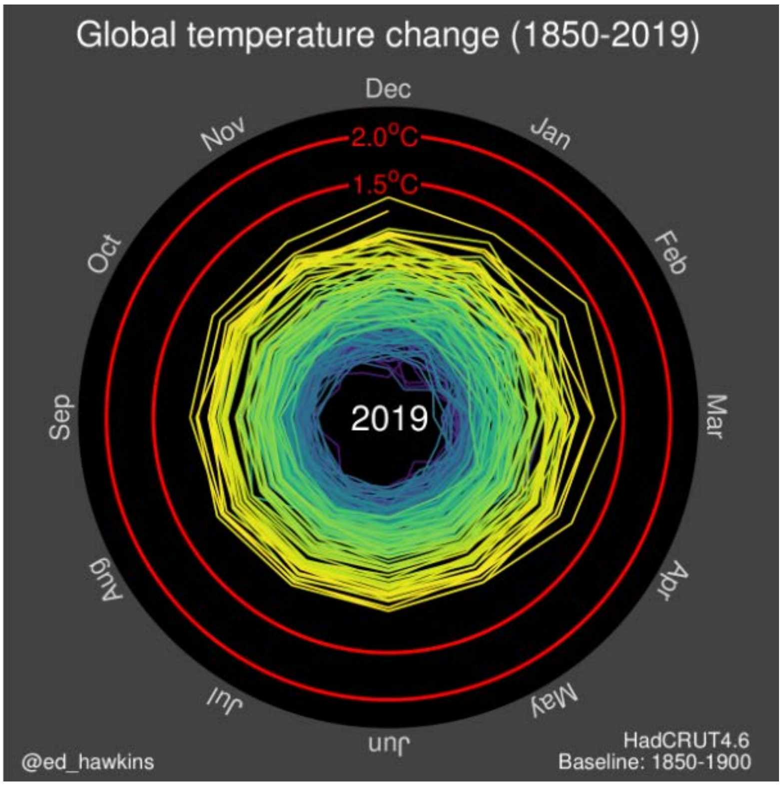
MetLink
Royal Meteorological Society

Changing Global Climate

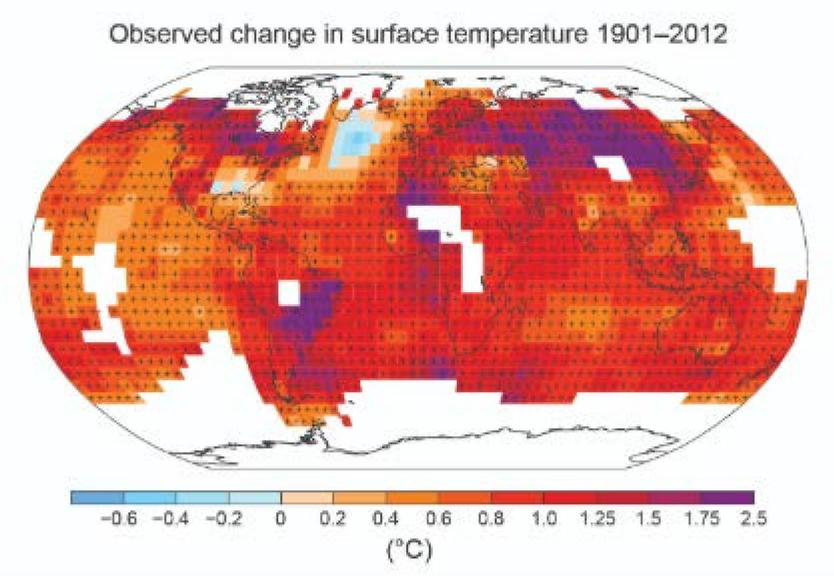
Background Information for Teachers

How has the Climate Changed?

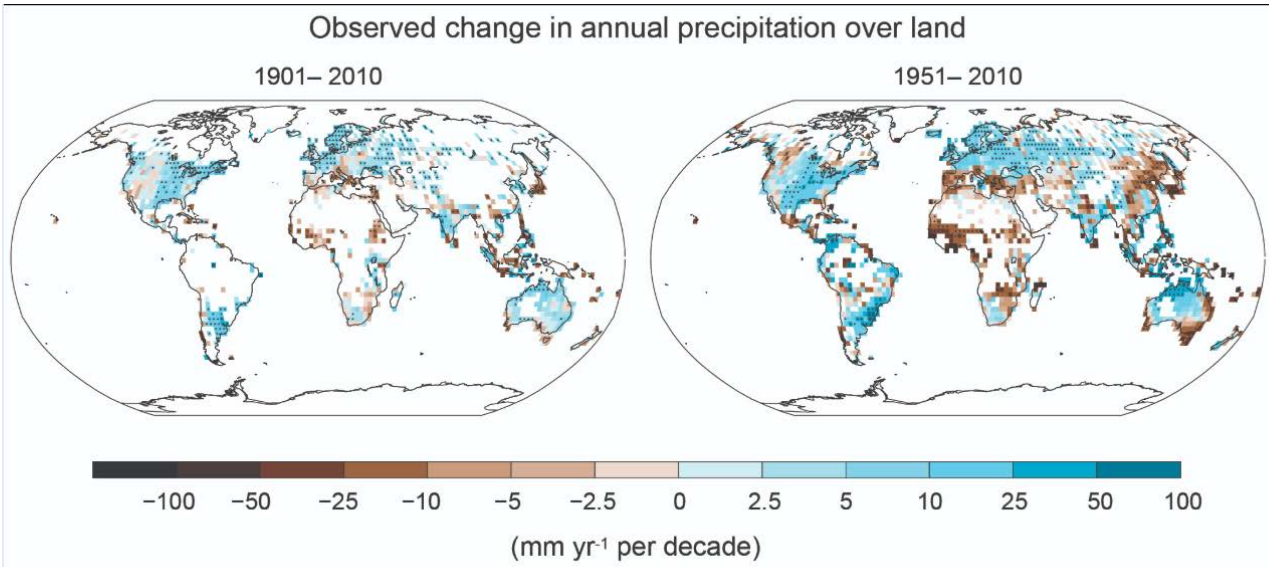
Temperatures in 2019 were just over 1°C warmer than the pre-industrial average. The 'climate spiral' in the image below illustrates how global temperatures have changed:



