

Greenhouse gases

- and their impact on the climate

The greenhouse effect is the best understood and well mapped of the mechanisms that can lead to climate change.

By Eigil Kaas and Peter L. Langen

■ Our planet's climate is largely determined by the balance between the energy supplied by sunlight and the energy that Earth loses to space in the form of infrared radiation.

Satellite measurements show that the solar energy irradiating Earth is about 342 Watts per square meter (W/m^2). This figure is an average over the entire planet, day and night, all year around. It therefore spans from zero W/m^2 at night when the satellite is in Earth's shadow, to approx. $1367 \text{ W}/\text{m}^2$ in places where the sun is at its zenith. Approximately 31% of the incoming solar radiation is reflected by clouds and atmospheric particles and the planetary surface. This is also referred to as the planetary albedo, where albedo is an index of reflectivity from 0 (no reflectance) to 1, (full reflectance). The planet thus has an albedo of 0.31. The reflected radiation can be seen from satellites as upward going



A snow-covered surface reflects massive amounts of sunlight and therefore has a cooling effect on the climate.

Photo: Peter Langen

light. In itself it has no effect on the climate system, but the 69% of solar radiation that remains does have an impact: The remaining $236 \text{ W}/\text{m}^2$, are the ones which warm our planet and its atmosphere.

Greenhouse effect

Earth loses the absorbed solar energy by emitting infrared radiation, or Planck radiation. It is known from physics (Stefan-Boltzmann Law) that the total energy emitted by a so-called black body (an excellent approximation in many applications) is proportional to a body's temperature to the fourth power. Over a long period, Earth on average emits just as much energy as it receives in the form of solar radiation, i.e. approx. $236 \text{ W}/\text{m}^2$. One can make a simple energy balance calculation, using the Stefan-Boltzmann Law, of what the temperature on Earth must be to maintain equilibrium between incoming and outgoing radiation (see box). Such a calculation results

Energy balance and climate sensitivity:

The Stefan-Boltzmann law says that the total energy emitted by a so-called black body is directly proportional to the fourth power of its absolute temperature:

$$E = \sigma T^4$$

Where E is the total energy radiated per unit area per unit time measured in W/m^2 , σ is the Stefan-Boltzmann constant ($5,67 \times 10^{-8} W/m^2/K^4$) and T is absolute body temperature measured in Kelvin.

By inserting $236 W/m^2$ on the left side of the equation (i.e. the amount of energy the earth radiates averaged over time) we find that Earth should have a temperature of $254 K$ (about $-19^\circ C$). This is Earth's effective temperature, T_E . That the actual temperature is higher is due to the greenhouse effect.

Simple calculation of climate sensitivity

As mentioned in the text climate sensitivity (λ) was introduced as an estimate of how large the change in global average temperature near the surface (ΔT_s) is as a function of a given energy input, i.e. forcing, ΔF , for example, as a result of increased atmospheric CO_2 content or a change in solar radiation. Thus we have the following relation:

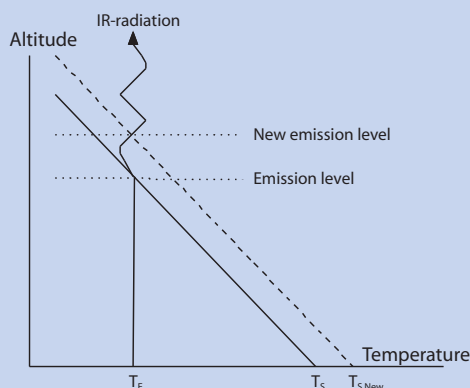
$$\Delta T_s \approx \lambda \Delta F$$

λ tells us how many degrees global temperature near the surface will increase if a change in the forcing of $1 W/m^2$ is produced.

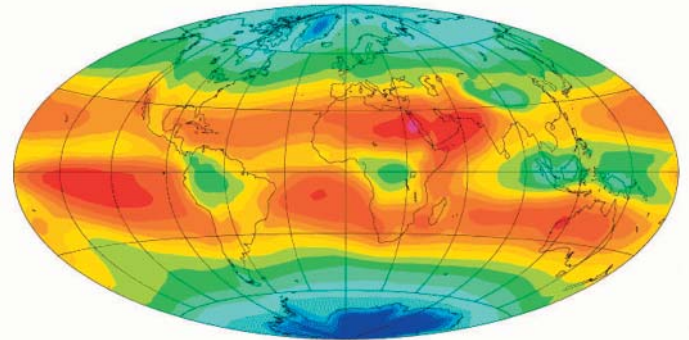
The easiest way to estimate λ is by calculating the ΔT_s -value required for upward infrared radiation to equal a given ΔF -value, i.e.:

$$\sigma(T_E + \Delta T_s)^4 - \sigma T_E^4 = \Delta F \text{ or } \Delta T_s = \sqrt[4]{\frac{\Delta F + \sigma T_E^4}{\sigma}} - T_E$$

