Climate Change: Understanding and Acting

A STEM-ESD-Program for high schools by the Faculty of Physics at LMU Munich

with experiments of the Climate Kit

Klimawandel verstehen und handeln

www.klimawandel-schule.de

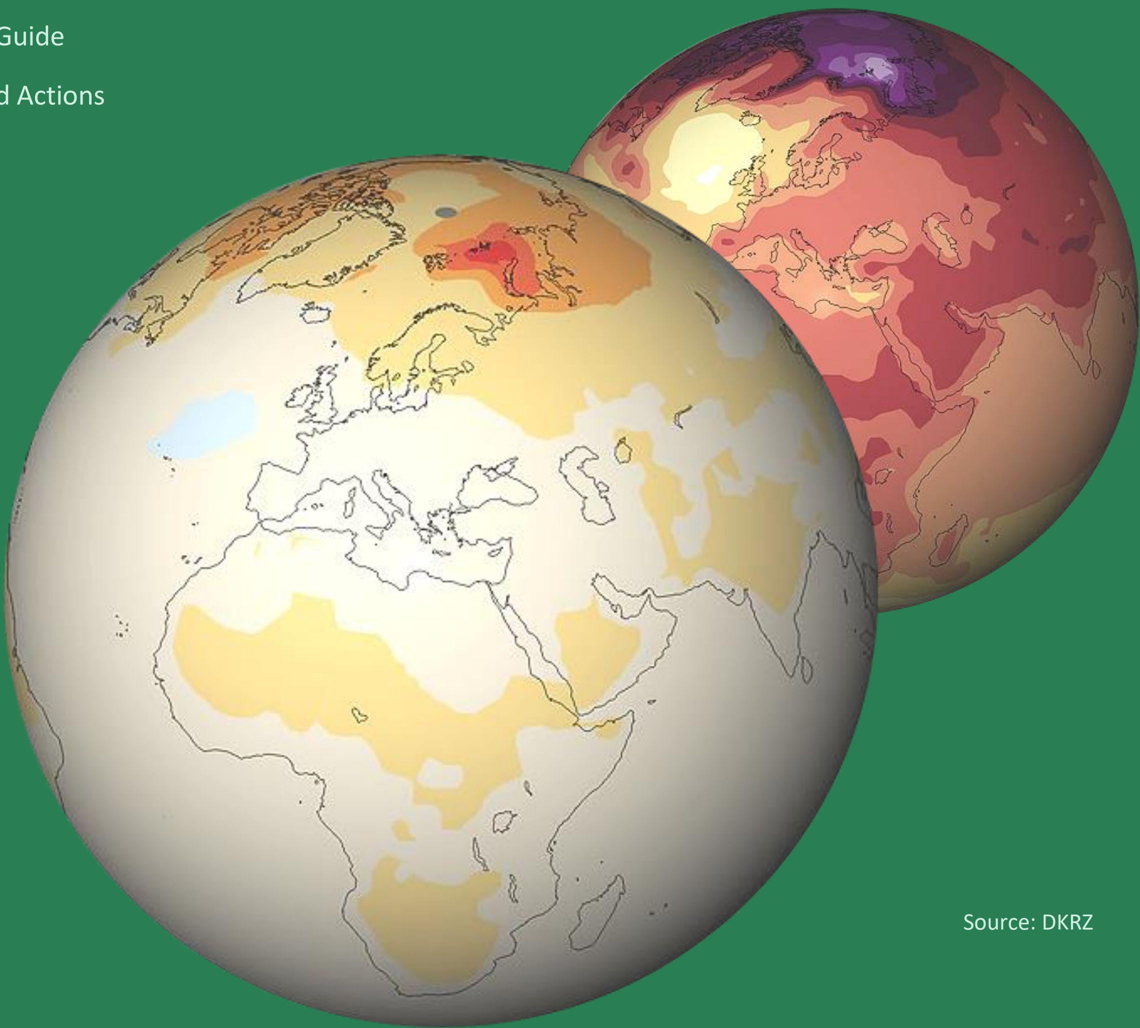
Handbook

Scientific Background

Experimental Guide

Recommended Actions

Version November 2023



Source: DKRZ

Dr. Cecilia Scorza
LMU Fakultät Physik
München

Prof. Dr. Harald Lesch
LMU Fakultät Physik
München

Moritz Strähle
Asam-Gymnasium
München

Dr. Dominika Sörgel
PIK
Potsdam

With contributions by Dr. Markus Nielbock, Gabriel Appl Scorza, Friederike Strähle, Rudolf Pausenberger, Dr. Pascal Eitner, Thomas Hensel, Dr. Uwe Scheithauer, Clemens Bröll, Markus Vogelpohl and Stefan Krühler.

PUBLISHED BY:
Fakultät für Physik der LMU
Schellingstraße 4, 80799 München
www.physik.uni-muenchen.de

Dr. Cecilia Scorza LMU Physik
E-Mail: c.scorza@lmu.de

CONTACT:
kontakt@klimawandel-schule.de
www.klimawandel-schule.de

GRAPHIC DESIGN:
Moritz Strähle

PHOTO CREDIT:
Christoph Hohmann

IMAGE CREDIT:
Dr. Cecilia Scorza

TRANSLATION:
David Danin, Hassnat Ahmad, Sabine Graf and
Philipp Schmidbauer

VERSION:
November 2023

Druckerzeugnis
www.natureoffice.com/DE-275-26FJJBH
klimaneutral
durch CO2-Ausgleich

The chart on the title page illustrates two simulations of the DKRZ (German Climate Computing Centre) and the associated temperature increases (see scale) on Earth in 2090 compared to the pre-industrial age.

In the more positive scenario (globe in the foreground, RCP2.6), the mean global temperature rise remains below 2 °C. In the other scenario, an average global temperature increase of 4.8 °C can be expected, with considerable regional fluctuations.

Mankind's efforts in the coming years will determine which scenario will be implemented.

Climate Change: Understanding and Acting

A STEM-ESD-Program for high schools
by the Faculty of Physics at LMU Munich

Contents

Preface

Climate change is the greatest global challenge of the 21st century. Although the history of our 4.6-billion-year-old planet has seen repeated climate fluctuations, there is no doubt that mankind is responsible for the largest share of current global warming as a result of carbon dioxide emissions. It is precisely the high speed at which climate change is progressing that poses an enormous problem. Neither flora and fauna nor humans can adapt that quickly to the changed environmental conditions. The destruction of animal and plant species, wars over water and other resources, famines and migratory flows are all areas of conflict which are mainly caused by climate change. Climate change is the topic of this century and thus also the decisive part of the future of today's pupils.

The global climate system and hence climate change are an interplay of different physical processes. These, and the resulting consequences, are presented in this handbook and illustrated with the help of experiments. The most important keywords are: Greenhouse effect, energy, energy balance, equilibrium temperature, heat radiation, radiation equilibrium, absorption behaviour of atmospheric gases, weather and climate and heat capacity. Cross-references between these topics support the idea of the complex and intertwined character of climate change. Due to the many points of contact, the topic is ideally suited for interdisciplinary and conjunctive work at schools, not only in the STEM subjects.

At least as important as a basic understanding of the context is the urgent call for action. Now, only those who are well informed about the scientific background can do this in a well-founded, motivated, argumentative, and responsible manner. Therefore, not only an understanding of the scientific processes behind climate change should be conveyed, but also possibilities for acting should be offered in order to shape the individual life and environment of the students.

Climate change is both an enormous challenge and an opportunity for interdisciplinary teaching in one of the most relevant contexts of our time.

The Authors

Call for Participation!

This handbook and the accompanying experimental kit are part of the project *Climate Change: Understanding and Acting,* initiated by the Faculty of Physics of the Ludwig Maximilian University of Munich and endorsed by the Bavarian State Ministry of the Environment and Consumer Protection.

The general aim of this project is to bring the topic of climate change more into the focus of the younger generation, to work out the necessity for ethical action through an understanding of the scientific background, and to motivate students to take concrete action.

We cordially invite you to participate!

If you are interested in working with us towards this goal, we look forward to hearing from you at: kontakt@klimawandel-schule.de

All information about the project can be found on our website:
www.klimawandel-schule.de

„We will [..] conclude on the absolute need to keep global warming well below 2°C, if we want young generations to be able to adapt to future climate change in the second part of this century and beyond. We will argue that research, innovation and creativity are essential for going towards this low carbon society but that this transition also requires large dedicated private and public investments.

Jean Jouzel, Member of the IPCC and as such Nobel peace prize laureate, in his opening lecture at the conference "Climate Change & Water 2018" in Tours, France, on February 5, 2018.

Chapter 1
Our Earth: An Extraordinary Planet

The Earth is the only planet in the solar system on which complex life has developed and survived over billions of years. Since the first discovery of planets outside the solar system in 1995, nearly 4000 exoplanets have been discovered (as at June 2018). However, only about a dozen of them are considered potentially life friendly. It follows that planets on which life seems possible are rare and must have special properties. By realizing how many seemingly random events had to come together to create a planet like Earth, we see how special our home planet really is! Therefore, our handbook begins with the description of the astronomical peculiarities of the Earth.

1.1. A Quiet Place in the Galaxy

Our home galaxy, the Milky Way, is a spiral galaxy that contains about 200 billion stars. The solar system is located in a quiet region of the Milky Way, outside a spiral arm and far away from the galactic centre (see Figure 1). It is thus also far away from areas with high star density and thus out of reach of stars that explode as supernovae and could have destroyed life on Earth with their gamma rays. This zone is called the "Habitable Zone of the Galaxy".

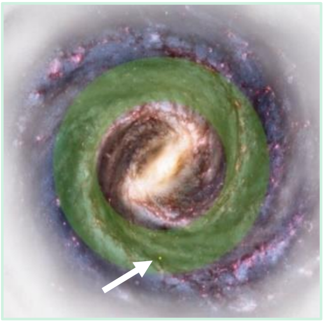


Figure 1 - Position of the Solar System in the Galaxy (Credits: Mandaro/edited by Scorza)

1.2. The Habitable Zone of the Solar System

Activity 1

Our solar system consists of one star (Sun), four terrestrial planets (Mercury, Venus, Earth and Mars), four gaseous planets (Jupiter, Saturn, Uranus and Neptune), five dwarf planets like Pluto, the moons of the planets, asteroids and comets. A measure of the vitality of a planet is its distance from the mother star: If the planet is located in the life zone of the star, i.e. where water can exist in liquid form, this increases the chance that life may develop. In the solar system, the life zone extends from Venus to Mars (see Figure 2), so the Earth is in the middle of it.