Or, looking in more regional detail:

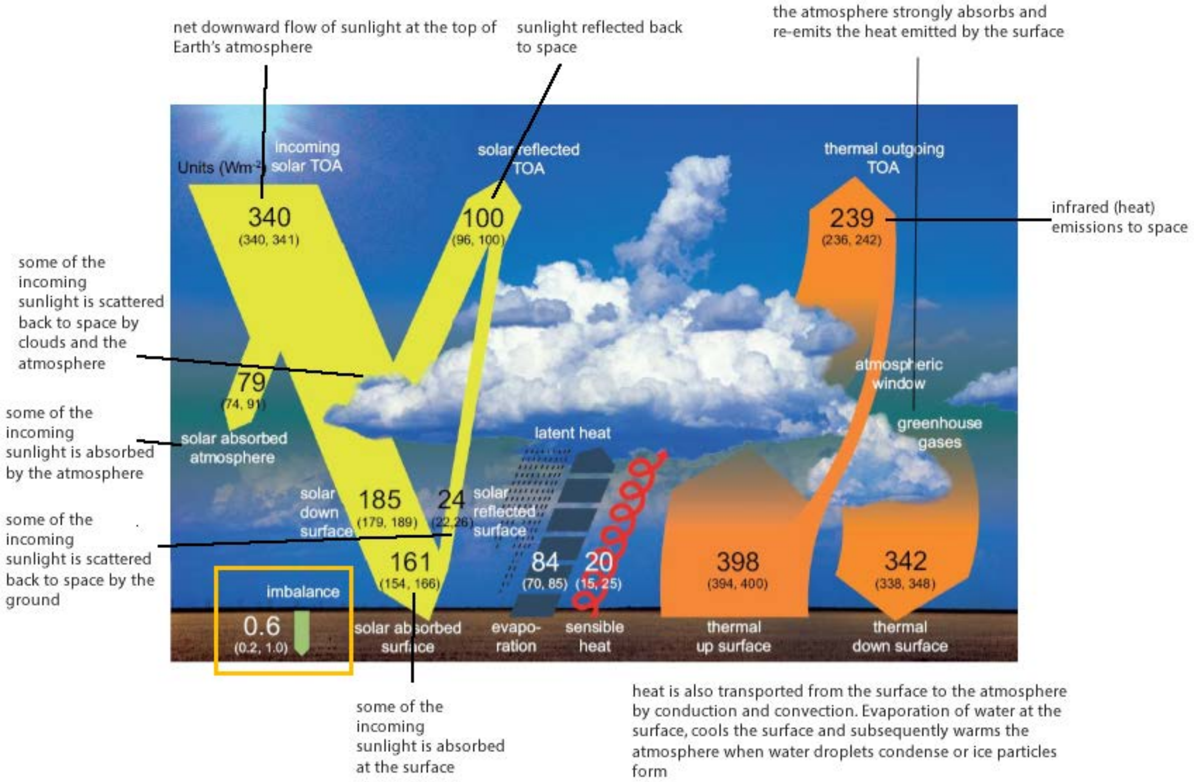


Source: IPCC 2013
http://www.climatechange2013.org/images/figures/WGI_AR5_FigSPM-1.jpg



Source: IPCC, 2013
http://www.climatechange2013.org/images/figures/WGI_AR5_FigSPM-2.jpg

The Earth’s Energy or Radiation Budget



This figure shows the current global annual average flows of electromagnetic and other energy. The numbers show the movement of energy in W/m^2 (Watts per m^2) and their uncertainty (in brackets). The incoming solar energy at the Top Of the Earth’s Atmosphere (TOA) is 340 W/m^2, some of which is scattered back to space by clouds, the atmosphere or the surface (100 W/m^2). The rest is absorbed within the atmosphere (e.g. ultraviolet which is absorbed by the ozone layer in the stratosphere) and at the surface. The amount of energy absorbed by the surface determines its temperature (currently around 15 °C), which in turn determines the amount of energy emitted by the surface (398 W/m^2). Water at the surface evaporates, which requires energy, and moves into the atmosphere, where it condenses into water droplets or forms ice crystals, releasing latent heat energy. This transports energy from the surface into the atmosphere. Conduction and convection also move heat from the surface to the atmosphere. Most of the heat emitted by the surface is absorbed and re-emitted by gases in the atmosphere rather than escaping to space – this is the greenhouse effect. The heat energy emitted to space (239 W/m^2) together with the reflected solar energy approximately balances the incoming solar energy.

Critically, the type of solar energy entering the atmosphere (ultraviolet, light and short wavelength heat radiation) is different to the longer wavelength heat radiation emitted by the Earth's surface – because the Earth is much colder than the Sun. This means that the processes operating on the incoming and outgoing energy can be very different.

Since 1950 the amount of solar energy reaching the surface has been changing. Until the 1980s it was decreasing (dimming) because of an increase in atmospheric pollutants called aerosols. An aerosol is a colloid of either a solid or a liquid suspended in air and some of these cause the atmosphere to scatter sunlight back to space and can also make clouds more reflective by increasing the number of water droplets in the clouds, which also increases the amount of sunlight reflected. Since then, national and international legislation has reduced the amount of aerosols which has increased the amount of solar radiation reaching the surface (brightening) in some places.

Human activities are affecting the Earth's energy balance by:

- Changing the emissions and resulting atmospheric concentrations of greenhouse gases, such as carbon dioxide, which reduce the amount of heat which escapes to space (the Greenhouse effect).
- Changing the emissions and resulting atmospheric concentrations of aerosols which reflect and absorb the sun's radiation.
- Changing land surface properties, which affects reflection, conduction and evaporation, e.g. by deforestation and increased urbanisation.

