Understanding global warming – The greenhouse effect and climate change

What's causing the global temperature to rise?

The fact that the warming trend over the past 50 years of 0.13°C per decade is nearly twice as high as that over the past 100 years is indisputable. In 2015, the global temperature increase was 0.85°C compared to the preindustrial level.

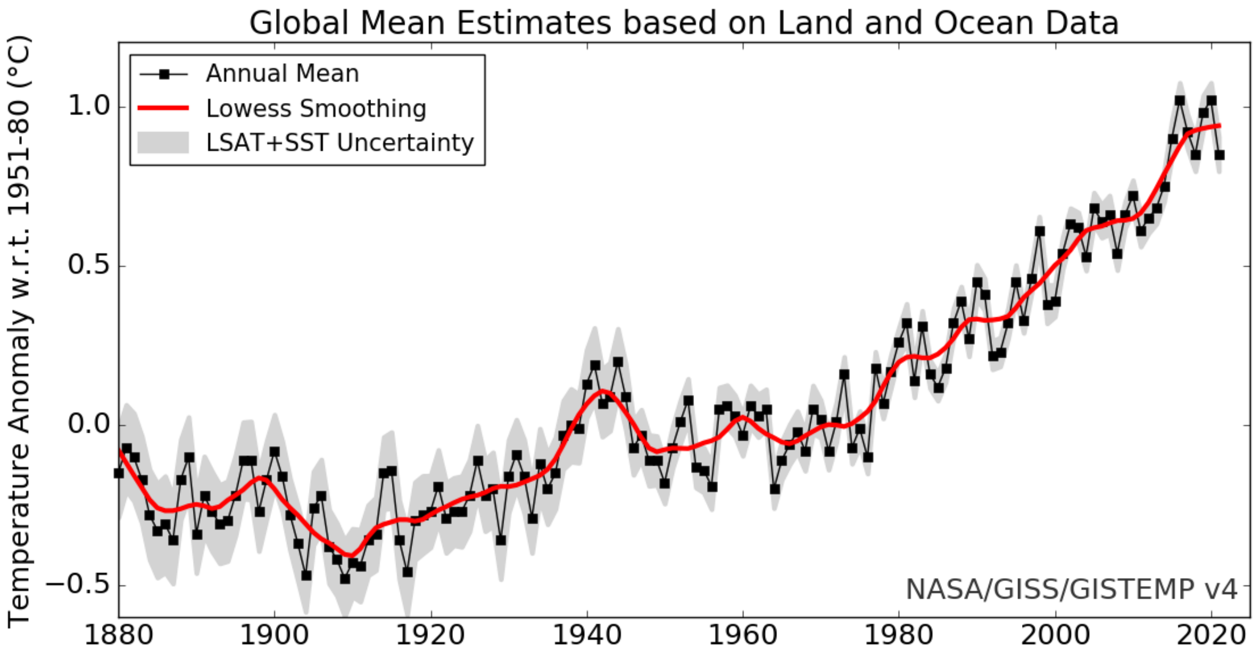

Fig. 1: Global land–ocean temperature index

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Critics of the anthropogenic (man-made) climate change theory say that there have always been very wide temperature variations in the Earth's climate history. These critics say that these variations occurred long before humankind could even influence the climate, for example, due to fluctuations in solar activity. However, we now have precise knowledge of the climate profile on Earth over the past 50,000 years.

Based on the study of sediments, tree growth rings, and ice core samples, we can trace the temperature profile of approximately the past 50,000 years precisely down to the individual year. Admittedly, the results show that a large number of wide temperature changes have taken place even without any human involvement. However, these temperature changes all occurred relatively rapidly within just a few years.

In contrast, a previously unprecedented continual warming has taken place over the past 150 years. This warming occurred in parallel with industrialization and the increase and intensification of agriculture and the associated increased production of greenhouse gases (such as CO_2, CH_4, N_2O, and others), as a comparison of Figures 1 and 2 shows. The existing data thus leave no doubt that climate change is caused by humans.