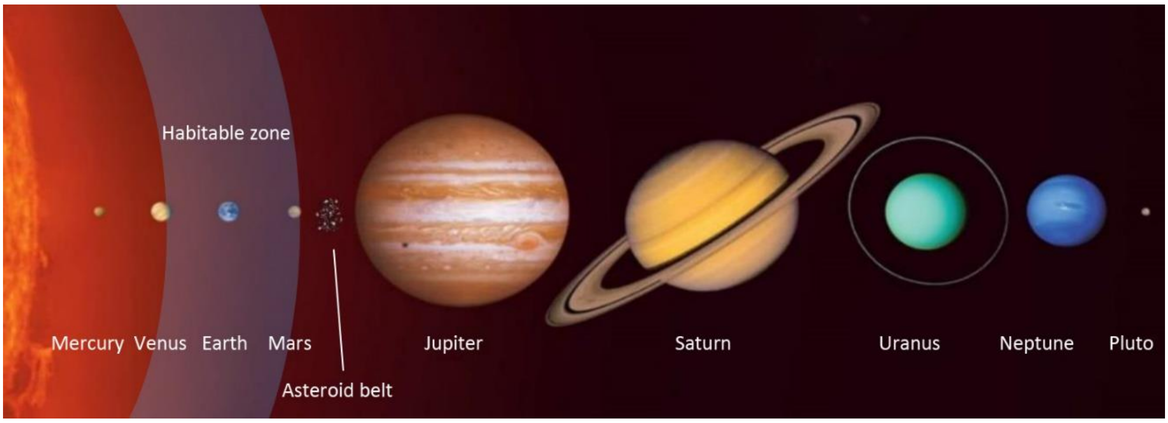


Figure 2 - Earth is in the Middle of the Solar System's Life Zone. Attention: In contrast to the planet sizes, the distances are not true to scale. (Credits: NASA/edited by Scorza)

1.3. The Formation of the Solar System and the Earth

Despite all present-day differences, the planets of the solar system, together with the Sun, were all formed from a protoplanetary gas and dust disk about four and a half billion years ago (see Figure 3). This disk was formed from the residual matter of a supernova explosion, in which all elements generated in the nucleus of the star by nuclear fusion and during the supernova explosion were present: from helium to carbon to iron, gold and uranium. After the supernova explosion, these elements and fine dust (consisting of silicates and graphite) mixed with hydrogen-containing gas clouds of the environment.

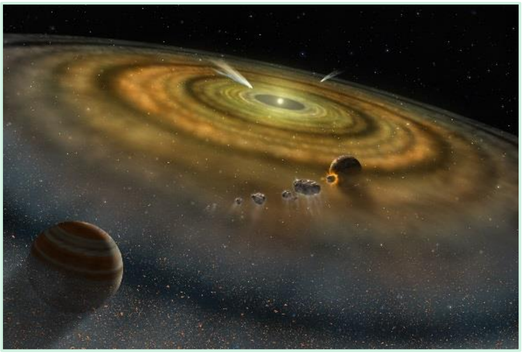


Figure 3 – The formation of the Solar System (Credits: NASA)

First, the gaseous planets Jupiter, Saturn, Uranus, and Neptune were formed in the protoplanetary disk. Since this happened at a great distance from the Sun, they were able to bind large amounts of gas around their large terrestrial nuclei relatively quickly due to the low temperatures and the gravitational force. Later, the nuclei of the rock planets Mercury, Venus, Earth, and Mars were formed from fine dust, which subsequently accumulated material through countless impacts of other celestial bodies and grew to planetary size. This formation process took about 100 million years.

1.4. Only the Earth Kept its Water

Due to the many collisions in the early development phase of the solar system, all rock planets were formed as very hot, glowing spheres. Once cooled down, they were dry. So, where did the water come from?

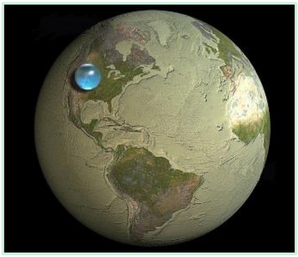


Figure 4 – The true-to-scale spherical water drop contains all the water on earth. (Credits: Cook and Perlman)

Water existed already in the protoplanetary disk. This precious element accumulated in remote areas beyond Mars (closer to the Sun it would have evaporated quickly) in the form of ice in porous asteroids and comets.

Due to migratory movements of the gaseous giants Jupiter and Saturn, many water-containing asteroids were catapulted out of their orbits. Some were attracted to the Sun and hit the surface of the inner rock planets, bringing them water.

This accumulated on the three planets in the life zone (Venus, Earth and Mars) in the form of water vapour. Due to the proximity to the Sun, the water vapor in the Venus atmosphere was split by the Sun's UV radiation and the volatile hydrogen component escaped into space. Mars, on the contrary could not hold the water vapour due to its little mass. Only on Earth, more and more water vapour accumulated in the atmosphere over time. As a result, the atmospheric pressure increased and as the Earth's surface cooled, the water fell as rain onto the surface. The seas and oceans were formed on Earth in this way. Large quantities of CO_2 were washed out of the air by the rain and stored on the seabed in the form of limestone. Rain has thus made the Earth's atmosphere more life friendly. Much later, when plants began to absorb more CO_2 and convert it into oxygen through photosynthesis, an ozone layer was formed that protected the Earth's surface from UV radiation - an important prerequisite for the Earth's biological diversity.

1.5. How the Moon Made the Earth Life-Friendly

Figure 6 –Collision of Theia with the Earth-The Formation of the Moon (Credits: NASA)

Our moon formed about 4.5 billion years ago from the collision of the Earth with the protoplanet Theia, which was twice as heavy as Mars. After the collision, a large part of the matter that had been cut off gathered and clenched in orbit around the Earth - the moon was born.

Previously, the Earth needed only three to four hours for one revolution and its axis of rotation staggered back and forth. On an Earth rotating that fast, the atmosphere would sweep over the surface at up to 500 kilometres per hour. Only the presence of our natural satellite slowed down the Earth's rotation to today's 24 hours per revolution. The axis of rotation was also stabilized by the moon and today is slightly inclined at 23.4° in relation to the ecliptic. This inclination causes the seasons and weakens the weather fluctuations of the Earth.

Excursus: The origin of water

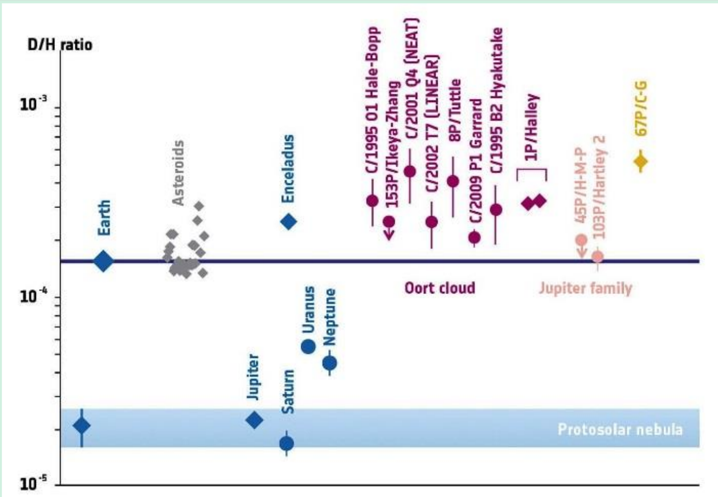


Figure 5 - Deuterium to Hydrogen (H/D) in the Solar System (Credits: ESA, after: Altwegg, K. et al., Science 10.1126/science.1261952, 2014, fig. 3)

An important indication for the origin of water on Earth is its chemical analysis: Our H_2O has a characteristic mass ratio of normal hydrogen to deuterium (heavy hydrogen) of $H:D = 1:1{,}5 \cdot 10^{-4}$, which can also be found in the water of (carbonaceous chondritic) asteroids.

1.6. A Magnetic Field as a Protective Shield for the Earth

Many planets have a weak, permanent magnetic field. The Earth, on the other hand, has a dynamic magnetic field, which is maintained by processes inside the Earth. In these, like a dynamo, kinetic energy is converted into electromagnetic energy. The underlying physics is not easy to understand. Roughly explained, the heat inside the Earth causes several thousand degrees hot and ferrous fluid to rise towards the Earth's surface. When cooling down, it partially sinks again and is forced onto screw tracks by the Coriolis force, thus generating the magnetic field.

Why does the Earth of all planets have such a strong and dynamic magnetic field? Most probably, the impact energy of the protoplanet Theia plays an important role. Its iron core sank practically completely into the centre of the Earth when it collided. It is thus jointly responsible for the heat inside the Earth and thus allows the build-up of a magnetic field. Without this protective shield, the Earth's surface would be at the mercy of the solar wind and its high-energy, destructive particles.

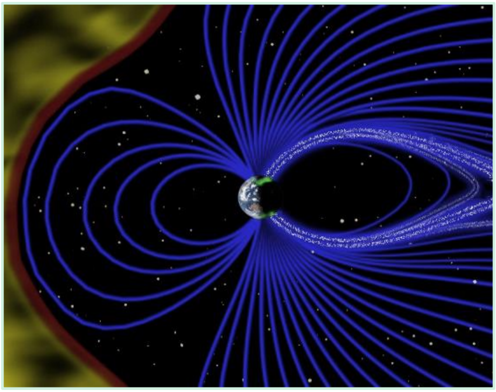


Figure 7 – The Magnetic Field of the Earth (Credits: NASA)

Without the large-scale magnetic field, life on the Earth's surface would be exposed to the destructive cosmic particle radiation of the Sun, the solar wind which consists of very fast charged particles that can destroy molecules and make it impossible to build more complex living beings. Our Earth's magnetic field protects us from this cosmic danger, because the charged particles of the solar wind are deflected by it. Sometimes one can see the sky shining in the far north and in the Antarctic; these are the northern and southern lights. They arise during storms of the solar wind. One then practically sees the Earth's magnetic field during its work as a protective shield. The kinetic energy of the solar wind particles is absorbed by the magnetic field lines of the Earth. As electric currents in the high atmosphere, they make the air glow, like a fluorescent tube. Small note: If anyone wants to visit Mars - it has no magnetic field. A dangerous endeavour.

All the astronomical events and geological characteristics and processes described above led to a dry rocky planet becoming a habitable world – the Earth.

Chapter 2
Understanding the Greenhouse Effect

2.1. The Sun as an Energy Source

As all other stars, our Sun is also a massive, self-luminous celestial body made up of very hot ionized gas, a so-called plasma. Due to the strong pressure exerted by the gas mass on the centre of the star, the temperature in the inner core of the Sun is about 15 million degrees Celsius. Nuclear fusion takes place at these high temperatures: First helium is formed from hydrogen and then, in further fusion steps, nuclei with a higher mass are formed. According to Einstein's equation $E = \Delta m \cdot c^2$, an immense amount of energy is released in the form of electromagnetic radiation. Every second, the Sun converts 500 million tons of hydrogen into helium.

The Sun emits electromagnetic waves (which can be divided into gamma radiation, X-rays, ultraviolet radiation, visible light, infrared radiation, and radio waves according to their wavelength) as well as a stream of particles (including protons, electrons and helium atom nuclei), the so-called solar wind.

Due to its surface temperature of about 5 500 °C in accordance with Planck's law of radiation, the Sun emits mainly electromagnetic radiation with wavelengths of about 400 (violet) to 750 nanometres (red). The largest portion of the radiation is emitted in the yellow to green spectral range. In the course of evolution, our eyes have adapted to this part of the spectrum so that we can see electromagnetic waves in this range.