The result of these activities is that the sum of the energy leaving the top of the atmosphere is less (239+100 W/m^2) than the energy entering it (340 W/m^2). The imbalance is estimated to be about 0.6 W/m^2. Most of this excess energy is absorbed at the surface (mainly by the oceans), as shown by the orange box, causing the observed increase in temperatures in the lower atmosphere and oceans.

Feedback Mechanisms

A feedback mechanism is an interaction in which a perturbation (change) in one climate quantity causes a change in a second, and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is increased.

Some examples of feedback mechanisms in climate change:

Polar Ice Melt

As the atmosphere and oceans warm, sea-ice melts which exposes a much darker ocean. This triggers a positive feedback by lowering the albedo of the ocean's surface and leading to more of the Sun's light being absorbed, amplifying the warming.

Water Cycle Feedback

As the concentration of other greenhouse gases in the atmosphere increases, the temperature of the atmosphere warms and so the concentration of water vapour in the atmosphere (absolute humidity) also rises, enhancing the greenhouse effect. *With every degree of air temperature, the atmosphere can retain around 7% more water vapour.*

As carbon dioxide concentrations in the atmosphere increase:

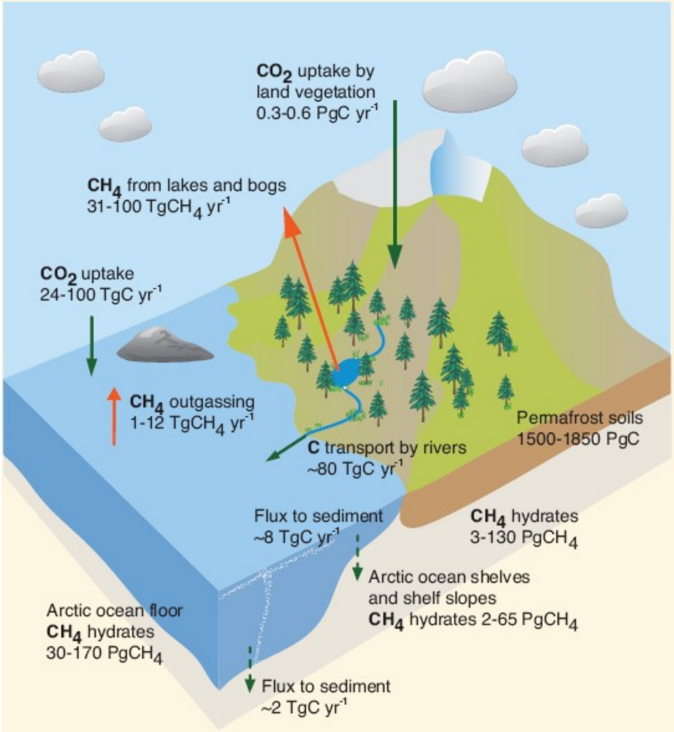
- The oceans will take up more CO_2 almost everywhere, but particularly in the North Atlantic and Southern Oceans.
- The take up of CO_2 by land areas will increase everywhere, particularly over tropical land and in humid regions where the amount of biomass is high. There is also a relatively large increase over Northern Hemisphere temperate and boreal latitudes, because of the greater land area and large areas of forest.
- Without this increased uptake of CO_2 by the land and ocean, annual increases in atmospheric carbon dioxide concentration would be around double the observed rates.

As the atmosphere warms:

- Tropical ecosystems will store less carbon, as will mid-latitudes.
- At high latitudes, the amount of carbon stored on land will increase, although this may be offset by the decomposition of carbon in permafrost.
- As sea-ice melts, more water is exposed and therefore more CO_2 can be taken into the water.
- As water warms, the solubility of CO_2 in water decreases and so less is taken up by the oceans.

- Ocean warming and circulation changes will reduce the rate of carbon uptake in the Southern Ocean and North Atlantic.

Carbon Release from the Arctic



IPCC 2013, Climate Change 2013, WG1 Chapter 6, FAQ6.1 Figure 1. Units are Petagrams (1,000,000,000,000 kg) or Teragrams (1,000,000,000 kg)

At the moment, vegetation in the Arctic is responsible for about 10% of the CO_2 uptake by land globally. Permafrost soils on land and in ocean shelves contain large pools of organic carbon. If permafrost melts, microbes decompose the carbon, releasing it as CO_2 or, where oxygen is limited (for example if the soil is covered in standing water), as methane, CH_4. As the climate of the Arctic warms, more permafrost will thaw. However, warmer Arctic summers would also mean an increase in the amount of vegetation and therefore photosynthesis and CO_2 uptake in the Arctic. As yet, scientists don't know which process will dominate over the next few decades. To complicate matters further, the microbes decomposing the carbon also release heat, causing further melting – a positive feedback.

Methane hydrates are another form of frozen carbon, found in deeper soils. Changes to the temperature and pressure of permafrost soils (and ocean waters) could lead to methane, a gas with a much stronger greenhouse warming potential than carbon dioxide, being released. However, most of the methane is virtually certain to remain trapped underground and will not reach the atmosphere.