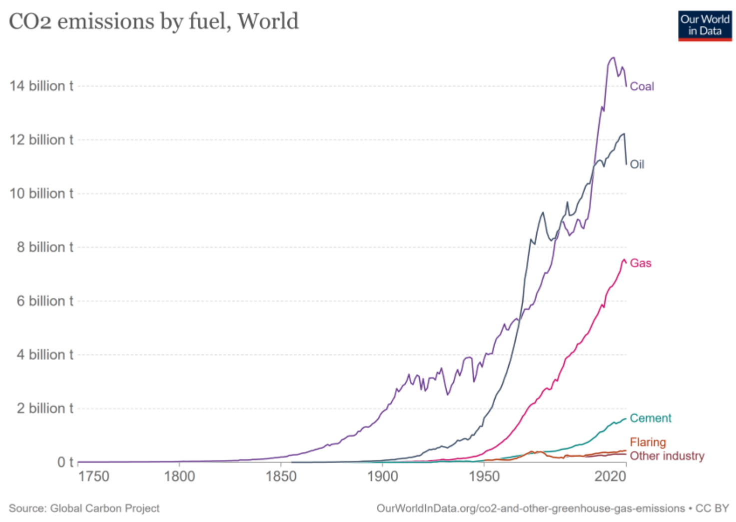

Fig. 2: Global CO_2 emissions due to fossil fuels from 1750 to 2020.

Graphic: Our World in Data; https://ourworldindata.org/emissions-by-fuel; License: CC BY

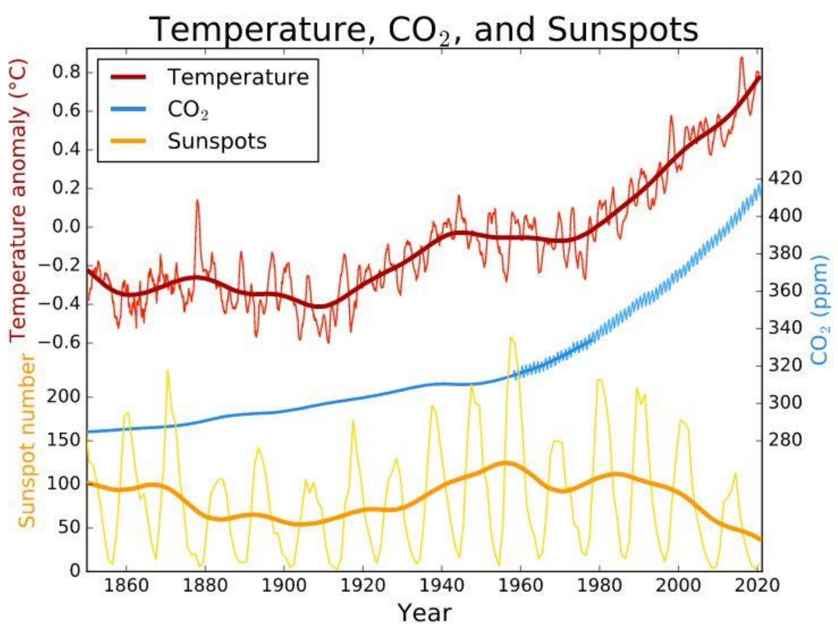

Fig. 3: Global average temperature, atmospheric CO_2, and sunspot activity since 1850. Thick lines for temperature and sunspots represent a 25 year LOWESS and moving average smoothing of the raw data.

By Leland McInnes at the English-language Wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=6696694;

Also, the assertion that climate change has come about due to fluctuations in solar activity does not hold up, as Figure 3 shows.

What is meant by the term "climate inertia"?

If it were possible to stop all our greenhouse gas emissions all at once, the temperature on Earth would stabilize but not drop, since the natural removal process in the atmosphere takes centuries to millennia.
Sea levels would also continue to rise, since oceans have warmed more slowly than the rest of Earth and the water thus will continue to expand until temperatures have equalized.

This means that it is possible to reduce the global temperature to the preindustrial level only by actively removing CO_2 from the atmosphere (for example, through reforestation or by filtering CO_2 from the air).

What significance does the so-called 1.5-degree target have?

At the 2015 Climate Change Conference in Paris, 195 countries adopted a climate agreement, pledging to limit global warming preferably to 1.5°C, that is, well below 2°C. While limiting global warming to 1.5°C is currently still possible, it necessitates swift, decisive action.
The 1.5-degree target can be achieved only if continuous major efforts to drastically reduce greenhouse gas emissions are undertaken around the world and in all sectors of the economy in the coming decades.

What influences the local climate, apart from the global climate?

