Greenhouse effect and climate change

What's causing the increase in the global temperature?

The fact that the warming trend over the last 50 years of 0.13 K per decade is nearly twice as high as that over the last 100 years is indisputable. In 2015, the global temperature increase reached 0.85 K.

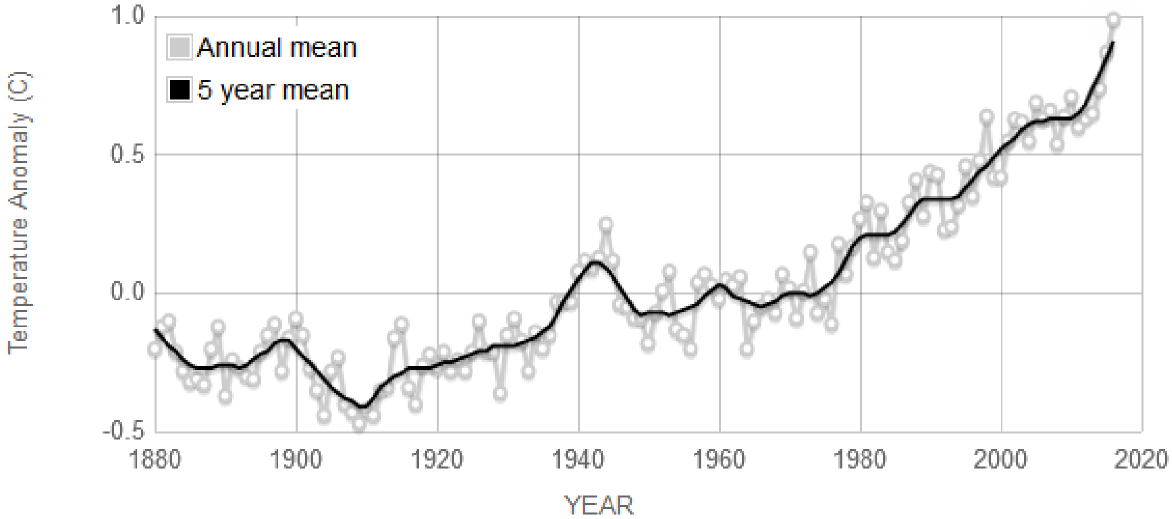

Fig. 1: Global land–ocean temperature index

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Critics of the anthropogenic (man-made) climate change theory say that there have always been very wide temperature variations in Earth's climate history, long before humankind could even influence the climate. However, we now have precise knowledge of the climate profile on Earth over the last 50,000 years.

Based on the study of sediments, tree growth rings, and ice cores, we can trace the temperature profile of approximately the last 50,000 years to one year exactly. 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 last 150 years. This occurred in parallel with industrialization and the increase and intensification of agriculture and the associated increased production of CO_2, CH_4, N_2O, and other man-made gases, which can be viewed as evidence of man-made climate change.