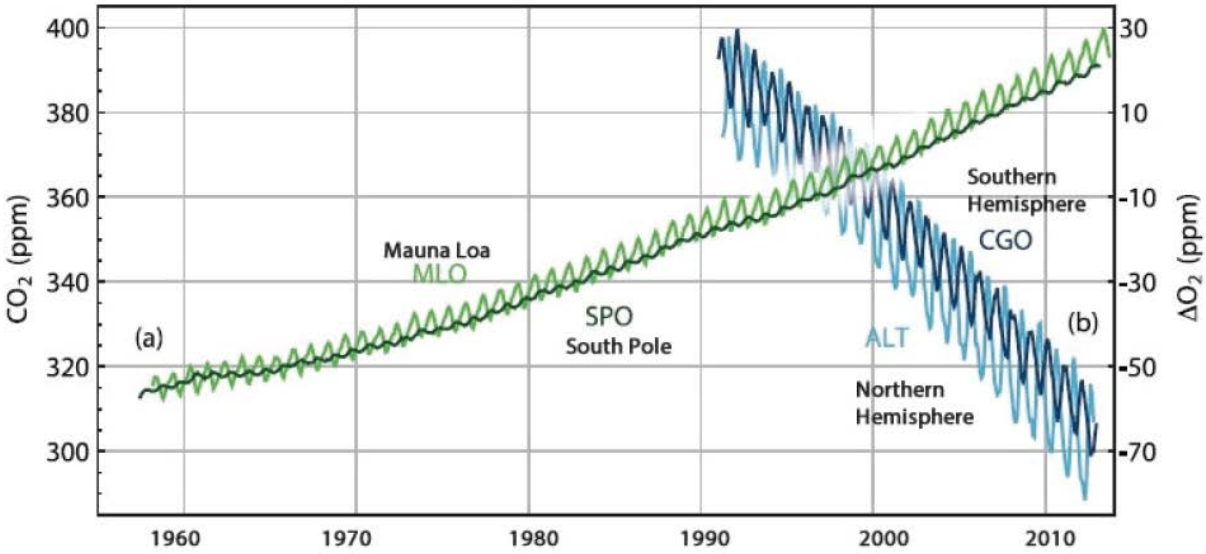
The release of carbon dioxide and methane from the Arctic will provide a positive feedback to climate change which will be more important over longer timescales – millennia and longer.

As Arctic and sub-Arctic regions warm more than the global average, the increase in temperature could lead to more regular fire damage to vegetation and soils and carbon release. More generally, increased vegetation cover lowers albedo, meaning that more of the Sun's light is absorbed which in turn warms the climate locally (another positive feedback), as well as increasing evapotranspiration and carbon uptake.

Greenhouse Gases

The most important Greenhouse gases, in terms of their concentration in the atmosphere, the length of time they remain in the atmosphere and the warming they produce are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CFCs.

Water vapour is the dominant greenhouse gas, but the concentration of water vapour in the atmosphere is determined only by the temperature of the atmosphere (see Chapter 9), so it is a positive feedback mechanism (see above) rather than a driver of climate change itself. As the concentration of other greenhouse gases in the atmosphere increases, the temperature of the atmosphere warms and so the concentration of water vapour in the atmosphere also rises, enhancing the greenhouse effect. With every degree of air temperature, the atmosphere can retain around 7% more water vapour.



Concentrations of carbon dioxide and oxygen in the atmosphere: Atmospheric concentration of a) carbon dioxide in parts per million by volume from Mauna Loa (MLO, light green) and the South Pole (SPO, dark green) from 1950 to 2013, and of b) changes in the atmospheric concentration of O_2 from the northern hemisphere (ALT, light blue) and the southern hemisphere (CGO, dark blue) relative to a standard value.

Carbon Dioxide

CO_2 increased from 278 ppm in 1750 to 441.4ppm ppm in 2019.

Most of the fossil fuel CO_2 emissions take place in the industrialised countries north of the equator. Consistent with this, the annual average atmospheric CO_2 measurement stations in the Northern Hemisphere record higher CO_2 concentrations than stations in the Southern Hemisphere. As the difference in fossil fuel combustion between the hemispheres has increased, so has the difference in concentration between measuring stations at the South Pole and Mauna Loa (Hawaii, Northern Hemisphere).

Because CO_2 uptake by photosynthesis occurs only during the growing season, whereas CO_2 release by respiration occurs nearly year-round, the greater land mass in the northern hemisphere imparts a characteristic 'sawtooth' seasonal cycle in atmospheric CO_2.

Past changes in atmospheric greenhouse gas concentrations can be determined with very high confidence from polar ice cores. During the 800,000 years prior to 1750, atmospheric CO_2 varied from 180 ppm during glacial (cold) up to 300 ppm during interglacial (warm) periods. Present-day (2011) concentrations of atmospheric carbon dioxide exceed this range. The current rate of CO_2 rise in atmospheric concentrations is unprecedented with respect to the highest resolution ice core records of the last 22,000 years.

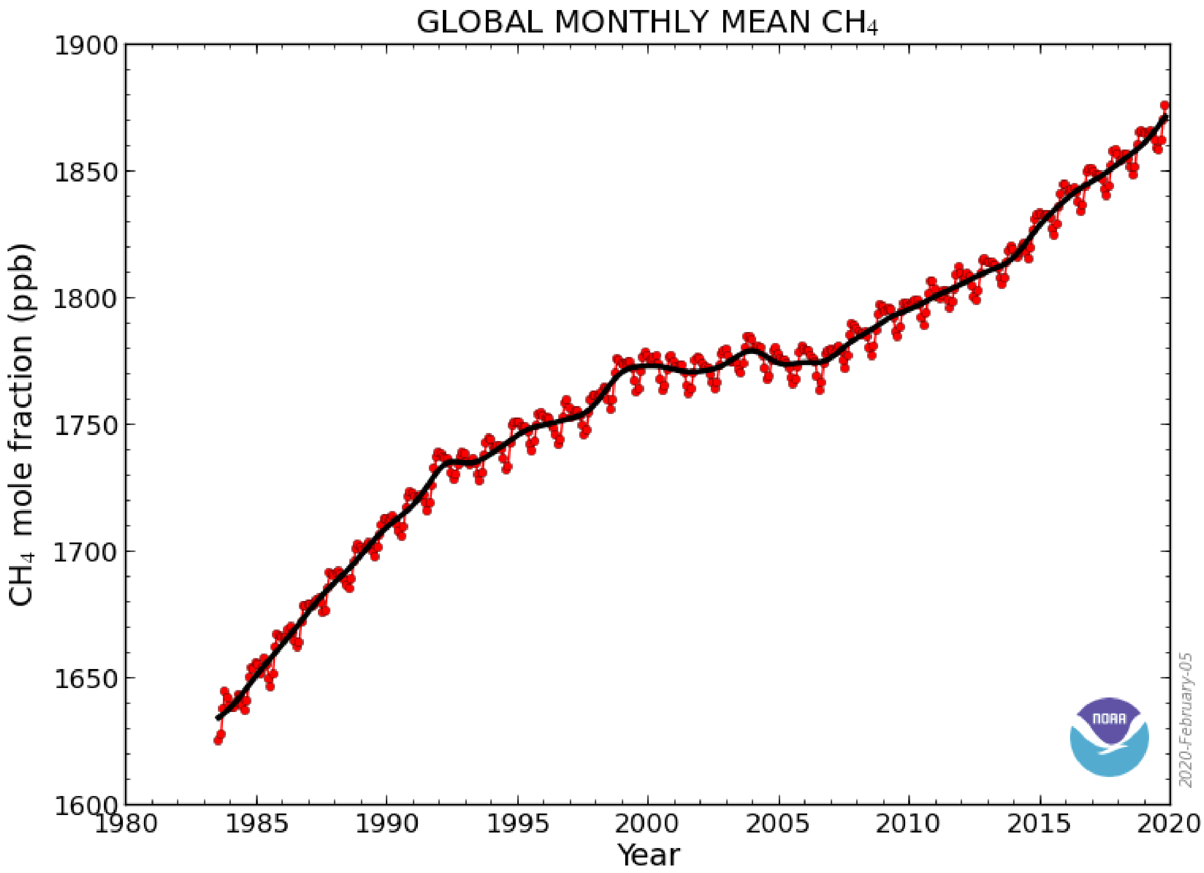
A year in the life of Earth's CO_2: https://youtu.be/x1SgmFa0r04