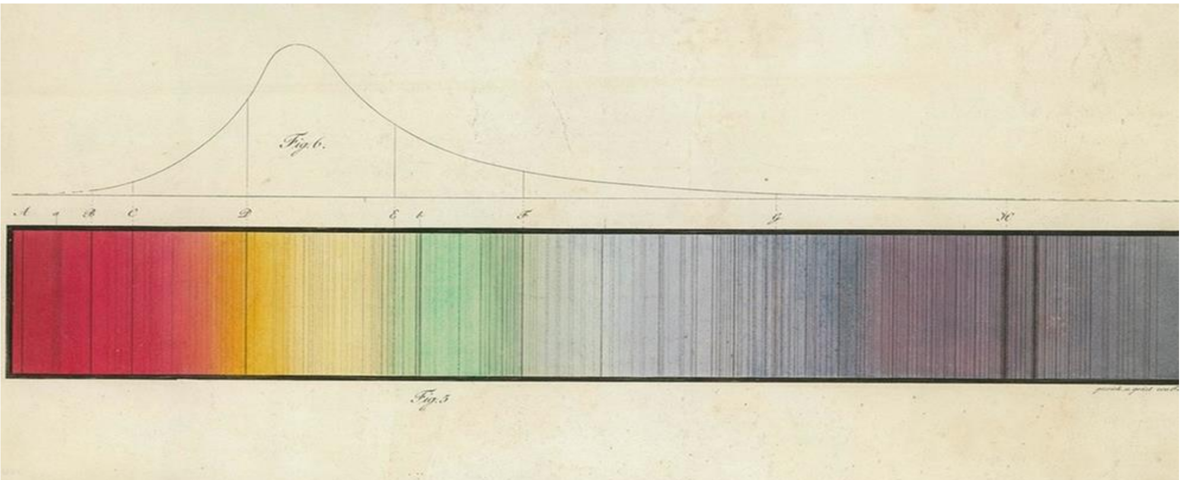


Figure 8 – Fraunhofer's Spectral Lines and Energy Distribution. X-axis: Frequency of the electromagnetic radiation, y-axis: Intensity. Original image: Deutsches Museum Munich

How Much Energy Does the Earth Get from the Sun?

The energy of the Sun is radiated uniformly in all directions. How much of it arrives at a certain planet depends on its distance from the Sun.

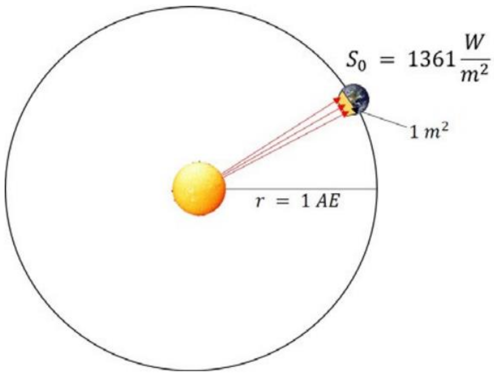


Figure 9 – To measure the solar constant, the power that hits on an area of 1m²at a distance of sun-earth has to be determined. (Credits: Scorza, Strähle)

The *solar constant S_0* is the irradiance that arrives on Earth, at a mean distance from the Sun and without the influence of the Earth's atmosphere, perpendicular to the direction of radiation. Measurements show that on an area of 1 m^2 above the Earth's atmosphere a radiant power of 1361 W [2] occurs (see Figure 9, 1AU = 1 Astronomic Unit = Distance Earth–Sun).

Excursus: Estimating the total radiant power (luminosity L⊙) of the sun

When the Sun's radiation propagates into space, the total radiant power of the Sun is increasingly distributed over a larger area ($\sim r^2$, Figure 10). To calculate the total radiant power of the Sun, generally called luminosity $L_{\odot}$, imagine a sphere with the Sun at its centre and a radius corresponding to the distance between the Earth and the Sun.

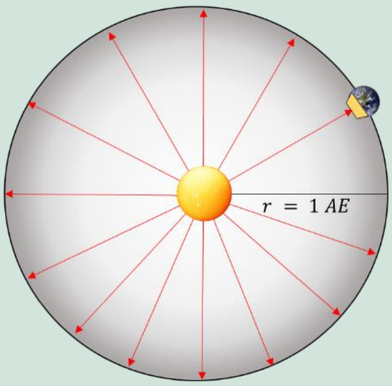


Figure 10: The Total Solar Radiation is Distributed on the Imaginary Surface of the Sphere (Credits: Scorza, Strähle)

$$S_0 = 1361 \frac{W}{m^2}$$

$$r = 1\ AE = 149{,}6 \cdot 10^6\ km = 149{,}6 \cdot 10^9\ m$$

$$A = 4\,\pi\,r^2$$

$$L = A \cdot S_0$$

$$L = 4\,\pi\,r^2 \cdot S_0$$

$$L_{\odot} = 4\,\pi\,(149{,}6 \cdot 10^9)^2\ m^2 \cdot 1361 \frac{W}{m^2}$$

$$L_{\odot} = 3{,}83 \cdot 10^{26}\ W = 3{,}83 \cdot 10^{23}\ kW$$

The radiation of the Sun is distributed on the surface of this imaginary sphere. The radius r of the sphere is known (1 AU) and thus the area A of the sphere can be calculated. The luminosity of the Sun $L_{\odot}$ is then determined by multiplying this area A by the solar constant S_0. With the calculated luminosity $L_{\odot}$ and the known distances of the other planets to the Sun, the solar constant on Mercury, Venus, Mars etc. can be determined. This can then be used, for example, to estimate the possibility of extra-terrestrial life.

2.2. Radiation equilibrium of the Earth

Activity 3

The transport of energy from the Sun to the Earth takes place via electromagnetic waves. In the visible spectral range, i.e. in the wavelength range from 400 to 750 nm, the gases in the atmosphere hardly absorb solar radiation. This relatively short-wave, visible part of the solar radiation therefore reaches the ground almost unhindered, is then partly absorbed there and thus contributes to the warming of the Earth's surface. The warm Earth radiates this absorbed energy as invisible infrared radiation (heat radiation) back to the universe.

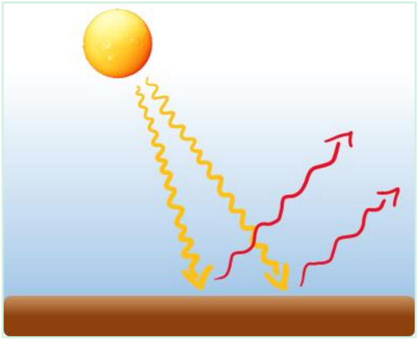


Figure 11 – The Short-Wave Solar Radiation (yellow) is Remitted from the Ground as Infrared Radiation (red). (Credits: Scorza, Strähle)

In the long run, the average energy of the heat, which is radiated from the Earth into space, must correspond exactly to the absorbed radiation energy from the Sun. The Earth is therefore in what is known as the *radiation equilibrium* with its surroundings. If this were not the case and if, for example, the Earth absorbed more energy than it radiated, it would continue to warm up over time. But since a body radiates even more energy, the warmer it is, this would only happen until the absorbed and radiated energy are at the same level again and the Earth is eventually in the radiation equilibrium.

In the radiation equilibrium, the solar radiation absorbed by the Earth's surface must be entirely radiated back into space again as long-wave heat radiation.

The energy radiated vertically by the Sun on Earth is $S_0 = 1361\ W/m^2$ (solar constant, see page 13). However, not the entire globe is irradiated vertically; towards the poles, the irradiation gets increasingly flatter. Further, only one hemisphere is irradiated, and the other hemisphere is in darkness. The average energy per m^2 radiated over the Earth's surface can be estimated by determining the ratio of cross-sectional area $Q = \pi \cdot r_{Erde}^2$ (is irradiated vertically) to the Earth's surface $O = 4\pi \cdot r_{Erde}^2$. This is obviously exactly $1/4$. Thus, $I_S = \frac{1361}{4}\frac{W}{m^2} = 340\frac{W}{m^2}$ results for the average intensity of solar radiation on Earth.

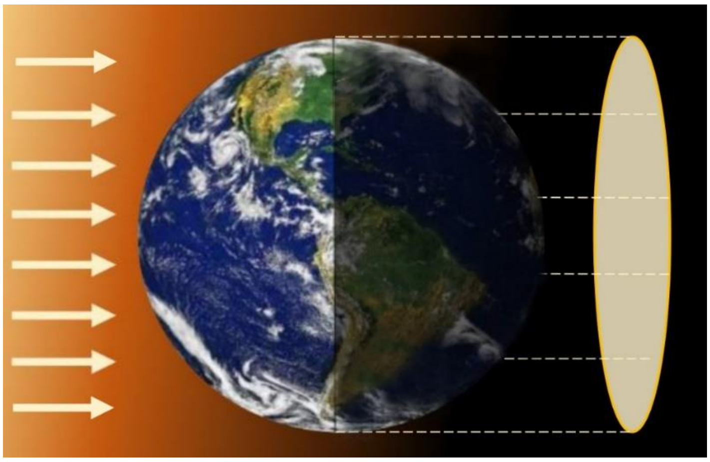


Figure 12 – The average energy per m^2 radiated over the Earth's projection surface (Credits: NASA/Scorza)

2.3. Estimate temperature on an Earth without an atmosphere[1]

Activity 4

The Earth, as we have already learnt, is in a state of equilibrium with its environment. The mean temperature can be estimated with the Stefan-Boltzmann law:

$$I = \sigma \cdot T^4$$

The law describes what radiation intensity I (in watt per m^2) a body radiates at a certain temperature T. Figure 13 shows this dependency. The hotter a body, the more heat it emits, proportionally to the fourth power of its temperature. At twice the temperature (measured in Kelvin), a body radiates 16 times more energy per second. The radiation constant $\sigma = 5{,}67 \cdot 10^{-8} \frac{W}{m^2 K^4}$ is to be regarded as a conversion factor between temperature and radiation intensity. This relation can be utilized to estimate the temperature of the Earth's surface.

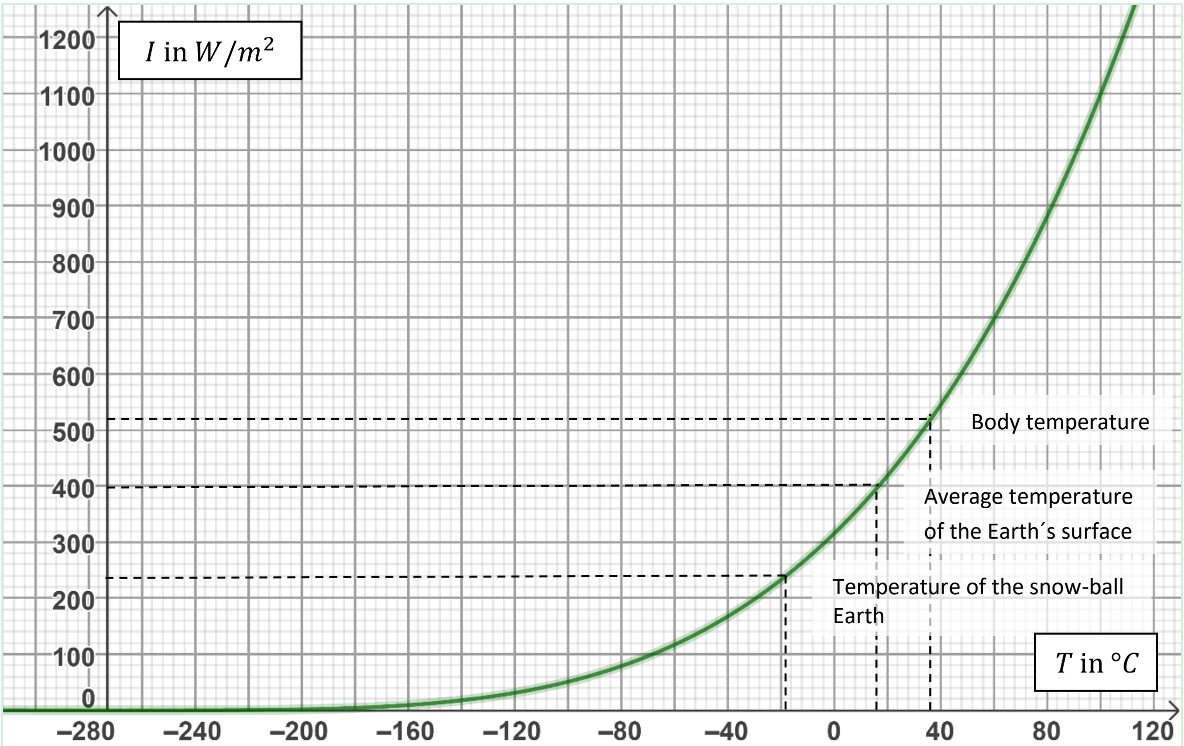


Figure 13: The figure shows the Stefan-Boltzmann law, i.e. the relationship between the temperature and the intensity of the thermal radiation of a body (Credits: Strähle, created with Geogebra)

Of the irradiated 340 W/m^2 approx. 30 % [3] are directly reflected into space. This reflectivity of surfaces is called *albedo* α and is particularly high in ice, for example. Thus, the earth's surface absorbs the lower intensity:

$$I_{Sun \to Earth} = (1 - \alpha) \cdot I_{Sun} = 0{,}7 \cdot 340 \frac{W}{m^2} = 238 \frac{W}{m^2}$$

Let us assume for a while, that the Earth had no atmosphere. Due to the equilibrium of radiation on this hypothetical rocky Earth, the energy irradiated by the Sun is completely emitted back. Thus, $I_{Sun \to Earth} = I_{Earth \to}$. See Figure 14.