Local temperature differences on Earth constantly produce air and ocean currents between warmer and cooler regions. For instance, due to the warm Gulf Stream, the climate in Central Europe is now warmer than the geographical location would predict. However, if the Gulf Stream were to slow down due to the warming of Europe, it could become even colder in Europe. The Gulf Stream is thermohaline, which means it is driven by the differences in the temperature and salinity.

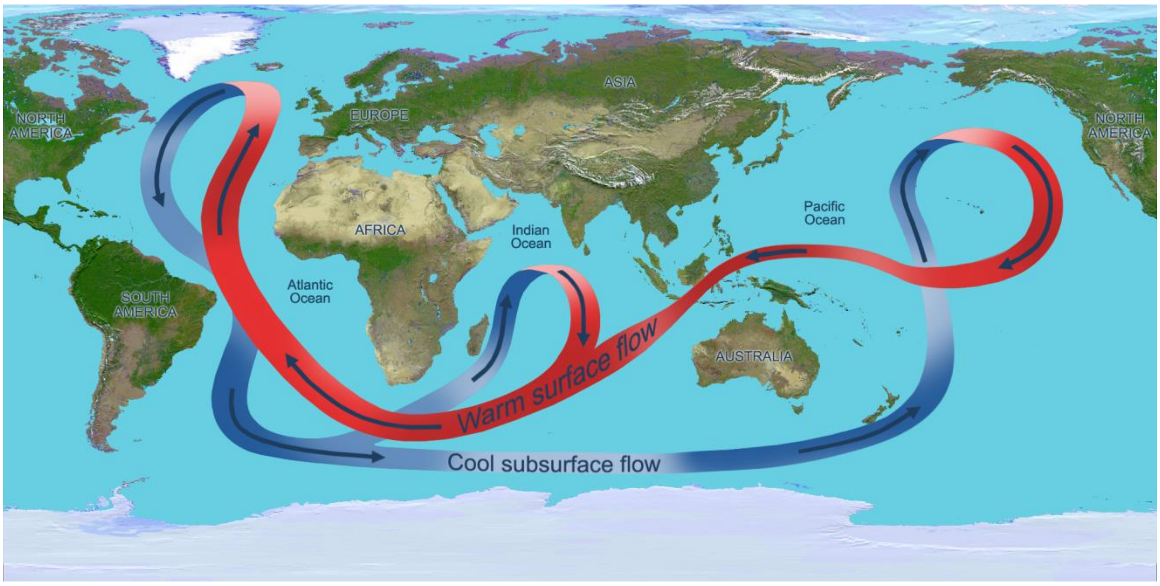

Fig. 4: The “global thermohaline conveyor belt.” The overturning circulation of the global ocean. Throughout the Atlantic Ocean, the circulation carries warm waters (red arrows) northward near the surface and cold deep waters (blue arrows) southward.

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Growing glaciers – doesn’t that contradict climate change?

Glaciers in the Alps, South America, and the Himalayas are melting, but they are growing in New Zealand. This trend is not a contradiction to global warming, since the higher ocean temperatures around New Zealand generate more water vapor and thus increase cloud formation. These clouds are transported long distances by the air currents. That is why it snows more than before high in the mountains (above 3,000 m) in New Zealand, and glaciers are growing there.

In contrast, the glaciers are melting in Greenland, and the Arctic ice cap is thinning and shrinking. The ice cover at the edge of Antarctica is currently melting, but it is growing in the interior of Antarctica due to heavier snowfall.

The greenhouse effect and its causes

The greenhouse effect is thought to be the cause of global climate change. But what exactly is this greenhouse effect? The greenhouse effect is falsely represented as something that is essentially negative. Before we begin, we therefore need to set the record straight and point out that without the natural greenhouse effect, life would not be possible on Earth at all. That's because without the greenhouse effect, that is, without the atmosphere, the average temperature of Earth's surface would be only -18°C instead of 15°C. We therefore make a distinction between the natural greenhouse effect and the greenhouse effect caused additionally by humankind – the anthropogenically intensified greenhouse effect.