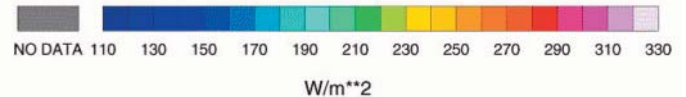
Inserting a forcing of ΔF of $1 W/m^2$ produces a $\Delta T_s = 0.269 K$ and thus a sensitivity of $\lambda = \Delta T_s / \Delta F = 0.269 K/(W/m^2)$. A λ -value of 0.269 is very (actually too) small, since we have not included the significance of feedback mechanisms.



Schematic illustration of the enhanced greenhouse effect. When incoming and outgoing radiation are in equilibrium, emission levels have the effective temperature, T_E . Following the temperature curve we obtain the surface temperature, T_s . If the amount of greenhouse gas emissions is increased and the atmosphere becomes "denser" (as seen from an infrared perspective), the level of radiation is moved upwards, whereby the atmosphere radiates from a colder temperature and hence with a lower intensity as well. The system is now no longer in balance, and it will warm up to the new emission level T_E , and the surface level thereby rises to $T_{s, new}$.



Credit: NASA



Satellite measurements of long wave radiation from the Earth Radiation Budget Experiment. The subtropical areas which have very dry air and few clouds are characterized by having a very high emissivity, since radiation originates from hot layers in the lower atmosphere. Along the equator, where there is more humidity, rising air and many high clouds, we find areas with very low emissivity, since part of the radiation comes from high and cold clouds. For instance, the mean annual radiation in Indonesia is about the same as in northern Norway. Clouds and water vapor move radiation levels up in the colder atmospheric layers, and radiation does therefore not directly reflect the actual surface temperature.

in a temperature of $254 K$ (about $-19^\circ C$), which is Earth's effective temperature (T_E). This temperature is some $34^\circ C$ lower than Earth's actual average surface temperature (T_s) which averages $+15^\circ C$. Since this energy balance calculation offers such an erroneous estimate of Earth's surface temperature, it is evident that a very effective heat preserving mechanism has been omitted. This mechanism is the greenhouse effect. Thus, the greenhouse effect is essential to life as we know it to be able to exist on Earth.

The mechanism behind the greenhouse effect

Our calculation of the effective temperature of Earth is an excellent starting point for understanding the greenhouse effect. Some of the gases that make up our atmosphere, for example, water vapor, carbon dioxide and methane, and some types of clouds are able to absorb some of the upward infrared radiation reflected by the planet's surface. When these gases and clouds lose the absorbed radiation it is emitted in all directions as

Planck radiation, i.e. half of the energy is emitted towards the surface and the other half into space. That means that, from a space perspective, Earth does not emit infrared radiation from its surface, but rather from the greenhouse gases and from the clouds in the atmosphere. Since the atmospheric temperature decreases the higher we get, greenhouse gases and cloud droplets, which are the same temperature as the surrounding atmosphere, emit lower temperature radiation than the planet's surface. Due to the greenhouse effect, the radiation that Earth and its atmosphere emit to balance the incoming solar radiation stems from higher and colder atmospheric layers, thereby allowing the surface to be warmer than it would otherwise have been. On average, this is the precise level at which the temperature is the effective temperature of $254 K$ (at a height of some $5 km$). From this level temperatures approximately increase by 6.5 degrees per km as we move downwards in the atmosphere and we can thus determine what the temperature