---

[1] In the following two sections, we have taken the presentation in the highly recommended book "Climate - The Earth and its Atmosphere through the Ages" by Christoph Buchal and Christian-Dietrich Schönwiese [3] as a model.

The average radiation power of the Earth's surface $I_{E\rightarrow}$ is equal due to the equilibrium of radiation and depends on the temperature of the Earth's surface, as shown above:

$$I_{Sun\rightarrow Earth} = I_{Earth\rightarrow} = 238\frac{W}{m^2} = \sigma \cdot T^4$$

$$T = \sqrt[4]{\frac{(1-\alpha)\cdot I_{Sun}}{\sigma}} = \sqrt[4]{\frac{238\frac{W}{m^2}}{5{,}67\cdot 10^{-8}\frac{W}{m^2K^4}}} = 255K = -18\,°C$$ [2]

Our fictive rocky earth, where the thermal radiation of the earth's soil can escape unhindered into space, would therefore have an average temperature of -18 °C!

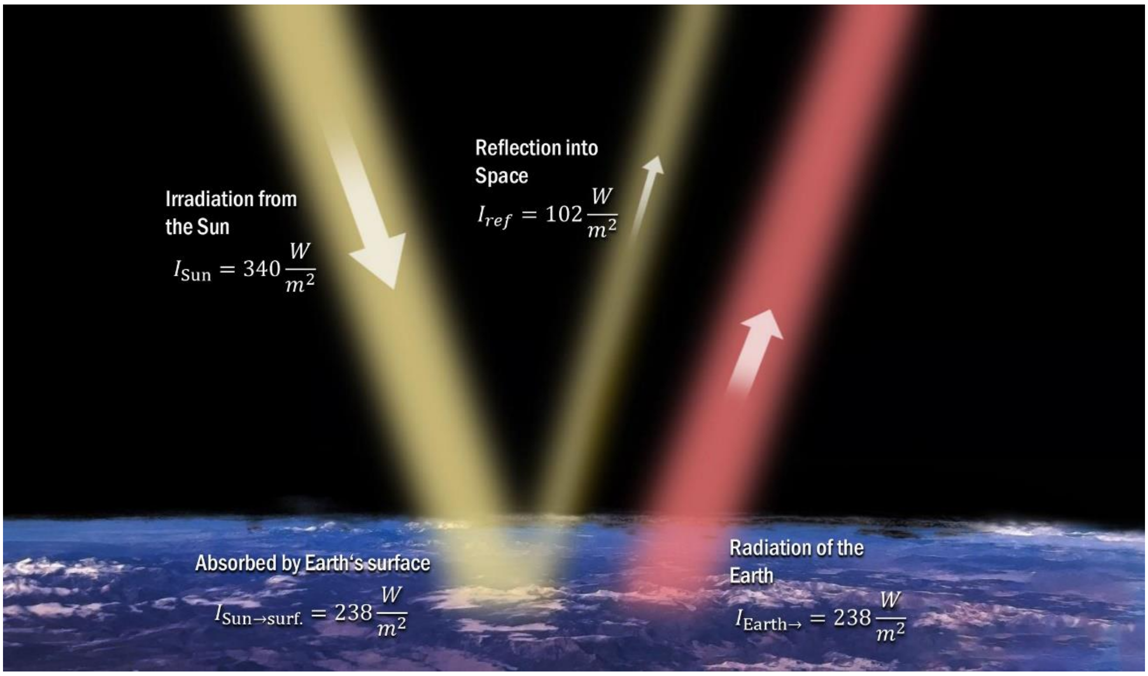


Figure 14: Net radiation of a rocky earth without an atmosphere (Credits: Hohmann)

Changes in the intensity of solar radiation I_{Sun} or changes in the albedo α always have a direct effect on the temperature of the Earth. If the albedo of the Earth changes for any reason, for example due to the melting of the frozen surfaces, the temperature of the Earth would increase until the radiation equilibrium would be restored at a new equilibrium temperature.

[2] Remember: 0 K equals a temperature of -273,15 °C

2.4. The Atmosphere and the Greenhouse Effect

Activity 4

Without its warming atmosphere, today's blue planet would be a white ice ball with an average temperature of $-18\ °C$, as shown in the previous chapter. Fortunately, the Earth's atmosphere partially absorbs the heat radiation of the Earth and radiates it back towards the surface. We will look at the underlying processes now:

The incident solar radiation is still $I_S = 340\ W/m^2$. Directly diffusely reflected is the fraction α, which we again apply with $\alpha = 0.3$, corresponding to a radiation of $I_{ref} = 102\ W/m^2$.[3] The Earth's surface thus absorbs the fraction:

$$I_{Sun \to Earth} = (1 - \alpha) \cdot\ I_{Sun} = 238\ W/m^2.$$

Activity 5

Since the earth is also in a radiation equilibrium in this case, this irradiated energy must, as in the case of rock earth, be emitted again in the form of infrared heat radiation. Greenhouse gases such as CO2, methane and water vapour now have the property of absorbing part of this thermal radiation emanating from the earth's surface. This can be demonstrated with a relatively simple experiment, as shown in Activity 5: The equilibrium temperature in the can, which is initially filled with air and irradiated with an infrared lamp, increases significantly after the addition of CO2.

Figure 15 - Set-up of the experiment from activity 5 of the climate kit

Back to our simple radiation model: Let's assume that the atmosphere allows the entire relatively short-wave solar radiation I_{Sun} to pass through but would absorb a large part of the infrared heat radiation of the Earth's surface $I_{Earth\to}$. For this simple estimate, we will assume a share of 80 % for the time being.[4]

Thus it results:

$$I_{Earth \to Atm.} = 0{,}8 \cdot I_{Earth \to} \quad (1)$$

[3] This reflection takes place in reality on clouds, aerosols, the atmosphere and the surface

[4] In reality, the processes are more complex (see Figure 18) and are presented in this model in a didactically reduced form in order to clarify the basic principle of the greenhouse effect.

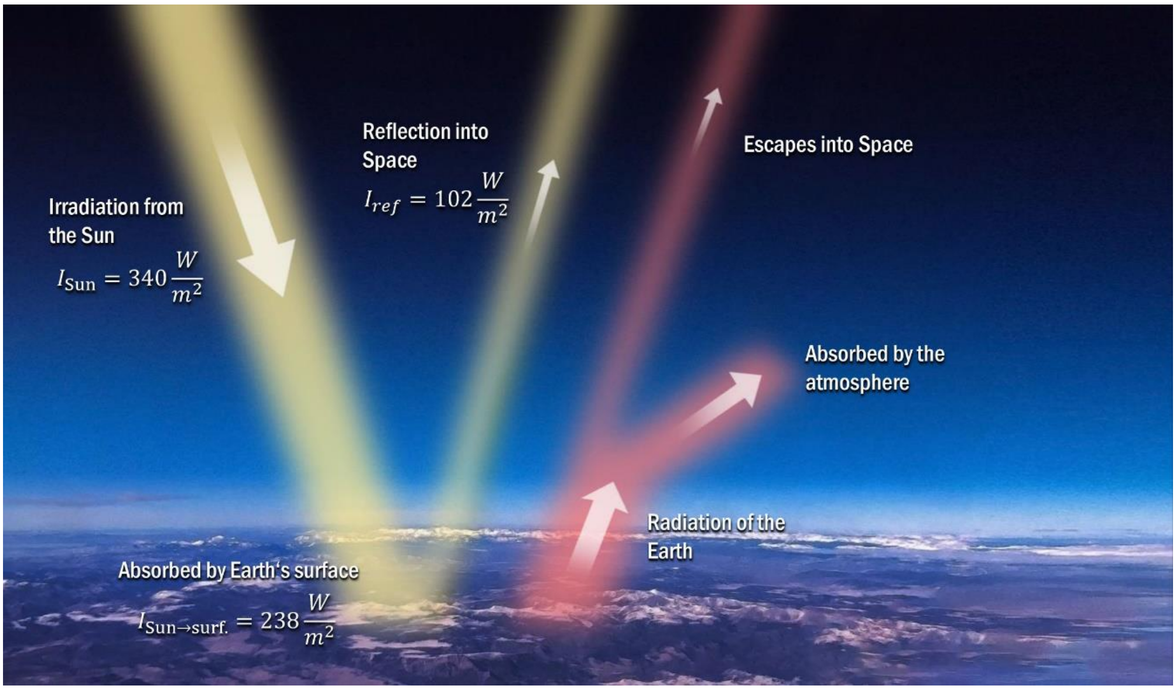


Figure 16: This radiation balance does not yet include the effects of absorption in the atmosphere (Credits: Hohmann).

Figure 16 illustrates the steps described above.

As a result, the atmospheric temperature rises and begins to radiate the absorbed heat towards the Earth's surface ($I_{Atm\to Earth}$) and towards space ($I_{Atm\to Space}$). Since the atmosphere does not radiate preferentially in any direction, we find that:

$$I_{Atm.\to Earth} = I_{Atm\to Space} \ (2)$$

However, the atmosphere will not continue to warm up forever, since a radiation equilibrium is also established at a certain equilibrium temperature:

$$I_{Earth\to Atm.} = I_{Atm.\to Earth} + I_{Atm\to Space} \ (3)$$

The findings in equations (1), (2) and (3) lead to following result:

$$\underbrace{I_{Earth\to Atm.}}_{\substack{energy\ absorbed\ by \\ the\ atmosphere}} = 0{,}8 \cdot I_{Earth\to} = \underbrace{I_{Atm.\to Earth} + I_{Atm.\to Space}}_{\substack{energy\ radiated\ by \\ the\ atmosphere}} = 2 \cdot I_{Atm.\to Earth}$$

So, we immediately receive as a result:

$$I_{Atm\to Earth} = 0{,}4 \cdot I_{Earth\to} \quad (4)$$

40 % of the radiation emitted by the Earth is therefore sent back to the Earth due to the atmosphere. And this is the fundamental difference between an Earth with atmosphere and the rocky Earth:

The surface of the Earth is emitted by the reflection of the atmosphere as an additional source of emission!