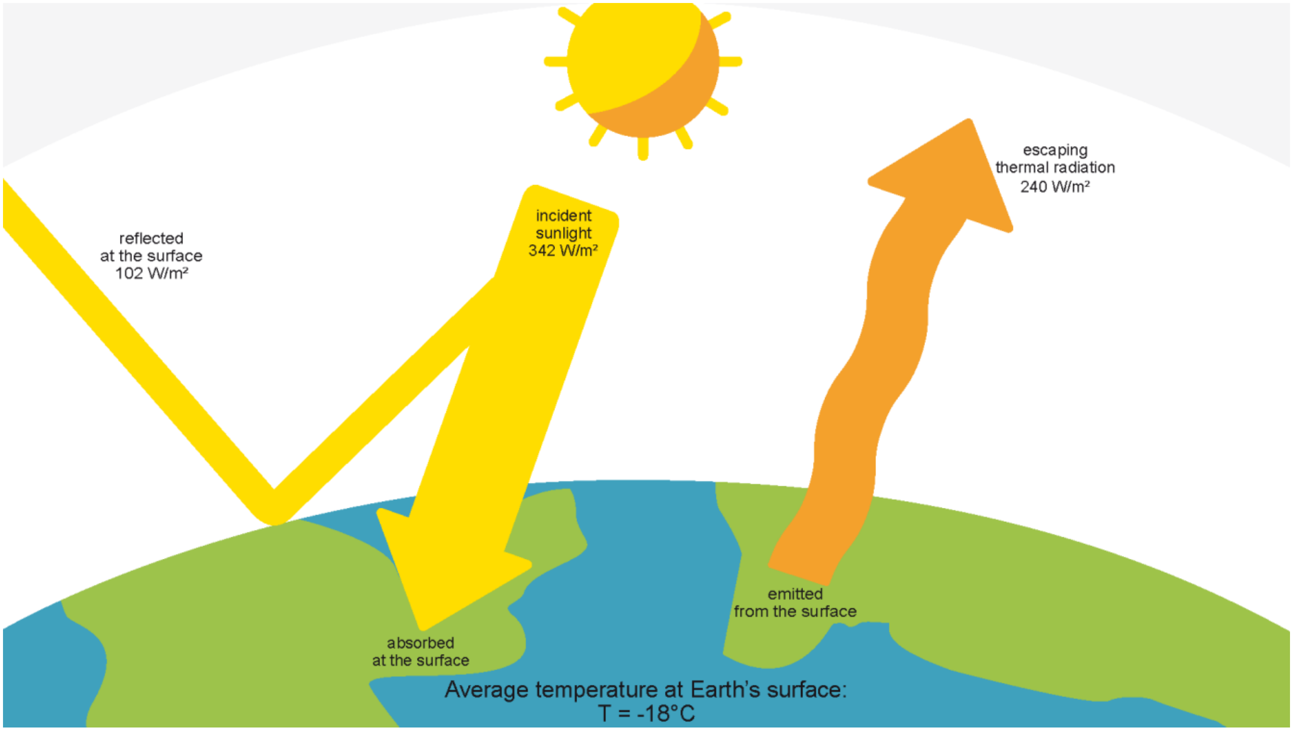

Fig. 5: Without the greenhouse effect, Earth's surface temperature would be –18°C.

Let's first imagine Earth without its envelope of gases, clouds, and dust. Earth would then be an "unprotected" sphere exposed to the sunlight that would heat up until a particular temperature was reached. The fact that this temperature doesn't continue to climb is based on the concept of "radiative equilibrium": Once the globe reaches a particular temperature, it gives off exactly as much energy per unit of time as it takes in; the radiation power is equal to the irradiation power. We see in the graphic (Fig. 5) that the sum of the radiation directly reflected by Earth's surface (102 W/m^2) and the power radiated again by Earth's heated surface (240 W/m^2) is just as great as the radiation received from the sun (342 W/m^2).

How is it that Earth's surface is as warm as 15°C?

As mentioned above, according to the law of radiative equilibrium, 100 percent of the energy radiated to Earth from the sun must be radiated back from Earth. Why is Earth's temperature nevertheless increasing?