Oxygen

Atmospheric oxygen is tightly coupled with the global carbon cycle. The burning of fossil fuels removes oxygen from the atmosphere. As a consequence of the burning of fossil fuels, atmospheric O_2 levels have been observed to decrease slowly but steadily over the last 20 years. Compared to the atmospheric oxygen content of about 21% this decrease is very small. However, it provides independent evidence that the rise in CO_2 must be due to an oxidation process, that is, fossil fuel combustion and/or organic carbon oxidation, and is not caused by volcanic emissions or a warming ocean releasing carbon dioxide (CO_2 is less soluble in warm water than cold). The atmospheric oxygen measurements also show the north–south concentration O_2 difference (higher in the south and mirroring the CO_2 north–south concentration difference) as expected from the greater fossil fuel consumption in the northern hemisphere.

Methane

Methane absorbs infrared radiation more strongly per molecule compared to CO_2. On the other hand, the methane turnover time is less than 10 years in the troposphere (much less than for CO_2).



Globally-averaged, monthly mean atmospheric methane abundance determined from marine surface sites.

The concentration of methane in the atmosphere has been rising sharply since 2006. The sources of CH_4 at the surface of the Earth include:

(1) Natural emissions of fossil CH_4 from geological sources (marine and terrestrial seepages, geothermal vents and mud volcanoes).

(2) Emissions caused by leakages from fossil fuel extraction and use (natural gas, coal and oil industry).

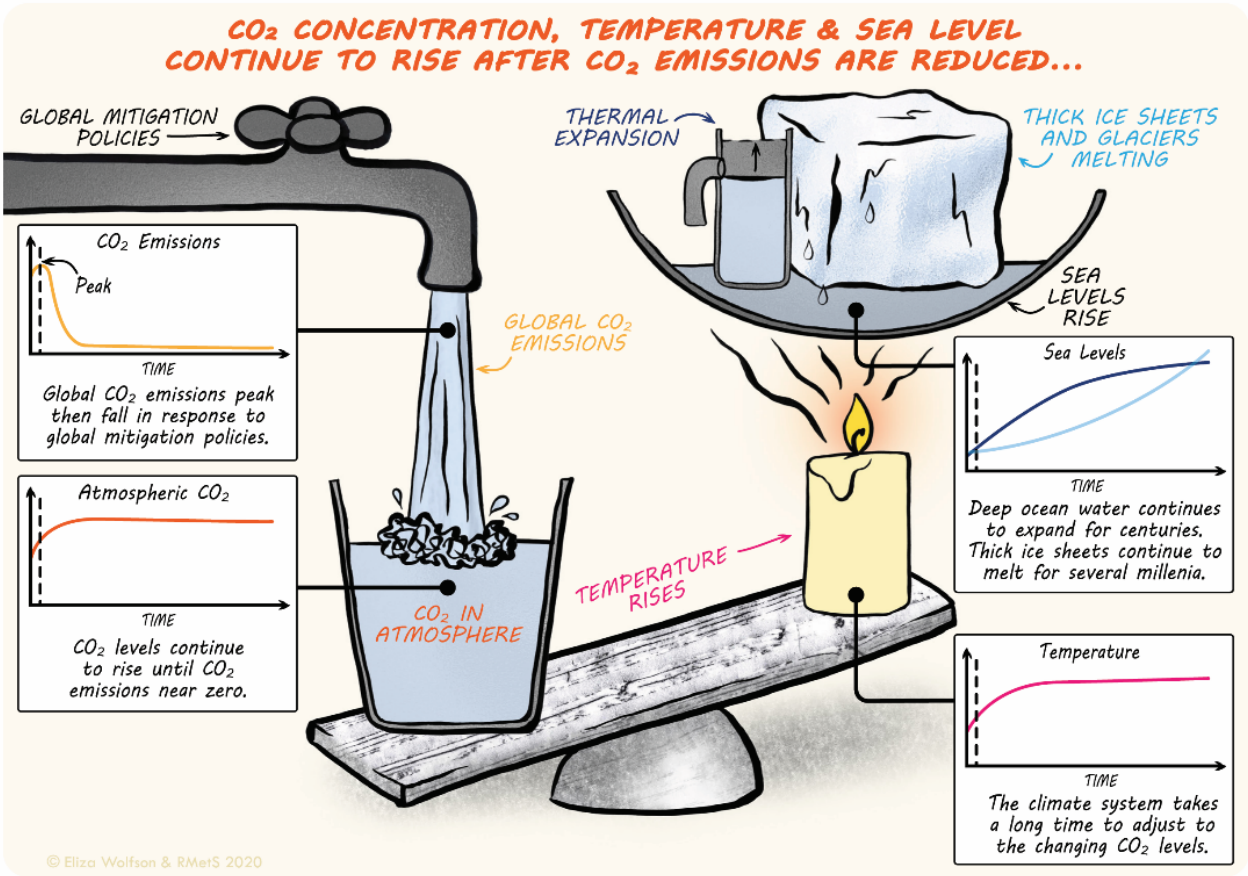
(3) Pyrogenic sources resulting from incomplete burning of fossil fuels and plant biomass (both natural and anthropogenic fires).