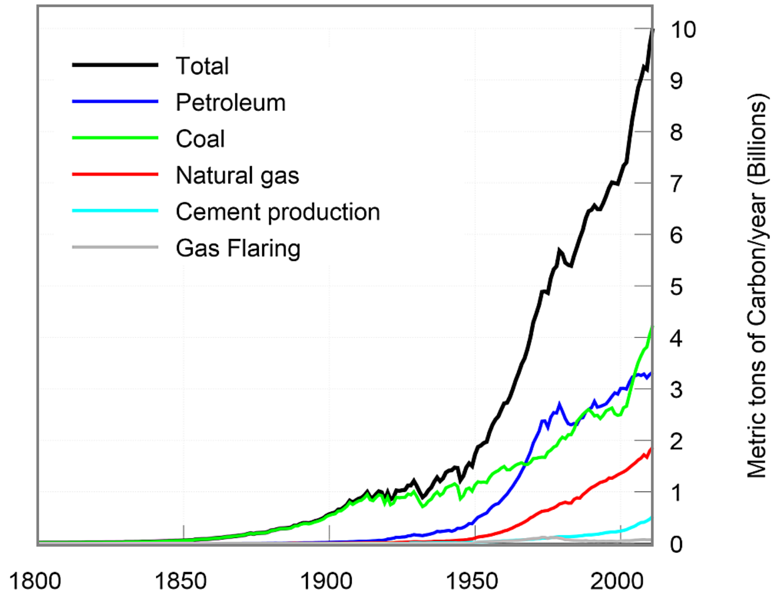

Fig. 2: Global CO_2 emissions due to fossil fuels from 1800 to 2007

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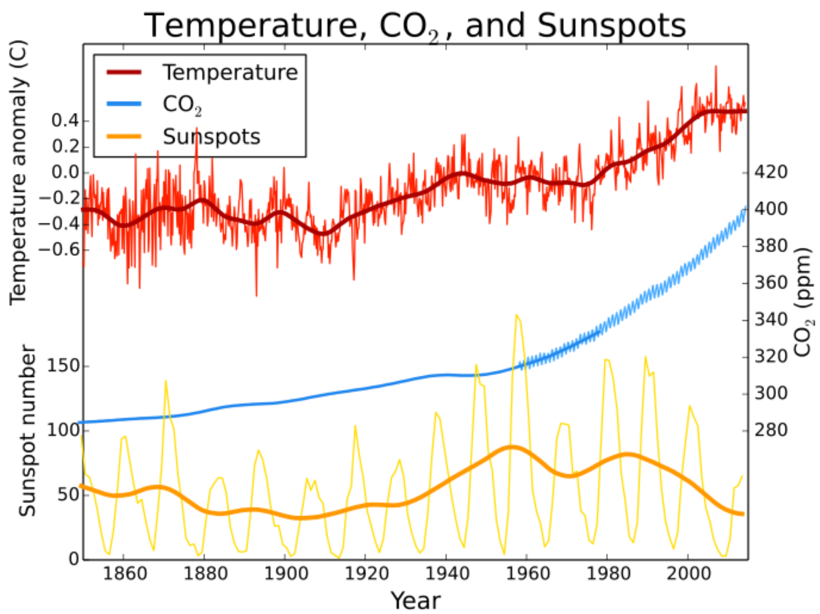

Fig. 3: This graph shows the average temperature, atmospheric CO_2, and sunspot activity since 1850. The thick lines for temperature and sunspot activity represent a smoothing of the raw data (25-year moving average).

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

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

Local temperature differences on Earth constantly give rise to 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, that is, it is kept going by the differences in the temperature and salinity.

Previously, the weather in Germany was primarily determined by west and east air currents. The fact that the weather in Germany has increasingly been determined by north and south currents for some years now, unlike in the past, is often explained as the result of changes in the Arctic Ocean water temperatures.

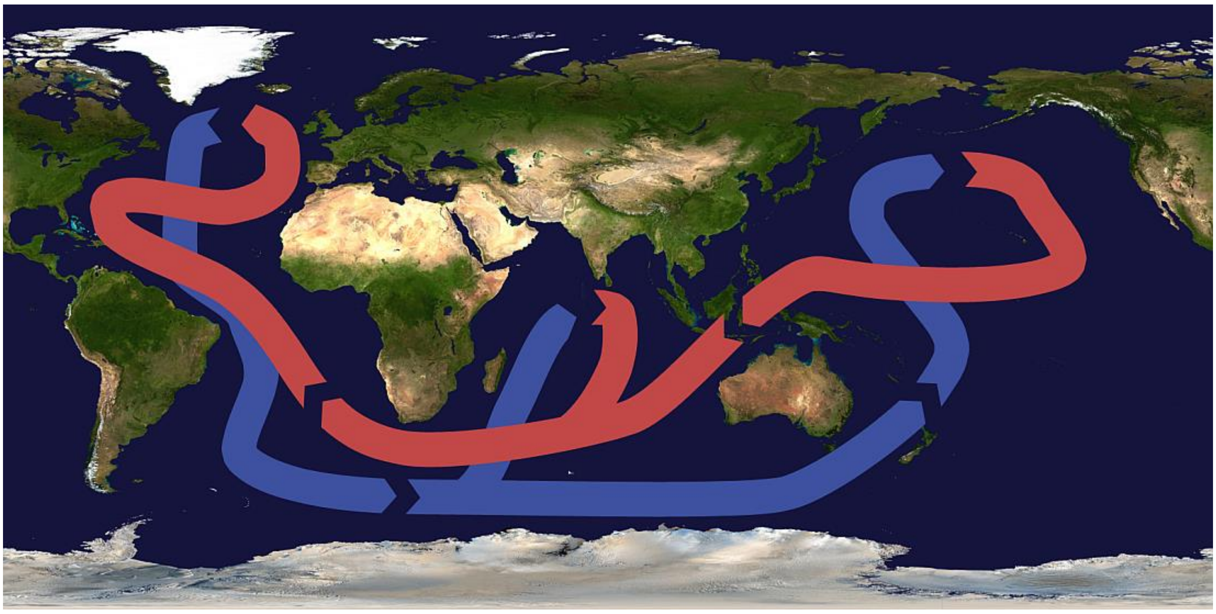

Fig. 4: The “global thermohaline conveyor belt”