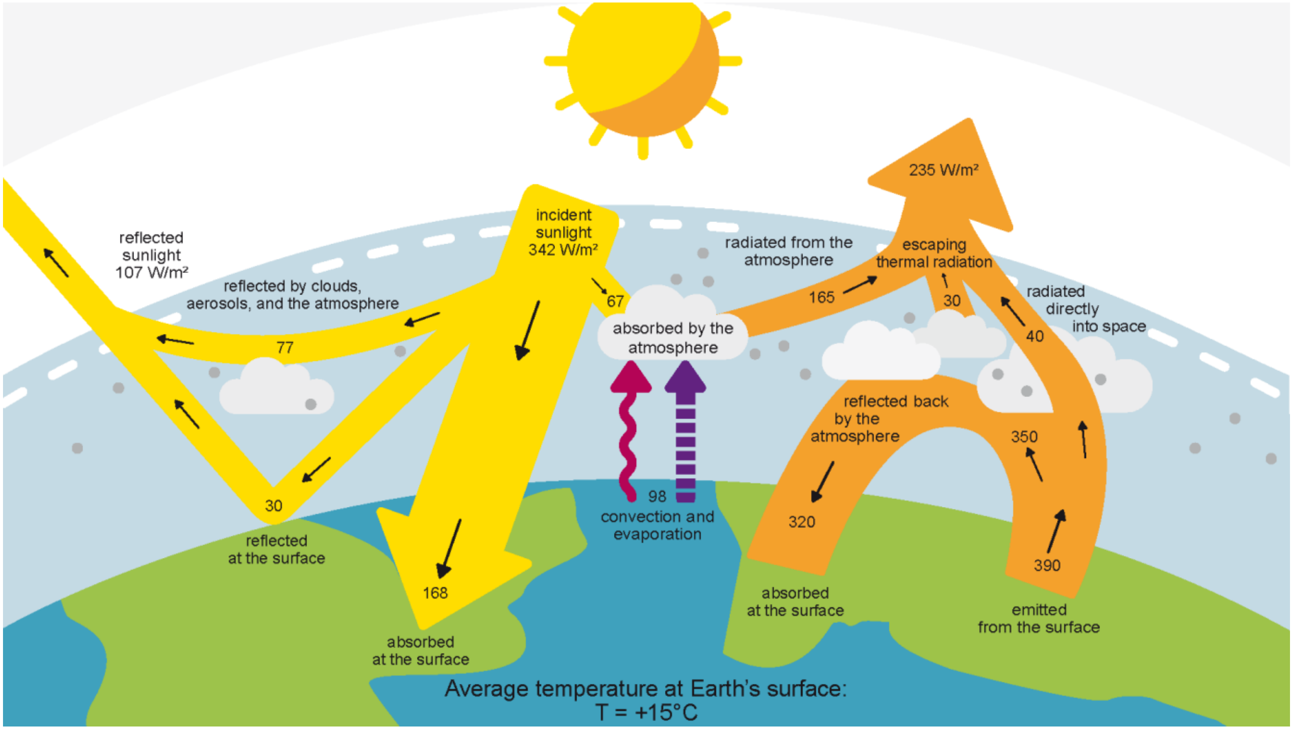

Fig. 6: The global radiation budget of Earth.

In somewhat simplified terms, that can be explained as follows:

Solar radiation

- Due to the high temperature of the sun's surface of approximately 6,000°C, the sunlight reaching Earth has relatively short wavelengths (mainly UV to near IR).
- When the sunlight reaches Earth's atmosphere, approximately 22 percent is directly reflected back into space. Most of the light (70 percent) penetrates the atmosphere because practically none of the radiation with these short wavelengths is absorbed in the atmosphere (CO_2, CH_4, N_2O, and other gases do not absorb radiation with short wavelengths). Only certain aerosols, ozone, as well as soot and ash particles absorb energy in this short-wavelength range (just under 20 percent).
- At Earth's surface, approximately 9 percent is reflected and goes from there back into space. The remaining 50 percent is absorbed by means of conversion of the radiant energy of light to thermal energy (= movement of the smallest particles of the material).

Convection and evaporation

- Approximately 58 percent of the thermal energy stored in Earth's surface is transported back to the atmosphere by heated layers of air that rise (convection) and water that evaporates (evaporation).

- These heated layers of air and cloud emit radiation in the long-wavelength range, of which a relatively large portion returns toward Earth's surface ("back radiation").

Reradiation by Earth's surface

- Earth's surface directly radiates 42 percent of the stored thermal energy. However, compared to the sun, Earth's surface temperature is very low, so its radiation has an extremely long wavelength (far IR).
- A substantial portion of this long-wavelength radiation is absorbed by the many gases in the atmosphere (H_2O, CO_2, CH_4, N_2O, etc.).