(4) Biogenic sources including natural emissions predominantly from wetlands, from termites and very small emissions from the ocean. Anthropogenic biogenic emissions occur from rice paddy agriculture, ruminant livestock (such as cows), landfills, man-made lakes and wetlands and waste treatment. In general, biogenic CH_4 is produced from

organic matter under low oxygen conditions by the fermentation processes of some microbes.

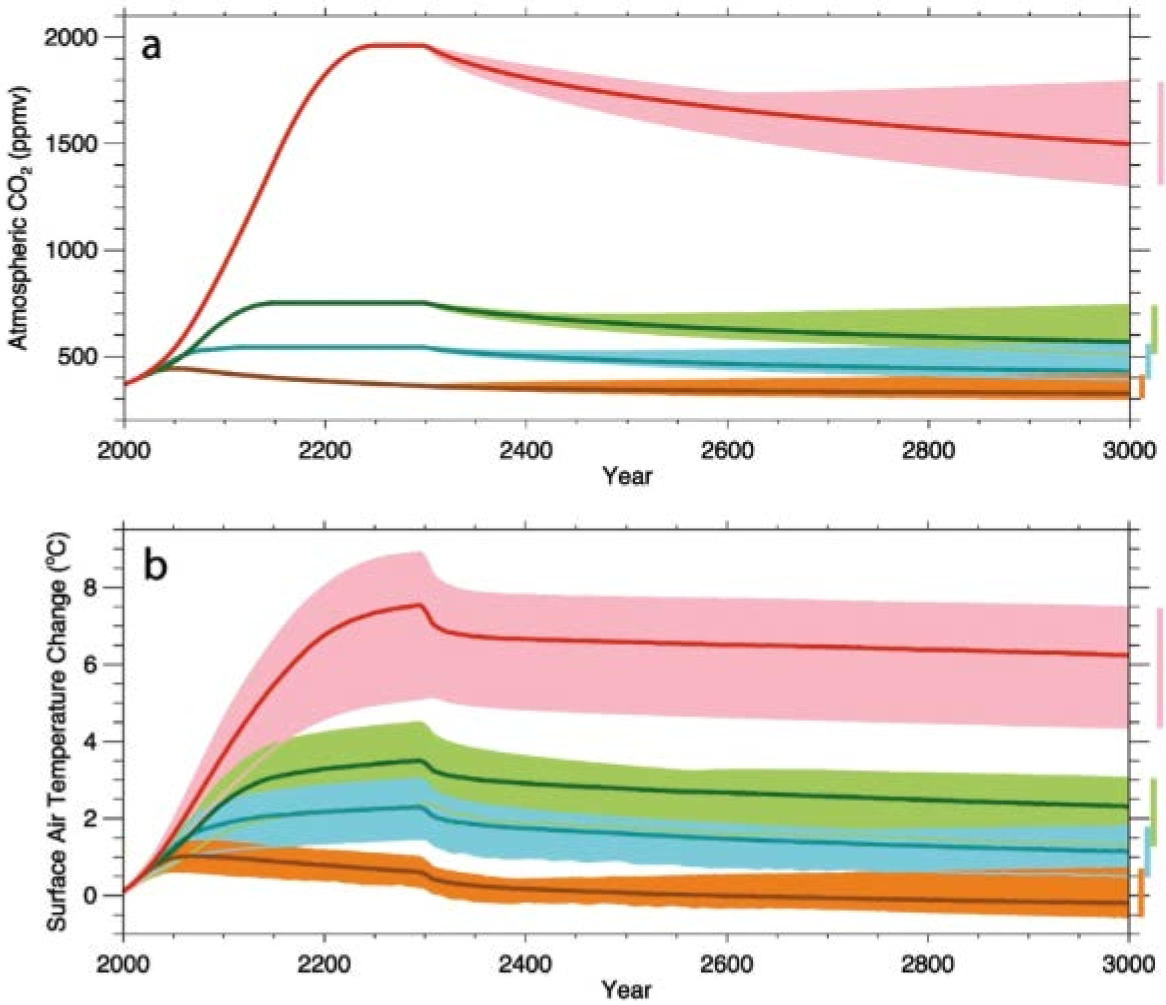
Both fossil fuels and biogenic sources are responsible for the recent increase in methane in the atmosphere. A recent study calculated that fossil fuels have contributed about 12-19 teragrams (Tg) of methane to the atmosphere each year since 2006 compared to 12-16Tg per year from biogenic sources. At the same time, emissions from biomass burning (wildfires and prescribed burning) decreased by 4 – 5Tg per year.

Delayed Response



Even if all emissions of greenhouse gases stopped immediately, the global temperature would still warm by a few tenths of a degree over the coming decades and centuries because the climate system takes a while to adjust to the new conditions. Specifically, the oceans, and particularly the deep oceans, are warming more slowly than the air and will take longer to stop warming.

It would take even longer for the levels of greenhouse gases in the atmosphere to start to fall and longer again before temperatures started to fall.