As a result to the thermal equilibrium, the surface of the Earth will radiate away the additional energy. So, following applies:

$$\underbrace{I_{Earth\rightarrow}}_{\substack{energy\ radiated\ from \\ the\ earth}} = \underbrace{I_{Sun\rightarrow Earth} + I_{Atm.\rightarrow Earth}}_{\substack{energy\ absorbed\ by \\ the\ earth}} = \underbrace{I_{Sun\rightarrow Earth} + 0{,}4 \cdot I_{Earth\rightarrow}}_{with\ equation\ (1)}$$

Solving for $I_{Earth\rightarrow Atm.}$ results in:

$$I_{Earth\rightarrow} = \frac{1}{1-0{,}4} \cdot I_{Sun\rightarrow Earth} = \frac{1}{1-0{,}4} \cdot 238\frac{W}{m^2} = 397\frac{W}{m^2}$$

Now, the balance between the respective emissions is fulfilled, or, in other words: The surface of the Earth is in the state of equilibrium and absorbs the same amount of energy as the amount which it irradiates away. The same applies for the area above the atmosphere, which can be verified in Figure 15.

This may come as a surprise because the Earth radiates more energy ($397\frac{W}{m^2}$) than it absorbs directly from the Sun ($238\frac{W}{m^2}$). This is because of the atmosphere: The solar energy is stored in it via the

Earth's surface and then sent back and forth, also driven by the Sun. The atmosphere is thus charged with energy (and the Earth-atmosphere system is heated up more and more) until a balance of radiation is achieved. This is comparable to pushing a freight wagon on a circular track: if the friction losses do not completely consume the drive power, the wagons become faster and faster, i.e. their kinetic energy increases constantly.

To irradiate with higher energy, the only possibility for the Earth’s surface is an increase in temperature. Given the Stefan-Boltzmann law, this new energy balance provides the temperature of the Earth's surface:

$$T = \sqrt[4]{\frac{397\frac{W}{m^2}}{5{,}67 * 10^{-8}\frac{W}{m^2K^4}}} = 289K = 16\ °C$$

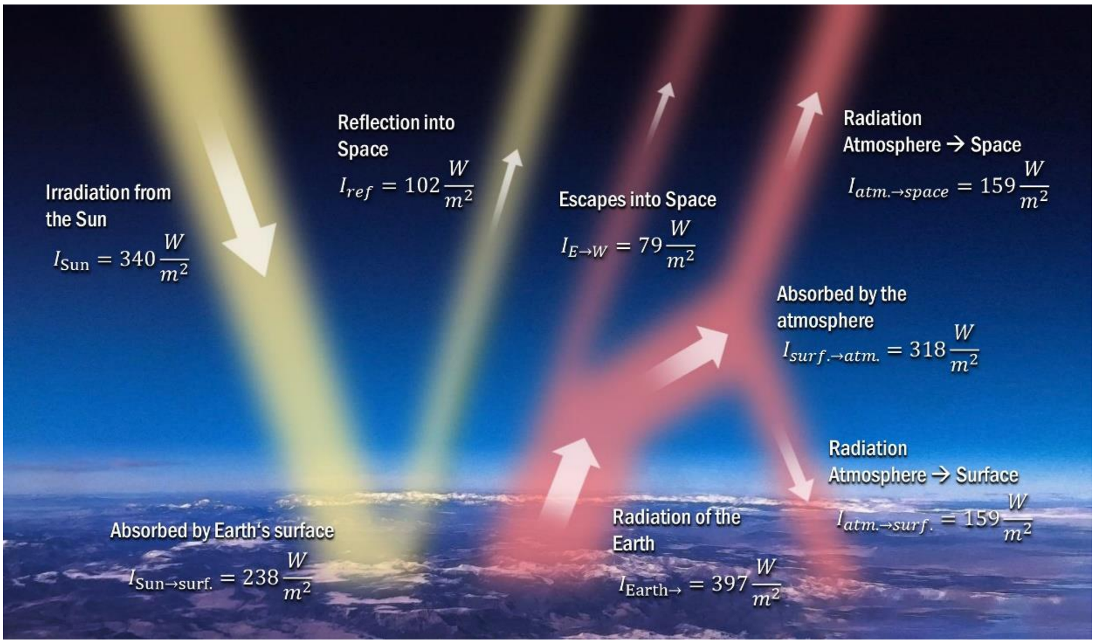


Figure 17: Radiation model with atmosphere (Credits: Strähle and Hohmann)

In comparison to the rocky Earth, an atmosphere that absorbs 80% of the Earth's heat radiation causes a back radiation that in our simple model of emission warms the Earth by 34 °C[5]. This process is the so-called *greenhouse effect*, having a great influence on the climate. Without it, life on Earth would probably not be possible.

This is where man comes in. The temperature on Earth depends on the ability of the atmosphere to absorb (and thus remit) the infrared heat radiation from the Earth's surface. What happens, if we humans increase the absorption ability?

Let us assume that the concentration of CO_2 in the atmosphere has risen due to exhaust gases and that it now absorbs 85 % of the heat radiation of the Earth instead of the 80 % assumed above. According to the above argumentation, $\frac{85\,\%}{2} = 42{,}5\,\%$ of the heat radiation absorbed by the atmosphere is now sent back to Earth. We receive:

$$I_{Earth\to} = \frac{1}{1-0{,}425} I_{Sun\to Earth} = \frac{1}{1-0{,}425} 238\frac{W}{m^2} = 414\frac{W}{m^2}$$

Thus, the temperature on the Earth's surface is given by

$$T = \sqrt[4]{\frac{414\frac{W}{m^2}}{5{,}67 * 10^{-8}\frac{W}{m^2K^4}}} = 292K = 19\,°C$$

An increase in the temperature of the Earth's surface by 3 °C!

[5] Contrary to the scientific agreement to indicate temperature differences in Kelvin, they are written here, as is usual in this context, in °C.

One could improve our radiation model step by step and, for example, simulate a temperature profile, i.e. the radiation would be absorbed to different degrees at different heights. Or we could let the atmosphere absorb some of the incident solar radiation, just as the ozone layer in our atmosphere does. And one could also consider the influence of clouds, water vapour and dirt particles (aerosols) in the air. This is best done in large-scale simulations, which also correctly represent the dynamics of the sea of air above our heads. But no matter how far we improve our model, the connections shown above retain their indisputable validity:

The more heat radiation our atmosphere absorbs, the warmer it gets on Earth!

The absorption capacity of the atmosphere is therefore *the* adjusting screw in which the whole problem of climate change is hidden. And mankind is currently turning this adjusting screw at a rapid pace!

Figure 18 shows the actual energy flows in the complex atmosphere resulting from long-term global measurements and a complex atmospheric mode [4]. The Earth's surface radiates $I_{Earth\rightarrow} = 396\,W/m^2$, which corresponds to an average temperature of $16\,°C$. In contrast to the model used above, the atmosphere absorbs about 20 % of the incident solar radiation. In addition, the Earth's surface releases energy not only through heat radiation, but also through evaporation of water (latent heat) and air currents (convection). 85 % of the heat radiation of the Earth's surface is absorbed by the atmosphere. The model considers the fact that the real air temperature decreases sharply when altitude increases, i.e. the lower atmosphere radiates more strongly. In fact, 66 % of the counter-radiation comes from heights around 100 m. Deep clouds form a particularly good heat deck.

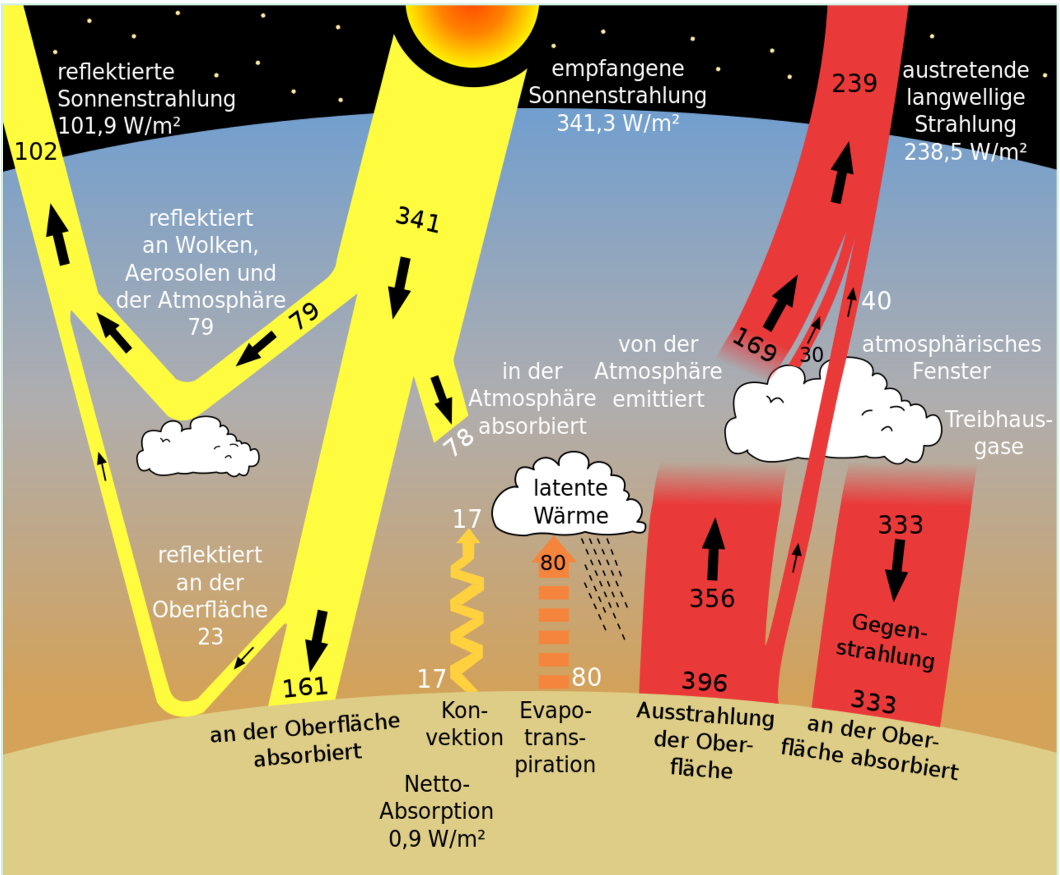


Figure 18 – Energy flows in the complex atmosphere. The balances above the atmosphere and above the ground are balanced (Credits: Keihl and Trenberth)

Excursus: On the role of clouds for the earth's radiation budget

PROF. BERNHARD MAYER - METEOROLOGICAL INSTITUTE OF THE LMU MUNICH

Clouds play a very special role in climate. Satellite observations have shown that clouds reflect part of the solar radiation (50 W/m^2) back into space, thereby cooling the earth and the atmosphere. On the other hand, they contribute - just like CO2 - to the natural greenhouse effect by retaining part of the infrared radiation in the system (30 W/m^2). The cooling effect dominates, but this depends strongly on the type of cloud: in low Stratus clouds, for example, the cooling component predominates by far, while in high Cirrus clouds the cooling and warming components largely compensate each other. This makes the question of the role of clouds all the more exciting, because whether clouds intensify or attenuate anthropogenic climate change - in other words, whether they provide positive or negative feedback - depends very much on how the clouds react to an increase in temperature: Will there be more or less high or low clouds? Will the degree of cloud cover or the water content of the clouds change? What about droplet sizes and precipitation formation, which in turn are influenced by the likewise variable particle numbers (aerosol) in the atmosphere? To make matters worse, clouds are extremely variable. Unlike a CO2 molecule, which - once emitted into the atmosphere - remains there for hundreds of years and contributes to increasing the concentration, clouds form and disappear every minute and change within a few metres. In climate models they therefore literally fall through the grid. This means that the spatial and temporal resolution of climate models is far from sufficient to depict clouds and their interaction with radiation. This is only possible in the form of parameterizations: Similar to the general gas equation, which is a parameterization of 1E23 molecules whose complex properties are perfectly represented by only three macroscopic variables pressure, volume and temperature, clouds must also be described approximately by a few parameters, which unfortunately may not work out well due to the diversity of clouds. So while a single number (the globally averaged concentration) is essentially sufficient for a quantitative description of CO2 due to its long lifetime, clouds are much more diverse and exciting. It is therefore not surprising that the climate impact of clouds represents the greatest uncertainty in climate forecasts. In fact, it is not yet clear whether clouds increase or reduce the anthropogenic greenhouse effect. What is clear is that they cannot fully compensate for it, because otherwise we would not have observed an increase in temperature in recent decades.