Back radiation of the atmosphere

- The heated* gas molecules emit absorbed radiation, of which a substantial portion returns toward Earth's surface ("back radiation").
  * The heat is stored as kinetic energy, in the form of molecular vibrations and rotations.

Increase in Earth's temperature due to formation of warm layers near the surface

- As a result, Earth's surface remains warm due to the formation of heated layers above its surface. However, except for the energy consumed in photosynthesis, over 99.99 percent of the radiation is emitted back to space (due to conservation of energy and radiative equilibrium).

Reflection does not explain the greenhouse effect!

It is common to come across incorrect explanations that attribute the greenhouse effect to reflection. But as we have seen, the greenhouse effect is essentially caused by greenhouse gas molecules absorbing the long-wavelength radiation emitted by Earth. In conjunction with the warm molecules transported through convection and evaporation, the reradiation (not the same as reflection!) by these molecules causes back radiation to Earth and the formation of heated layers close to Earth.
The atmosphere thus does not reflect the radiation emitted by Earth's surface, but rather it absorbs this radiation and emits it back.
In the physics of electromagnetic waves, reflection (Latin reflectere = to bend back) means bouncing back/reflecting waves at a boundary. In contrast, in absorption the energy form is converted. If a body heated by absorption then emits radiant energy, we speak of reradiation and not of reflection.

The man-made greenhouse effect

Rise in Earth's temperature due to the increase in greenhouse gases

Greenhouse gases thus do not produce energy. Rather, they help maintain an equilibrium at a level that keeps the atmospheric layer near the ground – the layer in which we live – warm enough to sustain life. If human activities increase the concentration of greenhouse gases in the atmosphere, absorption increases, leading to an increase in back radiation, which in turn leads to a rise in the temperature of the layers near the ground.