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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 increased 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. Therefore, before we begin, we need to set the record straight and point out that without the greenhouse effect, life wouldn’t 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! We therefore make a distinction between the natural greenhouse effect and the greenhouse effect caused additionally by humankind – the anthropogenically enhanced greenhouse effect.

Earth's temperature without the atmosphere

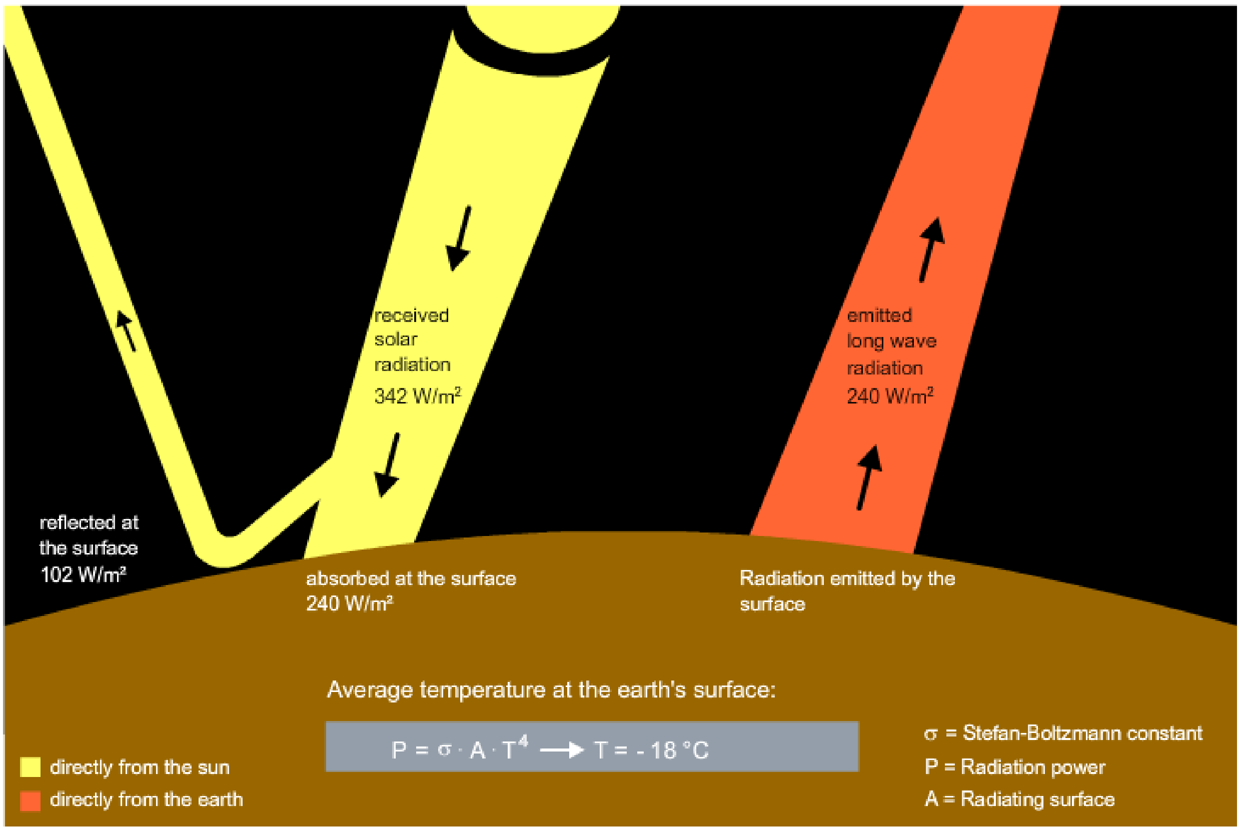

Fig. 5: Without the greenhouse effect, Earth's surface temperature would be –18°C.