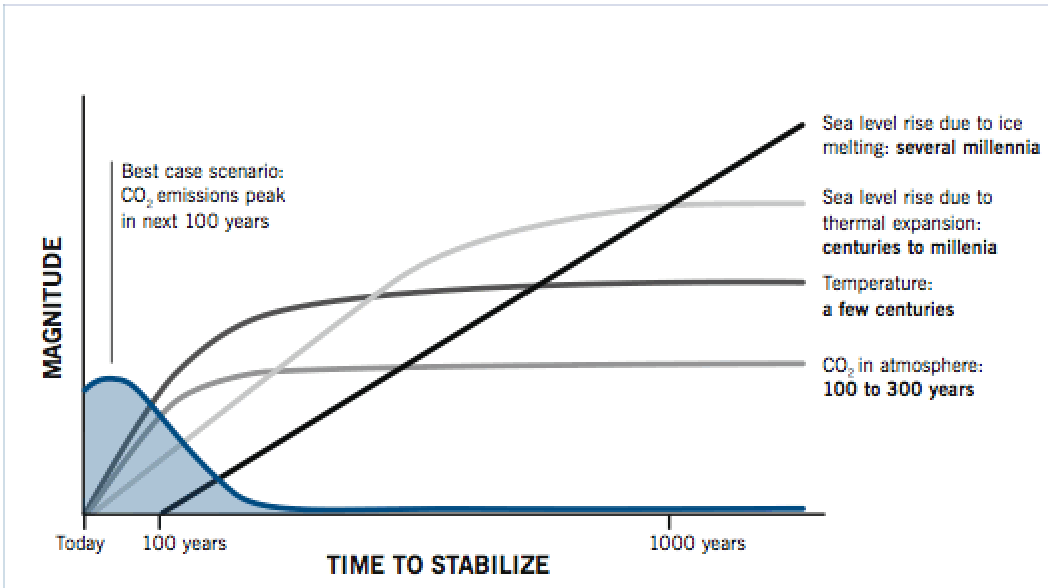


In these figures, (from Zickfeld et al., 2013) the orange lines show projections of what might happen if all emissions were stopped over 50 years.

Scenarios, Projections and Uncertainty

Projections of future climate change are made using computer-based climate models – the same models which are used to make daily weather forecasts. However, there are a number of unknowable factors – how the world's population will change, how the emissions of greenhouse gases per person will change etc. For this reason, it is not possible to say exactly how the climate will change, but a range of projections is given. The figure shown on the previous page shows the range of projected temperature changes with a scenario of business-as-usual emissions ceasing in 2300 (red), a scenario of aggressive emission reductions, falling close to zero 50 years from now (orange) and two intermediate emissions scenarios (green and blue).

The following figure shows how carbon dioxide concentrations in the atmosphere, atmospheric temperature and sea level respond to a peak in greenhouse gas emissions within the next 100 years (blue curve):



The International Process

The United Nations Framework Convention on Climate Change aims to prevent “dangerous” human interference with the climate system. 197 countries have ratified the convention.

A Conference of Parties (COP) happens every year to review the national communications and emission inventories submitted by the countries, or parties, which have ratified the convention. Based on this information, the COP assesses the effects of the measures taken by Parties and the progress made in achieving the ultimate objective of the Convention.

The ultimate objective of the Convention is to stabilize greenhouse gas concentrations "at a level that would prevent dangerous anthropogenic (human induced) interference with the climate system." It states that "such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner."

The Convention puts the onus on developed countries to lead the way. The idea is that, as they are the source of most past and current greenhouse gas emissions, industrialized countries are expected to do the most to cut emissions on home ground. They are called

Annex I countries and belong to the Organization for Economic Cooperation and Development (OECD). They include 12 countries with "economies in transition" from Central and Eastern Europe. Annex I countries were expected by the year 2000 to reduce emissions to 1990 levels.

The convention directs new funds to climate change activities in developing countries. Industrialized nations agree under the Convention to support climate change activities in developing countries by providing financial support for action on climate change-- above and beyond any financial assistance they already provide to these countries. A system of grants and loans has been set up through the Convention. Industrialized countries also agree to share technology with less-advanced nations.

Industrialized countries (Annex I) have to report regularly to the UNFCCC on their climate change policies and measures. They must also submit an annual inventory of their greenhouse gas emissions, including data for their base year (1990) and all the years since. Developing countries (Non-Annex I Parties) report in more general terms on their actions both to address climate change and to adapt to its impacts - but less regularly than Annex I Parties do, and their reporting is contingent on their getting funding for the preparation of the reports, particularly in the case of the Least Developed Countries.

Economic development is particularly vital to the world's poorer countries. Such progress is difficult to achieve even without the complications added by climate change. The Convention takes this into consideration by accepting that the share of greenhouse gas emissions produced by developing nations will grow in the coming years. Nonetheless, in the interests of fulfilling its ultimate goal, it seeks to help such countries limit emissions in ways that will not hinder their economic progress.

The Convention acknowledges the vulnerability of all countries to the effects of climate change and calls for special efforts to ease the consequences, especially in developing countries which lack the resources to do so on their own. In the early years of the Convention, adaptation received less attention than mitigation, as Parties wanted more certainty on impacts of and vulnerability to climate change. When the IPCC's Third Assessment Report was released, adaptation gained traction, and Parties agreed on a process to address adverse effects and to establish funding arrangements for adaptation.

In 2015, at COP21 in Paris, all parties adopted the Paris Agreement to limit global warming to less than 2°C and pursue efforts to limit it to 1.5°C.

Adaptation or Mitigation?

The argument about whether we should act to prevent, or mitigate, future climate change or just adapt to it as it happens is ongoing. Economic, ethical and environmental points can be debated.

Back in 2006, the Stern Review on the Economics of Climate Change concluded that:

- A 2-3°C rise in temperatures could reduce global economic output by 3%.
- If temperatures rise by 5°C, up to 10% of global output could be lost. The poorest countries would lose more than 10% of their output.
- In the worst case scenario global consumption per head would fall 20%.
- To stabilise at manageable levels, emissions would need to stabilise in the next 20 years and fall between 1% and 3% after that. This would cost 1% of GDP.

Although many of the assumptions made in the report are now out of date, the basic message remains that it is globally cheaper, in the long term, to mitigate climate change than to adapt to it as it happens.

However, we are already committed to a certain amount of climate change and so our actual response will require an element of both. Adaptation can happen on a local level more effectively than mitigation, which requires (multi-) national action.