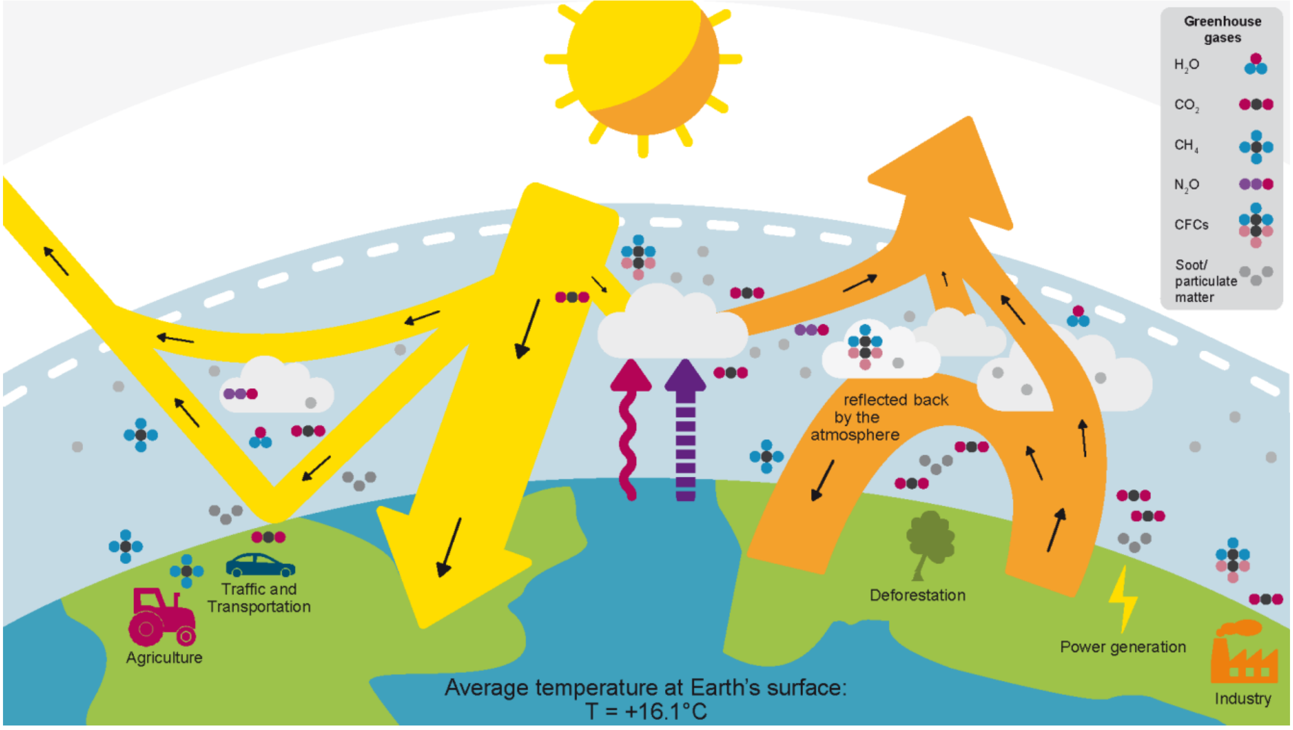

Fig. 7: Rise in Earth’s temperature due to man-made greenhouse gases

What gases contribute to the greenhouse effect?

Naturally occurring gases such as water vapor (H_2O), carbon dioxide (CO_2), and methane (CH_4) absorb the heat radiated by the Earth’s surface and intensify the counter-radiation that is bounced back to Earth. With gases in particular, the emission and absorption capacities depend greatly on the wavelength of the radiation. Three major greenhouse gases, water vapor, CO_2, and CH_4, are particularly capable of absorbing energy that is reradiated. Oxygen (O_2) and nitrogen (N_2) are the two main gases that make up approximately 99 percent of the atmosphere. They do not have any emission and absorption capacity in the long-wavelength thermal radiation range that is important in terms of Earth’s energy.

In terms of quantity, water vapor naturally contributes by far the most (approximately two-thirds) to the greenhouse effect. This is followed by CO_2 with a proportion of approximately 15 percent, O_3 with around 10 percent, and finally nitrous oxide (N_2O) and CH, each at around 3 percent. For a precise calculation of the proportions, the influence of clouds and of floating particles such as dust and aerosols on the solar and thermal radiation would also need to be known.

For example, the ash particles released by a strong volcanic eruption and the SO_2 concentration in the atmosphere can cause Earth’s temperature to drop over several years due to the shielding of Earth’s surface from the sunlight. Such volcanic eruptions have happened many times in Earth’s history.

The physics of the greenhouse effect in detail

Incident radiation power

The radiative equilibrium explained above results in the Earth's surface temperature, which in turn can be calculated based on the Stefan-Boltzmann law:

$$S_E = \sigma \cdot T^4 \Rightarrow T = \sqrt[4]{\frac{S_E}{\sigma}}$$

S_E is the radiation density in W/m^2. The density of solar radiation on Earth's orbit around the sun is 1,370 W/m². Because this cosmic radiation does not act on Earth's spherical surface ($4 \cdot \pi \cdot r^2$) but on its cross section ($\pi \cdot r^2$), the incident radiation density, relative to Earth's spherical surface, is calculated as follows:

$$1{,}370 \cdot (\pi \cdot r^2)/(4 \cdot \pi \cdot r^2) = 342 \text{ W/m}^2.$$

According to the Stefan-Boltzmann law, the resulting surface temperature of Earth without an atmosphere would be –18°C. Without any further warming effect, Earth at a temperature of –18°C would be uninhabitable for humans.

The physics of greenhouse gases

In molecules, the strength of the bonding forces between the atoms and the change in the bonding forces during vibration determine the wavelength range in which energy is absorbed. Long-wavelength thermal radiation can be absorbed only by those molecules that consist of several types of atoms and that change their dipole moment during vibration. Diatomic nonpolar gases such as O_2 and N_2 can execute only symmetrical vibrations without changing the dipole moment. Triatomic carbon dioxide carries out both symmetrical and asymmetrical vibrations. These are stimulated by thermal radiation in the range 4.3 µm to 15.3 µm – a range that overlaps well with the radiation spectrum of Earth's warmed surface, which goes from approximately 3 µm to 60 µm. In this context, the CO_2 concentration in the atmosphere is particularly significant.

The “Experimento | 10+: B2 Greenhouse effect in a drinking cup” media package available on the Siemens Stiftung Media Portal includes experimentation instructions for an experiment that makes climate change tangible based on a model.
Other applications of the greenhouse effect in technology and everyday life: Practical applications of the greenhouse effect include greenhouses and energy-saving houses. Other phenomena include, for example, that in the winter, a car parked in the sun can heat up nicely on the inside despite freezing temperatures, or that clear winter nights are colder than cloudy nights.