Let's first imagine Earth without its envelope of gases, clouds, and dust. The 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 per unit of time; 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).

This temperature of Earth's surface, which corresponds to the radiative equilibrium, can be calculated according to 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 the 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 received 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.

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?

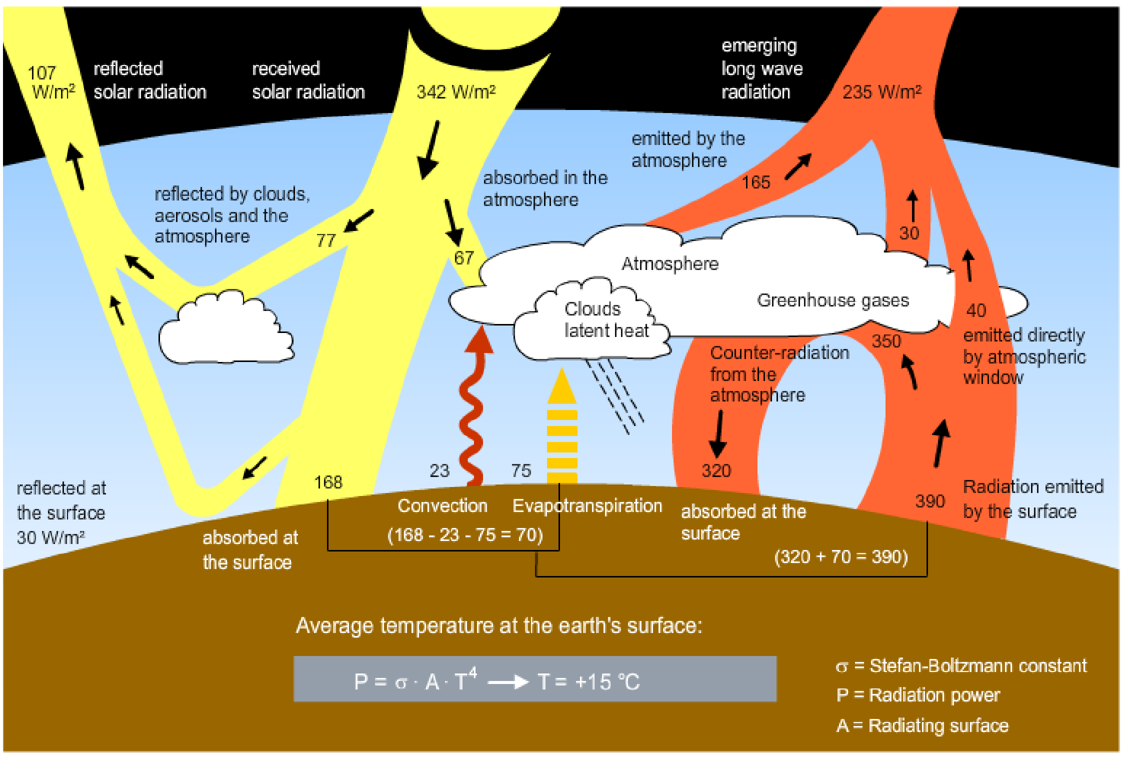

Fig. 6: The global radiation budget of Earth

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 wavelength (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 through the atmosphere because practically none of these short wavelengths are absorbed in the atmosphere (CO_2, CH_4, N_2O, and other gases do not absorb short wavelengths). Only certain aerosols as well as soot and ash particles absorb in this short-wave 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 evapotranspiration

- Approximately 58 percent of the thermal energy stored in Earth's surface is transported back to the atmosphere by convection (rising of heated layers of air) and evapotranspiration (evaporating water).
- These heated layers of air and cloud emit radiation in the long-wave 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. But 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-wave radiation is absorbed by the many gases in the atmosphere. That's because the absorption bands of H_2O, CO_2, CH_4, N_2O, etc. lie precisely in the wavelength range of the radiation from Earth's surface (for example, the maximum absorption of CO_2 occurs at approximately 15 µm).

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 like vibration and rotation.