The study of clouds is one of the central topics at the Meteorological Institute of the LMU. On the roof of the university, we experimentally combine various sensors for the remote sensing of clouds: with a cloud radar, a microwave radiometer and a lidar, the LMU is part of the European measurement network ACTRIS. We are regularly involved in international aircraft measurement campaigns such as EUREC4A (Elucidating the role of clouds-circulation coup-ling in climate) in January 2020 in the tropical Atlantic, where observations from four research aircraft, four ocean-going research ships and ground-based remote sensing at the Barbados Cloud Observatory of the Hamburg MPI are combined with modern high-resolution climate models. Such measurement campaigns will investigate, for example, how clouds react to a changing ocean surface temperature or how they affect the dynamics of the atmosphere. One part of the instrumentation of the research aircraft HALO is the "specMACS" sensor developed at LMU - a kind of high-end camera that takes spatially and spectrally high-resolution images of the structure of clouds and thus provides information on geometry, microphysics and the temporal course of cloud formation. To interpret the data, we are developing three-dimensional radiative transfer models that calculate the interaction of radiation and clouds more precisely and enable the interpretation of the new high-resolution remote sensing methods in general. On the theoretical side, we are also working on the improved consideration of clouds in weather and climate models and the investigation of the interaction between aerosol particles and clouds.

Figure 19 - Clouds in the tropical Atlantic, from the research aircraft HALO (Credits: Prof. Bernhard Mayer)

2.5. What Defines a Greenhouse Gas?

The natural greenhouse effect described above increases the global mean temperature of the Earth from –18 °C to approx. 14 °C [5]. This makes liquid water and thus life on Earth possible.

The chemical composition of the atmosphere plays a major role in the greenhouse effect. In the case of the Earth, the main components nitrogen (78.1 vol%[6]), oxygen (20.9 vol%) and argon (0.93 vol%) are not relevant as they do not absorb the heat radiation of the Earth's surface. The trace gases water vapour, carbon dioxide, methane and nitrous oxide, which occur in small quantities, have this ability and can absorb energy from heat radiation.

In simple terms, as shown in Figure 20, the molecules vibrate due to the incoming radiation, converting radiant energy into vibrational energy. In the course of the time, the molecules radiate this vibrational energy away at random. Thus, infrared radiation is submitted into space as well as to the surface of the Earth.

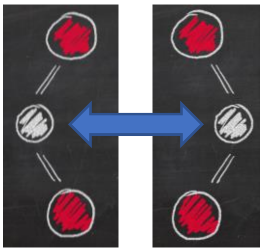


Figure 20 - Bending Vibration of a CO_2 Molecule (Credits: Prof. B. Mayer)

[6] Percentages of volume (vol%) are the fractions of volume, as opposed to mass percent, for example.

Quantum Physics Excursus: How Do Molecules Do That?

Atoms and molecules absorb energy by changing their quantum mechanical state. In the case of atoms, the energy absorption occurs through excitation of the electrons in the atomic shell. In the case of molecules, it can also occur through a change in the oscillation or rotational state. Electromagnetic waves in the visible wavelength range excite electrons in the atomic shell, light in the upper microwave range excites molecules to rotate. The slightly less long-wave infrared radiation in the wavelength range in between stimulates oscillation transitions of molecules.

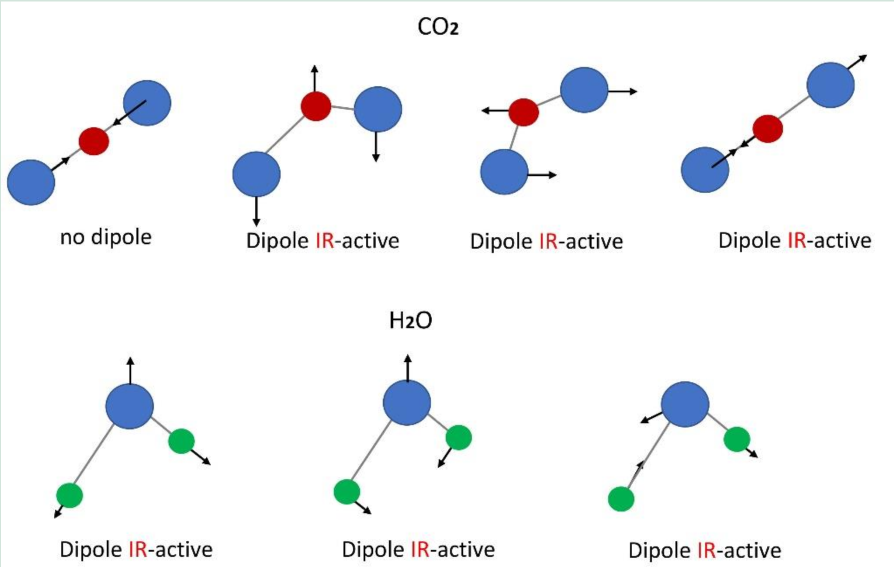


Figure 21 – IR-active Dipole-Molecules (Credits: Scorza)

However, this absorption of infrared radiation can only occur if the electrical dipole moment[7], which acts as a "lever" for the incoming radiation, changes during the oscillation. Molecular oscillations with this property are called IR-active. All symmetrical molecular oscillations in which the charge centre does not shift are therefore IR-inactive.

Dipole molecules have a constant dipole moment because the electrons are not distributed symmetrically. An example of this is the water molecule (see Figure 21, bottom row). Here, in addition to the polar H-O bonds, two free electron pairs reinforce the permanent dipole moment and all oscillation and rotation transitions are IR-active.

In contrast, the symmetrical CO_2 molecule has no constant dipole moment, since it is linear and the charge centres for positive and negative charges coincide. Despite this, bending vibrations of this molecule cause the symmetry to be broken up (Figure 21, upper row). The resulting dipole moments cause CO_2 to absorb infrared radiation and to act as a greenhouse gas.

[7] A molecule has an electrical dipole moment when the charge centres of the positive and negative charges do not coincide.

Chapter 3
The Earth’s Climate System

3.1. Distinction between Weather and Climate

In order to understand how human actions, influence the climate, we will first establish an overview of the Earth's climate system. A clear distinction between the terms climate and weather is essential:

The current state of the Earth's atmosphere at a certain time and place is called weather. The weather takes place on time scales from hours to weeks - i.e. in relatively short periods (see Table 1) and is determined e.g. by solar radiation, high- and low-pressure areas, convection, and precipitation.

The climate, on the other hand, refers to the average weather over many years, usually over a period of at least 30 to several thousand years. Short-term amplitudes or anomalies are therefore not decisive.

Phenomenon	Timescale	Examples
Micro-turbulence	seconds - minutes	Dust devil, gust of wind, heat shimmer
Weather	hours - days	Low pressure area, tropical storm, fair weather clouds
Weather conditions	weeks - months	Cold winter
Climate	years 12.500 years 200 years 100 years	Holocene climate optimum, small ice age (beginning of the Holocene), glacial retreat in the 20th century

Table 1 – Distinction between Weather and Climate (Credits: Scorza)

3.2. The Earth’s Climate System and its Components

The Earth's climate is mainly determined by solar radiation on the Earth's surface and by the interactions between the *main components of the climate system*. These are:

- Hydrosphere (oceans, lakes, rivers)
- Atmosphere (air)
- Cryosphere (ice and snow)
- Pedosphere and Lithosphere (soils and solid rock)
- Biosphere (life on land and in the ocean)

These components have different reaction rates to changes and thus decisively determine the dynamics of the climate system. We now take a brief look at each of them:

Climate Moderation through Oceans (Hydrosphere)

Activity 8

The oceans play an essential role in the Earth's climate system. They cover about 2/3 of the Earth's surface and absorb a large part of the incident solar radiation.

From a physical standpoint, water is an effective heat accumulator. A certain mass of water can absorb significantly more heat energy at the same temperature increase than, for instance, the same mass of air. The central physical term in this context is *heat capacity*. It is different for each substance, indicating how much energy is needed to heat one kilogram of a substance by one Kelvin. Water requires $4{,}183\ kJ$ of thermal energy, so it has a specific thermal capacity of $c_{Water} = 4{,}183 \frac{kJ}{kg \cdot K}$.

Air, on the other hand, has a significantly lower specific heat capacity of $c_{Air} = 1{,}005 \frac{kJ}{kg \cdot K}$.[8]

We know the following relationship of energy input ΔQ, mass m, and temperature increase ΔT:

$$\Delta Q = c \cdot m \cdot \Delta T$$

The different heat capacities mean that our oceans considerably buffer the energy brought in by the anthropogenic greenhouse effect. This becomes clear in the following simple model:

Two cuboids, each filled with $1\ kg$ of air, are to be heated by supplying energy around $\Delta T = 1K$. According to the above formula, the following energy quantity is necessary.

$$\Delta Q = c_{Luft} \cdot 2kg \cdot 1K = 2{,}01kJ$$

If one of the cuboids is replaced by a cuboid filled with water (also $1\ kg$), we get a quite simple model of the Atmosphere-Ocean system. To heat this system by $1\ K$ much more energy is needed:

$$\Delta Q = c_{Luft} \cdot 1kg \cdot 1K + c_{Wasser} \cdot 1kg \cdot 1K = 5{,}19kJ$$

In other words: If the energy quantity of $2{,}01\ kJ$ from the first model is added to this system, both atmosphere and water only heat up by approx. $0{,}4\ K$!

In total, around 93% of the additional energy introduced into the Earth's climate system by the anthropogenic greenhouse effect is stored in our oceans! However, the oceans not only extract heat energy from the atmosphere, but also CO2, which dissolves in the water. The oceans thus buffer the anthropogenic greenhouse effect twice over - but not without consequences, as we will see later.

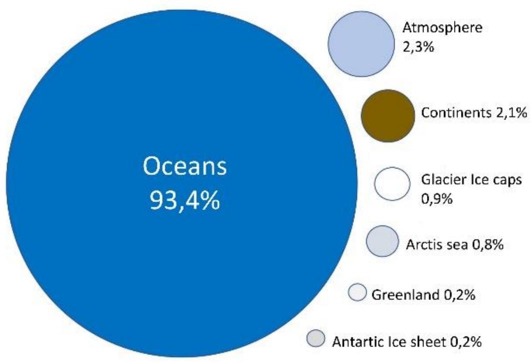


Figure 22– Heat Accumulators in the Earth System (Credits: Scorza)

---

8 The values are given under standard conditions, in the case of air with 0 % humidity.

The Changeful Atmosphere

The atmosphere is the most unstable component of the climate system. Above all, its lowest layer, the troposphere, is a place of very changeful weather events. Temperature differences are quickly balanced out and air masses that collide can lead to violent weather reactions such as storms, thunderstorms and heavy precipitation.