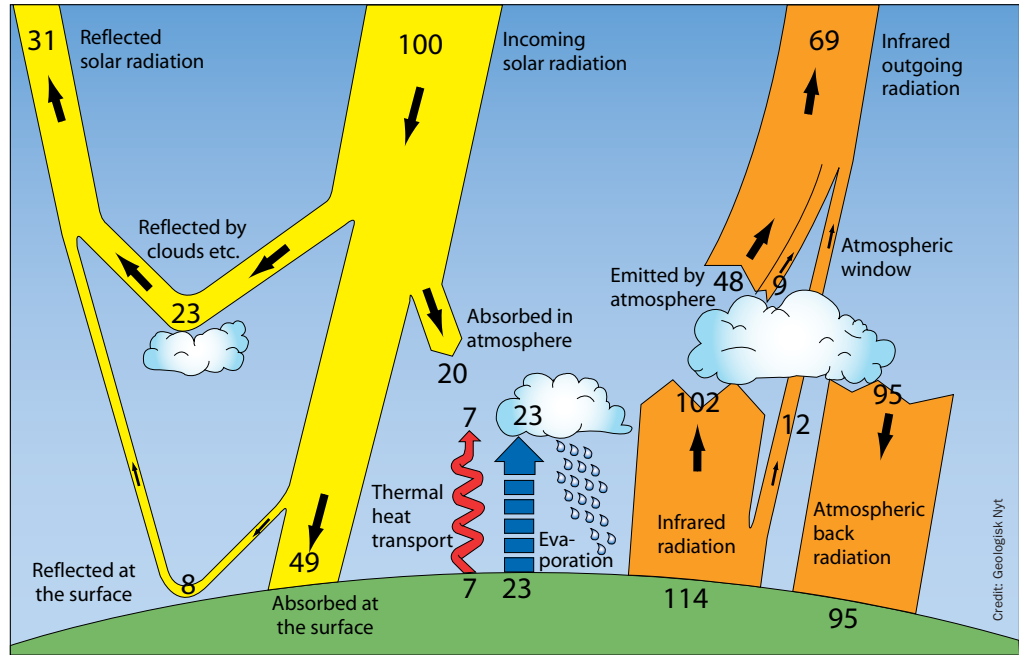
will be at surface.

If we increase the amount of greenhouse gases in the atmosphere, the level at which infrared radiation is emitted will become higher, and will come from a lower temperature (see figure). This means that the amount of outgoing infrared radiation is reduced and the system will have an energy surplus, since the incoming solar radiation remains unchanged. This generates a warming of the atmosphere, and at some point in time the warming will be so great that the temperature at the new level from which radiation is emitted will again reach the effective temperature (T_E). As atmospheric temperature change with height remains unchanged, the surface temperature will increase, since the radiation level now lies at a greater distance from the surface. This is the warming we expect to experience as a result of the increase in the quantity of atmospheric greenhouse gases.

Carbon dioxide has relatively large role

The main greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), CFCs and ozone (O_3). It is impossible to rank the different greenhouse gases and clouds in an unequivocal way by their contribution to the greenhouse effect. However, one can in very broad terms say that the relation between the three main contributors to the natural greenhouse effect, namely water vapor, clouds and carbon dioxide is about 2-1-1.

It may come as a surprise that carbon dioxide plays such a relatively large role, considering that this gas is present in only very small quantities when compared to water vapor. The reason for this is, that water molecules are not nearly as effective at absorbing and emitting infrared radiation as carbon dioxide molecules are. Carbon dioxide primarily absorbs infrared radiation at wavelengths from 12-18 μm . Water vapor absorbs at many different wavelengths



One of the most recent estimates of energy flows as a percentage for the entire planet. 100% corresponds to the average incoming solar radiation of 342 W/m^2 during the day and over the year at the top of Earth's atmosphere.



Cirrus clouds (left) often have a warming effect on the climate because they provide a major contribution to the greenhouse effect and have small albedo. Stratocumulus (right – here seen from above) have a strong cooling effect on the climate because their contribution to the greenhouse effect is rather small, while they usually have a very high albedo (they are very white when seen from above).

but does so less effectively. At the wavelength range from 8-12 μm greenhouse gases generally absorb and emit very little radiation. These wavelengths are called the atmospheric window, because radiation can pass relatively unhindered through the atmosphere, though not as freely as visible light does. Clouds absorb and emit infrared radiation at all wavelengths,

and therefore also in the atmospheric window.