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's common to come across incorrect explanations that attribute the greenhouse effect to reflection. But as we have seen, the greenhouse effect is essentially based on the absorption by the

greenhouse gas molecules of the long-wave radiation emitted by Earth. In conjunction with the warm molecules transported through convection and evapotranspiration, 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 off 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

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

Greenhouse gases do not produce energy in this sense. Rather, they help maintain an equilibrium at a level that keeps the atmospheric layer near the ground – in which we live – warm so that it's "friendly to life." If human activities increase the concentration of greenhouse gases in the atmosphere, absorption increases, leading to an increase in back radiation and an increase in the temperature of the layers near the ground.

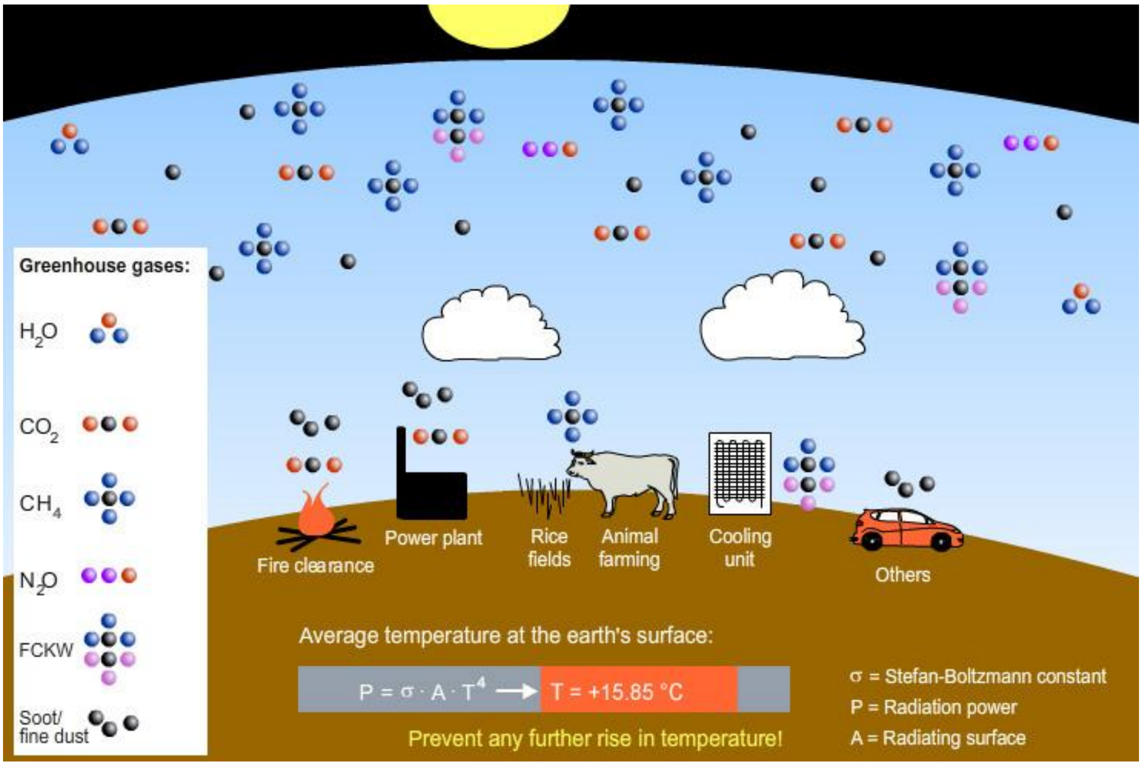

Fig. 7: Increase in Earth's temperature due to man-made greenhouse gases

The physics of greenhouse gases

In molecules the strength of the bonding forces between the atoms and their change during vibration determines the wavelength range in which energy is absorbed. Long-wave 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 heat 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.

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 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. This is particularly true in the case of the three major greenhouse gases water vapor, CO_2, and methane. 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-wave heat radiation range that is important in terms of Earth's energy.
In terms of quantity, water vapor naturally contributes 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 volcano 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. This has happened many times in Earth's history.

See also the "Where do greenhouse gases come from?" information sheet on the sources, effectiveness, and lifetime of man-made greenhouse gases. See also the "Development of greenhouse gas emissions" information module on the increase in greenhouse gas emissions. The two media are available on the media portal of the Siemens Stiftung.

Greenhouse effect in a drinking cup as a model of the greenhouse effect in Earth's atmosphere

This experiment uses a transparent drinking cup made of PET. First the cup is placed in sunlight empty and with the lid off; then the cup is covered with the lid and lined halfway with black cardboard.
In the second case, the temperature will rise considerably more.