With its ability to absorb long-wave heat radiation, the atmosphere provides pleasant temperatures on Earth (see "The Atmosphere and the Greenhouse Effect" on page 17). Unfortunately, since industrialisation it has been increasingly used as a landfill for gaseous waste, leading to the greenhouse effect and other problems (e.g. ozone hole, fine dust pollution, etc.).

Clouds form in the atmosphere when water vapour cools down. They can have a strong local influence on the permeability of both the Sun's radiation and the ground's thermal radiation. Hence, they are a decisive factor in the climate system. A distinction is made between different types: High cirrus clouds are almost completely permeable to solar radiation, whereas low and dense stratus clouds reflect the Sun's radiation during the day and have a cooling effect; at night, they reflect the ground's heat radiation and have a heating effect. For instance, a deep cloud cover on a winter night prevents the heat radiation from escaping into space; compared to a starry, cloudless winter night, it remains significantly warmer.

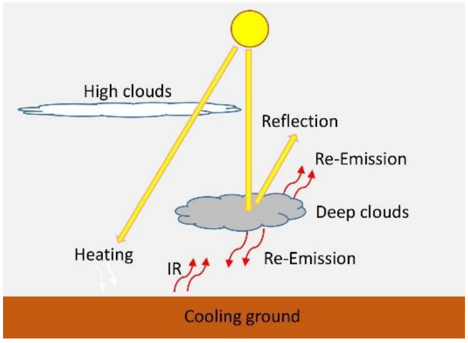


Figure 23 – Effect of high and low clouds (Credits: Scorza)

The Role of the Cryosphere regarding the Radiation Balance

Ice and snow surfaces play an important role in the Earth's radiation balance, since both have a much higher reflectivity (albedo) than soil and water. While the oceans and the ground have an albedo of 10-20 %, accordingly absorbing up to 90 % of the incident solar radiation and converting it into heat radiation, the albedo of ice and snow is 50-90 %.

With a growing ice and snow cover on Earth, the global albedo increases. Due to the stronger reflection, less energy is absorbed by the Earth. This cooling further increases the formation of ice and snow, which in turn increases the albedo. Geologists and climate researchers are currently discussing whether our planet has even experienced phases of complete icing in the course of its history, as was the case according to the hypothesis of the "Snowball Earth" some 750 to 600 million years ago. It is assumed that volcanism which caused massive CO_2 emissions and thus the associated greenhouse effect, liberated the Earth from its ice shell.

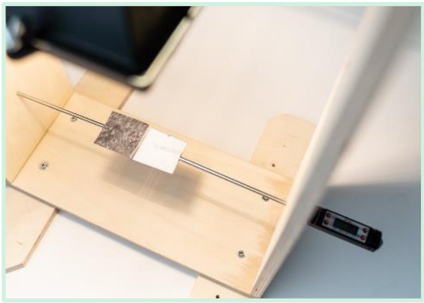


Figure 1 – Model experiment on the Albedo from the climate case. The dark body heats up more strongly under the same lighting.

Of course, this effect can also occur in the opposite direction: Melting ice and snow reduce the albedo and thus increase the ground warming of ground, air and water, which further accelerates the melting process. The size of a planet's ice and snow surfaces therefore has a major impact on its climate.

The Pedosphere and Lithosphere in the Climate System

It has already been shown that the energy exchange from soil to atmosphere takes place via the emission of heat radiation. Another form of energy release, latent heat, occurs through the evaporation of water near the ground: energy is extracted from both the surrounding ground and the air in order to evaporate water, which enters the atmosphere as water vapour. If the soil is relatively dry, less latent heat can be released into the atmosphere, since due to the lower occurrence of evaporation, less energy can escape as latent heat, which leads to an increased temperature of the soil. Since less water vapour also enters the atmosphere, fewer clouds form and the radiation on the ground is intensified - the ground becomes warmer and drier and a positive feedback begins.

The Role of the Biosphere

The influence of the biosphere on the climate is determined by the gas exchange with the atmosphere, especially in the carbon dioxide cycle. Originally, the Earth's atmosphere consisted mainly of carbon dioxide and nitrogen. The primitive algae of the primordial oceans added oxygen via photosynthesis, enabling more developed forms of life.

Even today, the significance of the biosphere regarding climate lies primarily in its influence on the chemical composition of the atmosphere and thus on the strength of the greenhouse effect: plants constantly remove carbon dioxide from the atmosphere by means of photosynthesis. The concentration of methane and nitrous oxide, which also act as greenhouse gases in the atmosphere, is also partly controlled by processes in the biosphere. The greenhouse gas methane is produced naturally mainly by the anaerobic decomposition of organic material (e.g. in the stomach of a cow) while the formation of nitrous oxide is strongly influenced by the activity of bacteria in soil and water. Furthermore, a plant cover on the Earth's surface increases the albedo.

Excursus: Atmospheric circulation systems and climate change

PROF. THOMAS BIRNER - METEOROLOGICAL INSTITUTE OF THE LMU MUNICH

Global warming is primarily a consequence of the altered energy balance of the Earth's atmosphere as a whole, caused by increased concentrations of greenhouse gases (see Section 2.4). However, the extent to which the redistribution of available energy in the Earth's atmosphere changes is also decisive for regional climate change. This redistribution is directly related to atmospheric circulation systems - e.g. low and high pressure areas - and is highly variable in some regions. Moreover, there are still gaps in our basic understanding of such circulation-driven climate changes. This motivates not only an improvement of computer climate models for better long-term predictions, but also further basic research. Our group at the Meteorological Institute of the Faculty of Physics at the LMU is working on "Stratosphere-Troposphere Dynamics and Climate" and aims to improve the fundamental understanding of the variability and long-term change of large-scale circulation systems.

Why do large-scale circulation systems occur at all?

There is a general energy imbalance between the tropics and higher latitudes: in the tropics, more solar energy is absorbed by the sun than is radiated back into space by the Earth system

- an energy surplus; at high latitudes, more energy is radiated into space, i.e. absorbed by the sun - an energy deficit. This energy imbalance between the tropics and higher latitudes generates heat transport, which manifests itself in the form of large-scale circulation systems. In this sense, the atmosphere is a huge heat engine, with the circulation systems constantly tending to reduce the temperature difference between the tropics and higher latitudes, thus balancing the energy imbalance.

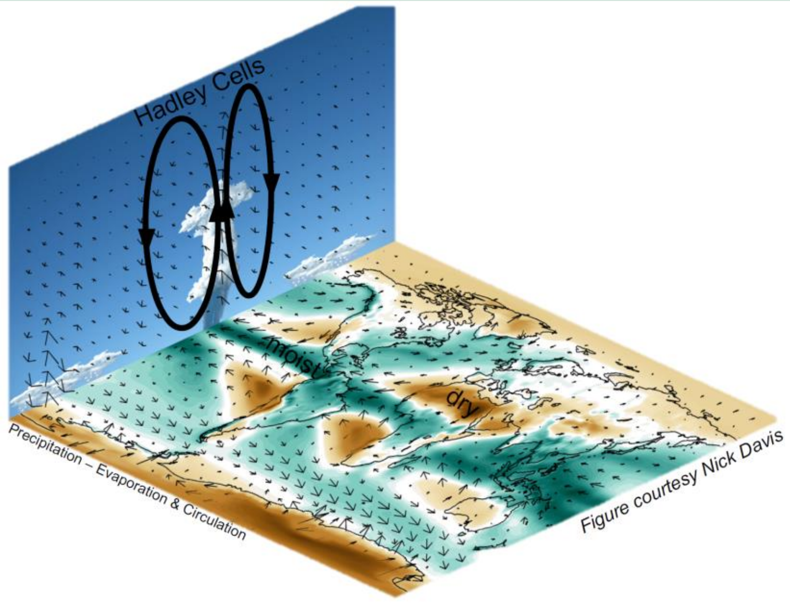


Figure 25 - Hadley circulation diagram (Credits: Nick Davis)

In the tropics and subtropics this redistribution of energy takes place in the form of the so-called Hadley circulation. In this Hadley circulation, warm and humid air rises near the equator within high-reaching thunderstorms, flows slowly polewards at an altitude of ~15 km, sinks in the subtropics as dry air and flows back towards the equator near the ground. In the process, the high-altitude current is deflected eastwards by the Coriolis effect, thus creating subtropical jet streams. In a similar way, the airflow near the ground is deflected to the west and thus generates the trade winds. The dry, sinking air in the subtropics prevents cloud formation and rain and is therefore responsible, among other things, for the dry zones typical of this climate zone. A signal of climate change that has been increasingly documented in recent years is a poleward expansion of the Hadley circulation and thus a shift of the subtropical dry zones towards mid-latitudes. For regions that have had just enough rainfall to date, e.g. for agricultural purposes, the associated change towards a predominantly dry climate has dramatic consequence

In our group we investigate, among other things, how the extent of the Hadley circulation varies from year to year and which processes are responsible for this variability. This allows us to draw conclusions about the mechanisms that determine the typical location of subtropical dry zones. For these investigations we mainly use data from global calculations with modern computer weather forecast models, which are combined with observational data. Such so-called reanalyses currently represent the best source of information on the actual state of the atmosphere and the currents contained therein with global coverage. They contain information on temperature, wind components, humidity and other meteorological variables and are now available with high quality and global coverage for the so-called satellite era (since 1979). We use modern statistical methods to evaluate these data, e.g. to find dominant patterns of variability.

In addition, we investigate mechanisms of the expansion of the Hadley circulation over climatic periods using simplified global computer climate models. In doing so, certain processes are deliberately neglected in order to be able to consider possible mechanisms in isolation. Using such computer model simulations, we have found, for example, that the interaction of high and low pressure systems, which sometimes move from mid-latitudes into the subtropics, with the Hadley circulation plays a decisive role in the poleward expansion of the Hadley circulation caused by climate change.

At higher latitudes, the highs and lows mentioned above are responsible for the poleward heat transport (e.g. in the case of a low-pressure system in the northern hemisphere - a rotating circulation counterclockwise when viewed from space - cold polar air flows south on its western side and warm subtropical air flows north on its eastern side). These lows and highs usually migrate along the jet stream of mid and polar latitudes (~polar front jet), but at the same time influence this jet stream by their induced heat transport. A robust projected signal of climate change is a poleward shift of this jet stream, which is not yet well understood. Our research results have contributed to a better understanding of the coupling of both poleward displacement signatures (Hadley circulation and jet stream) of climate change.

A further coupling, which has been described more and more in recent years, exists with the circulation of the stratosphere (height range ~10-50 km) in winter and spring. Here the so-called polar vortex is formed by the strong cooling of the polar cap in winter. The strength of this polar vortex sometimes varies greatly. Due to certain dynamic processes, this vortex can sometimes collapse abruptly. Although the stratosphere has less than 20% of the mass of the atmosphere, analyses of observational data have shown that these variations of the stratospheric polar vortex can influence the circulation down to the ground. This happens both in shorter weather periods and in longer climate periods. However, the future change in the polar vortex caused by climate change is rather uncertain, especially in the highly variable northern hemisphere. Our group therefore investigates the mechanisms of the variability of the polar vortex and the coupling to the circulation of the troposphere to the ground. For this purpose, we again use reanalysis data and simulations with simplified computer climate models.