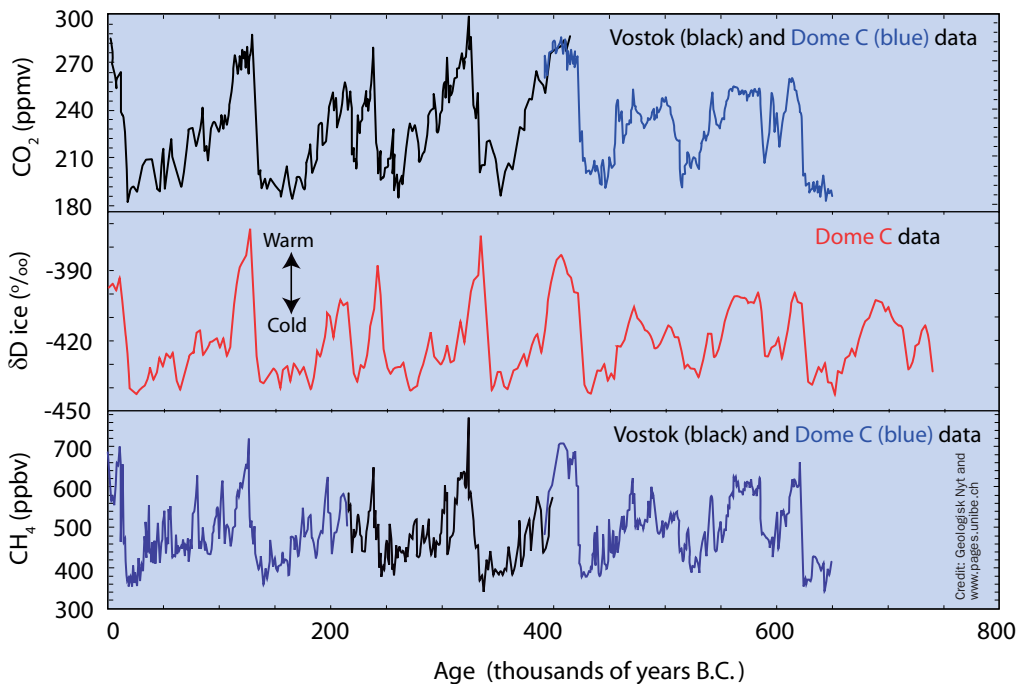
An increase in atmospheric carbon dioxide gives a slightly larger increase in the greenhouse effect in the tropics than it does at high latitudes.

Climate Sensitivity

A warming caused by an increase in greenhouse gas concentrations (or any other change

of climate parameters) is defined by a number, called the climate sensitivity.

Climate sensitivity tells us how many degrees global temperature will change near the surface if a change in the power supply of 1 W/m^2 occurs. Such a change in energy intake may be due to a sudden increase in the concentration of CO_2 and other greenhouse gases in the



Data from two Antarctic ice cores. The upper and lower curves show the carbon dioxide and methane concentrations through time (back to 650,000 years before the present date). The middle curve shows δ -Deuterium, which is an indicator of temperature. The three fluctuate synchronously – the temperature tends to rise (or fall) first and then the greenhouse gases follow suit thereby reinforcing the temperature change.

Feedback Mechanisms in the climate system

The climate is a closely interconnected system with a wide range of components, such as temperatures, winds, water vapor, clouds, ice, snow, oceans, vegetation and much more. If the temperature changes, it will lead to changes in other components, which in turn may cause additional temperature change. Thus the playing field has been readied for a host of mutually interacting feedback effects. Some examples are:

Ice and snow cover

Warming will lead to a reduction (by melting) of snow covering the continents and of sea ice. This in turn causes a reduced reflection of sunlight from the Earth's surface and thus creates more warming and additional melting of snow and ice. The ice and snow cover feedback is therefore positive.

Clouds

In total, clouds in the Earth's atmosphere have a cooling effect ($\approx 20 \text{ W/m}^2$), because in spite of their contribution to the greenhouse effect their cooling albedo effect is greater. Clouds are very diverse and occur at

different altitudes in the atmosphere. There are both negative and positive feedbacks from clouds, depending on height and type. The total feedback from clouds is uncertain and requires further study.

Water vapor

When the temperature rises, the atmosphere can hold more water vapor, nearly 7% more for each degree the temperature rises. This reinforces the greenhouse effect, and causes additional warming, i.e. a positive feedback.

Temperature-profile

Typically, the temperature changes more rapidly at the radiation level than at surface level, and radiation will quickly adapt to the forcing. On the surface we will therefore only experience a slight change. This is a negative feedback.

Heat transport

The transports of energy in the atmosphere and in oceans can be affected by a changed climate, and this may cause a feedback but further study is necessary to determine if it is positive or negative.