NASA writes:

Mitigation – reducing climate change – involves reducing the flow of heat-trapping greenhouse gases into the atmosphere, either by reducing sources of these gases (for example, the burning of fossil fuels for electricity, heat or transport) or enhancing the “sinks” that accumulate and store these gases (such as the oceans, forests and soil). The goal of mitigation is to avoid significant human interference with the climate system, and “stabilize greenhouse gas levels in a timeframe sufficient to allow ecosystems to adapt naturally to climate change, ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner” (from the IPCC 2014 report).

Adaptation – adapting to life in a changing climate – involves adjusting to actual or expected future climate. The goal is to reduce our vulnerability to the harmful effects of climate change (like sea-level encroachment, more intense extreme weather events or food insecurity). It also encompasses making the most of any potential beneficial opportunities associated with climate change (for example, longer growing seasons or increased yields in some regions).

Tipping Points

A climate tipping point is a critical threshold when global or regional climate changes from one stable state to another stable state. The tipping point event may or may not be reversible.

Aspects of the Earth's climate system have tipped in the past, and projections suggest that increasing greenhouse gas concentrations may lead to future tipping points being reached.

The most likely abrupt, but reversible, change to the climate system expected in the 21st century is the decline of Arctic sea-ice, especially in the summer.

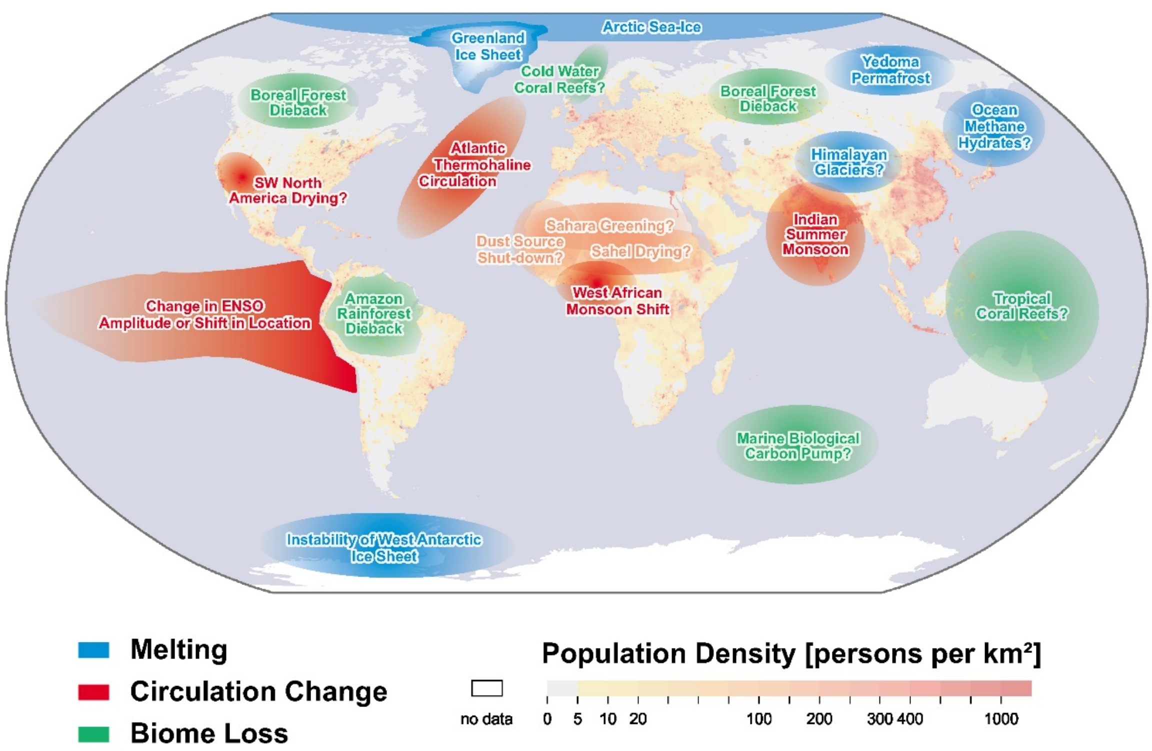


Image reproduced with permission from Prof. Tim Lenton, University of Exeter from Tipping elements in the Earth's climate system. PNAS 105(6), 1786–1793, doi: 10.1073/pnas.0705414105.

The map above shows potential tipping elements in the climate system, overlain on global population density. The subsystems indicated, including the cryosphere, the circulation of the atmospheres and oceans and biomes, could exhibit threshold-type behaviour in response to anthropogenic climate forcing, where a small perturbation at a critical point qualitatively alters the future fate of the system. They could be triggered this century and would undergo a qualitative change within this millennium. Systems in which any threshold appears inaccessible this century (e.g. the East Antarctic Ice Sheet) or the qualitative change would appear beyond this millennium (e.g., marine methane hydrates) have not been included. Question marks indicate systems whose status as tipping elements are particularly uncertain.

Summer Arctic Sea-Ice

The rapidly declining summer Arctic sea-ice cover might already have passed a tipping point, although this is hard to identify due to high year-to-year variability. In this case, the Arctic will change from having year-round to seasonal sea-ice cover.

It is likely that the Arctic Ocean will become nearly ice-free in September before 2050. The transition will be abrupt but, if the amount of CO_2 in the atmosphere falls, the loss of sea-ice could be reversed within years to decades.

The effect of rapid changes to Arctic sea-ice might have consequences throughout the climate system, particularly on cloud cover.

Sources of Information

Many, including:
Current atmospheric carbon dioxide content
https://www.esrl.noaa.gov/gmd/ccgg/trends/weekly.html
Intergovernmental Panel on Climate Change https://www.ipcc.ch
Global carbon atlas – current country by country carbon dioxide and methane emissions
http://www.globalcarbonatlas.org/en/CO2-emissions
Warming stripes https://showyourstripes.info and https://www.climate-lab-book.ac.uk
State of the Climate https://www.ametsoc.org/index.cfm/ams/publications/bulletin-of-the-american-meteorological-society-bams/state-of-the-climate/
Carbon Brief https://www.carbonbrief.org
Real Climate http://www.realclimate.org