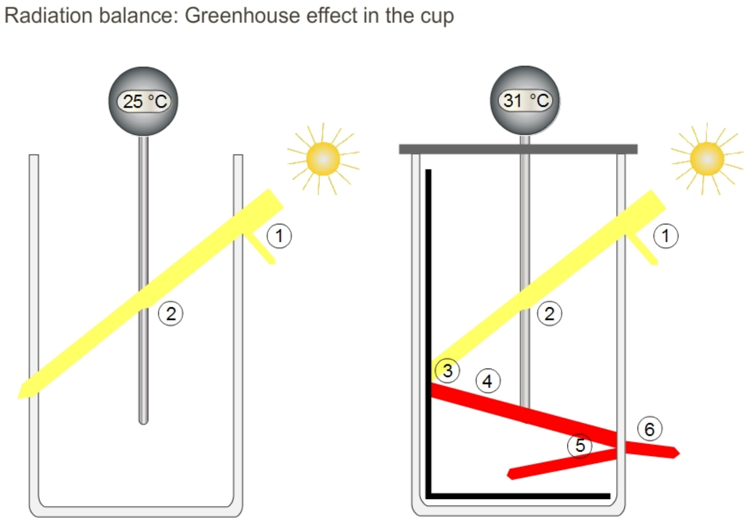

Fig. 8: Greenhouse effect in the cup

Image legend

1. Reflection at the container's wall
2. Absorption by the probe
3. Absorption by the black cardboard
4. Long-wave radiation from the black cardboard
5. Absorption and reradiation by the container's wall
6. Radiation by the container's wall to the surroundings

In the experiment, energy is introduced into the climate cup in the form of radiation, but energy output of the cup's contents through radiation is "restricted". Why is this so? It's easiest to understand this if the process is observed in several stages.

Short-wave irradiation: Sunlight shines at a temperature (= color temperature; see Planck's radiation curve) of up to 6,000 K, a halogen light bulb at a temperature of up to 3,400 K. Compared with far infrared, these two sources of light mainly correspond to ultra-short-wave radiation of approximately 250 nm to approximately 1,000 nm (thus UV light, visible light, and near infrared). Almost 100 percent of this short-wave radiation goes through the sides of the plastic cup without being absorbed. This is similar for Earth's atmosphere, which allows nearly two-thirds of the irradiated sunlight to pass through (approximately one-third is reflected).

Absorption in the cup: If material such as black paper is in the cup, it will absorb nearly 100 percent of the short-wave light and will warm up as a result. (The same is true for Earth's surface.)

Long-wave reradiation of the absorber paper: The absorption material is warmed up to approximately 310 K. It then emits some heat into the air inside the cup through collisions of its smallest particles. It also emits absorbed radiation. Due to the low temperature, the spectrum of emission of the heated air and of the absorber paper covers only wavelengths of several µm in the long-wave infrared range.
(When Earth's surface is heated up, it also emits its warmth primarily through radiation. However, a substantial portion is transported away through convection, that is, air and water vapor that is heated by Earth's warm surface rise upward and transport heat away. We experience this effect in our cup, but we inhibit it with the lid.)

Reflection, absorption, and reradiation by the container's wall: The long-wave radiation is partially reflected, partially absorbed by the cup's surface. The surface is heated up through this

absorption, and it radiates part of the energy back into the inside of the cup and part into the environment outside of the cup. As a result of direct reflection on the cup surface and emission of the heated cup surface, the emission of energy is halted and the inside of the cup remains warmer than the environment. Thus, the inside of our cup cannot emit radiant energy directly to the environment, because only a small part of this energy can penetrate the cup's surface.
(The same effect occurs with Earth's surface: Part of the energy radiated from Earth's surface is absorbed in the clouds and the gas particles in the air. These clouds and particles radiate only part of the energy into space and the rest back to Earth again. This reflection significantly helps to increase Earth's temperature. It is even stronger if proportionately more gases that absorb radiation in the long-wave range, such as CO_2, are present in the atmosphere.)
However, we must note that in our experiment setup, a considerable amount of heat is lost not through radiation, but through convection inside on the cup's surface and through direct heat conduction through the cup's surface.

Other applications of the greenhouse effect in technology and everyday life: Practical applications of the greenhouse effect include greenhouses and energy-saving houses. Another phenomenon is, 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.