Vegetation

The distribution of vegetation types and their volume may change, and this will affect the albedo. The exchange of water vapor between the surface and atmosphere will typically be affected by vegetation as well. Both effects may be sources of feedback.

CO₂ feedback

We have previously described CO₂ as a forcing factor of the climate system, but on a long time scale CO₂ is actually also a part of the feedback system. For example, the solubility of CO₂ in seawater is reduced in a warmer climate, and the sea will thus serve to reinforce the CO₂-forcing. Further, a number of biological processes in both sea and on land are temperature dependent. These feedbacks can start in two different ways:

- 1) Glacial fluctuations are believed to start with an astronomical forcing; changing the temperature, which in turn changes the CO₂ concentration. This further strengthens the temperature signal.
- 2) Anthropogenic CO₂ emissions can cause the temperature to rise, and this then affects the CO₂ concentrations.

atmosphere as well as due to an increase in solar radiation.

The climate sensitivity term was introduced in order to correlate the temperature increases derived from different types of climate effects. As it turns out, if we only know the numerical values for the change in energy input (called forcing), the initial temperature change will be independent of the reason for the change in energy input.

Climate sensitivity is perhaps the most important of all the climatic parameters, but unfortunately it is not well known. A rough way to estimate climate sensitivity is to calculate the temperature increase required in order for upward infrared radiation to correspond to a specific increase in the power supply. A simple calculation tells that a change in the power supply of 1 W/m^2 gives a sensitivity of $0.269 \text{ K} / (\text{W/m}^2)$ (see box).

This simple estimate results in far too low a climate sensitivity. In the real world there are a number of so-called feedback mechanisms, whereby a change in temperature causes a change in other parameters, such as the atmospheric water vapor content, which in turn changes the energy balance and thereby causes an additional temperature change. Feedbacks that reinforce a warming or cooling are called positive, while those that suppress them are called negative.

Feedback Mechanisms

Water vapor is a greenhouse gas and increased water vapor content in the atmosphere enhances the greenhouse effect. Water vapor high up in the troposphere gives a particularly strong greenhouse effect, since it is much colder there than on the surface. As a warm atmosphere can hold more water vapor than a cold atmosphere, a warming may increase its water vapor content, enhancing the greenhouse effect, thereby increasing the warming even further. Water vapor feedback is positive. All simulations of future climate (using climate models) include the effect of increasing



Cooling towers by a power plant.

Photo: Colourbox

water vapor through the physical processes which link air temperature and air's ability to contain water vapor.

Climate sensitivity is thus affected by the overall effects of feedback mechanisms. In order to determine it with greater accuracy than can be done with a simple calculation without feedback mechanisms, we utilize detailed climate models which represent physics such as ocean and air currents, radiation, and thermodynamics of the atmosphere, ocean, and land. Observations of climate trends over the last 150 years and reconstructions of climate change on longer time scales (for example, ice ages) are also used to determine sensitivity. With these methods we come to an approximate value of $0.75 \text{ K} / (\text{W}/\text{m}^2)$, and feedbacks thus create more than a doubling of the sensitivity compared to calculations without feedbacks. It is impor-

tant to note that there are significant differences between sensitivity calculations. Estimates range from about 0.5 to more than 2.

When calculating temperature changes as a result of a change in atmospheric CO_2 content, it is associated with a certain degree of uncertainty. The main contributor to this uncertainty however, comes from sensitivity rather than forcing. The cause for this is that the forcing is reasonably well known (for example, a doubling of CO_2 in the atmosphere will lead to an increased energy input of $3.7 \text{ W}/\text{m}^2$), while the different models and different data methods offer great variation in the value of sensitivity. The reason for this variation, as mentioned previously, is that the climate system's feedback mechanisms give a strong increase of sensitivity and the strength of these feedbacks var-

ies from model to model.

This means that regardless of what previously has driven and today keeps driving the climate changes – whether it is greenhouse gases, volcanic activity or astronomical effects – all calculations face the uncertainties derived from the climate sensitivity. This uncertainty is further increased due to uncertainties regarding the forcing, and here the greenhouse effect is the best understood and mapped mechanism.

It should be noted that the geographic pattern of climate change does not follow the geographic pattern of the forcing. Internal dynamics of the climate and local feedback mechanisms cause the increases in temperature resulting from increasing atmospheric carbon dioxide concentration to be greatest in the Polar regions, even if the forcing is more pronounced in the tropics. ■

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