3.3. The Origin of Climate Zones

The term "climate" is derived from "klinein", the Greek word for "incline", since the seasons are a consequence of the inclination of the Earth's axis relative to the orbital plane of the Earth around the Sun. The inclination causes the northern hemisphere to be irradiated more vertically and thus more intensively by the Sun during the northern summer (position a. in Figure 26), while the Sun's rays in the

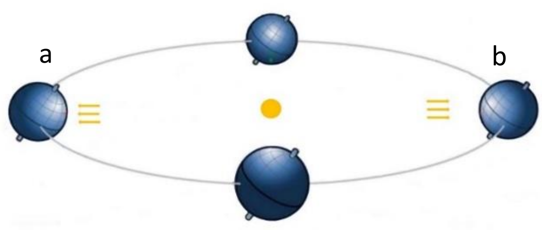


Figure 26 – The Four Seasons (Credits: Scorza)

southern hemisphere are relatively oblique. Six months later, the southern hemisphere is irradiated more intensively (position b. in Figure 26) and winter prevails in the northern hemisphere.

A second consequence of the inclination of the Earth's axis is that the mean temperature is highest around the equator during the year and decreases towards the poles. Thus, the different angle of incidence at which solar radiation hits the globe is also the reason why different climate zones exist on Earth.

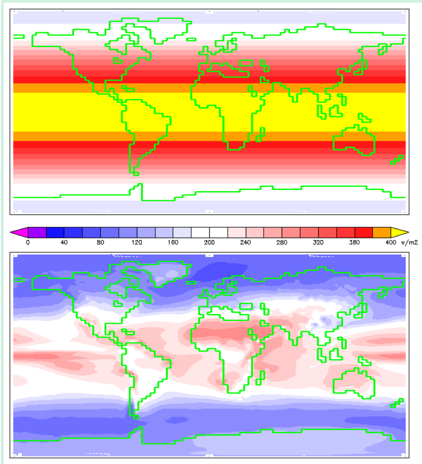


Figure 27 - Annual Mean Value of Solar Radiation outside the Earth's Atmosphere (Top) and on the Earth's Ground (Bottom) in W/m^2 (Credits: William M. Conolley)

Climate zones are groups of areas which extend around the Earth in an east-west direction, having common features (e.g. regarding vegetation) due to the climatic conditions.

In the tropics it is warm and humid all year round. Depending on the location, tropical rainforests as well as tropical steppes and deserts can be found. There are only a dry and a rainy season while the temperature fluctuations within one day are greater than the annual ones. On the other hand, the seasons are clearly distinguished in the climate zone where Germany is located. In the interior of continents, it is dry and coniferous, deciduous, and mixed forests grow. In the polar regions, the Sun comes in relatively shallowly all year round and it is therefore much colder on an annual average. The vegetation is less luxuriant with grasses and low shrubs. A characteristic of this zone is the three-month polar day in summer and the three-month polar night in winter.

With the climate zones it becomes visible what effects it has if the Earth's surface is supplied with different amounts of energy. Thus, for example, the average angle of solar radiation on an annual average has a significant influence on vegetation. The additional energy flow towards the Earth's surface caused by the anthropogenic greenhouse effect will change the position of these climate zones and shift them from the equator towards the poles - a movement that most of the species, specialized in their respective ecosystem, won't be able to follow.

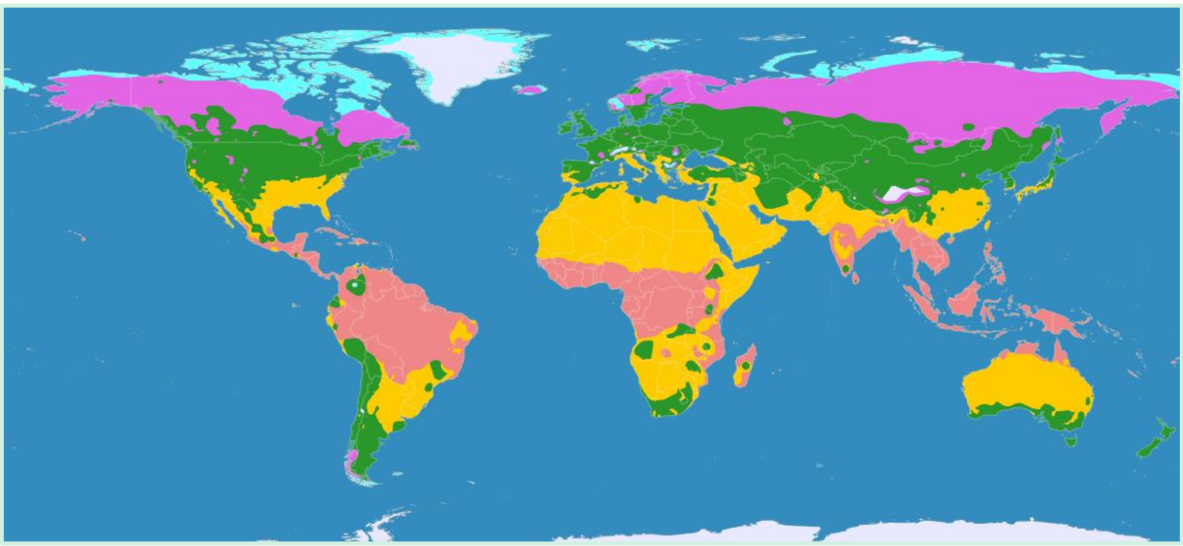


Figure 28 - The Earth's climate zones (Source: LordToran - Self-created on the basis of this geodata:, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=2301350)

Excursus: Weather and Climate Models

Meteorologists derive the weather forecast from calculation results of computer simulations (so-called *weather models*). A high-performance computer calculates from a given initial state of the atmosphere the state at a later point in time, using equations based on physical correlations. The initial state results from numerous station observations, such as measurements with buoys, ships, airplanes and weather balloons, as well as from satellite and radar data (see Figure 29). The aim is to be able to give as accurate a forecast of local weather as possible.

The difficulty with weather calculations lies in the fact that the atmosphere is a complex system with partly chaotic behaviour. This means that the future state of the atmosphere depends strongly on the initial conditions, which cannot be determined exactly. Model calculations therefore become increasingly uncertain with increasing prediction time. For this reason, the weather is generally predictable for about seven days on average.

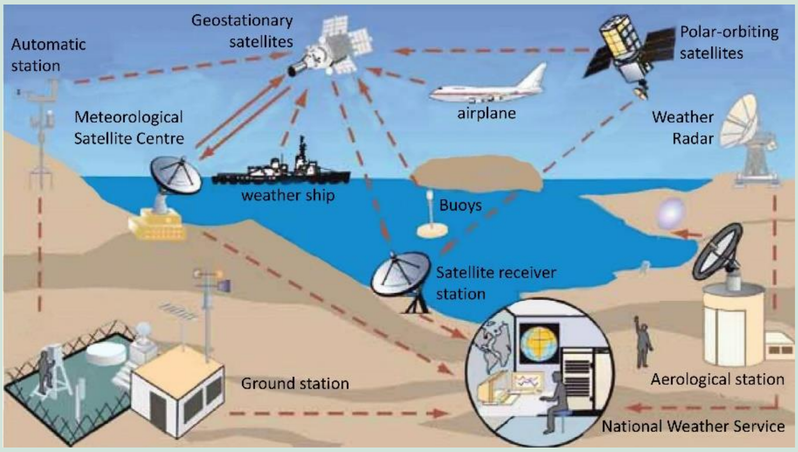


Figure 29 - The global meteorological observation system (Source: weather service.de DWD

Global *climate models* are just as complex physical models; they represent the Earth's climate system in simplified form. The climate simulations calculate with linked atmosphere-ocean models the reaction of the system to changed conditions, such as changes in solar radiation or changed energy flows in the climate system. For this purpose, the atmosphere and oceans are divided into a three-dimensional grid. The exchange of mass and energy between adjacent lattice points is solved step by step by fundamental physical differential equations from fluid dynamics, hydrology and chemistry. In this way, for example, it can be investigated how increased greenhouse gas emissions affect the future climate.

While the prognosis of a weather model can be checked directly by observation, the results of climate simulations can only be compared with averaged weather values. In order to check whether a climate model delivers plausible results, it is fed with measured data and plausible assumptions and then tested whether it can correctly simulate the current climate, but also, for example, that of past ice ages. In order to make a climate forecast, different climate models are fed with a range of available data and assumptions to predict the range of future developments.

Chapter 4
The Anthropogenic Climate Change

4.1. The Anthropogenic Greenhouse Effect

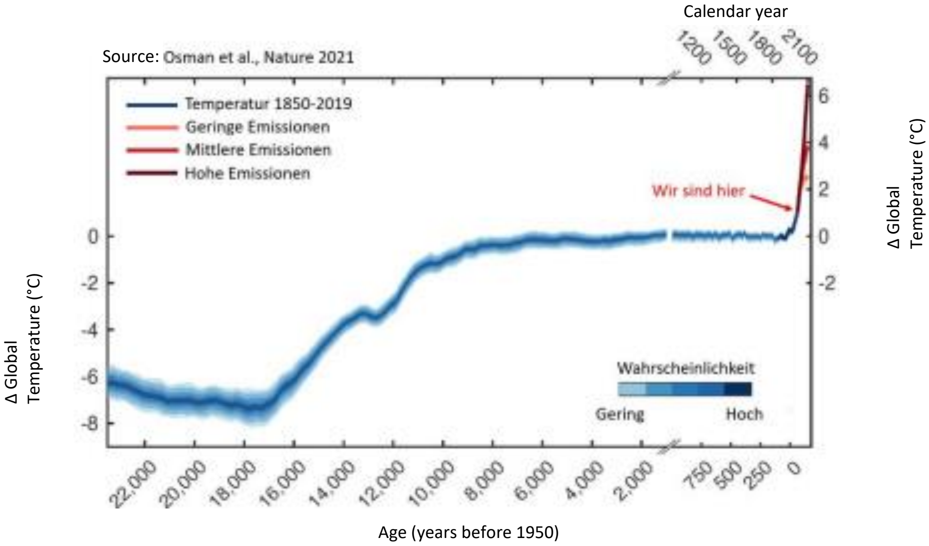


Figure 30 - The graph shows the global temperature trend since the last ice age, with future scenarios. The last 2000 years have a higher resolution (source: Osman et al., Nature 2021).

The Earth was formed about 4.6 billion years ago. Since then it has seen climatic fluctuations and large changes again and again. Since the beginning of the Holocene about 12,000 years ago and thus since the last ice age, our climate has been relatively stable compared to earlier periods (see Figure 30). Since 1980, however, a significant increase in the mean atmospheric temperature has been observed.

Today, there is a consensus in climate research that the current climate change cannot be explained without human activity:

"Among those who understand the nuances and science behind long-term climate processes, there seems to be virtually no debate about the fact of global warming and the role of human activity in it. The challenge seems to be how to effectively communicate this fact to politicians and the general public, who mistakenly assume a debate among scientists."

Quote from a study in which the consensus among geoscientists on the question "Do you think that human activities have a decisive influence on the change in average global temperatures?" was examined. [6]

Activity 4 Activity 5

Carbon dioxide plays a decisive role in the anthropogenic (caused by humans) greenhouse effect [7]. For thousands of years, the CO_2 level in the Earth's atmosphere has been below the 300ppm[9] mark (see Figure 31). Since the Industrial Revolution of 1800, however, the concentration has risen sharply by more than 40 % from around 280 ppm to over 400 ppm today and is now higher than at any time in the last 400,000 years.[10]

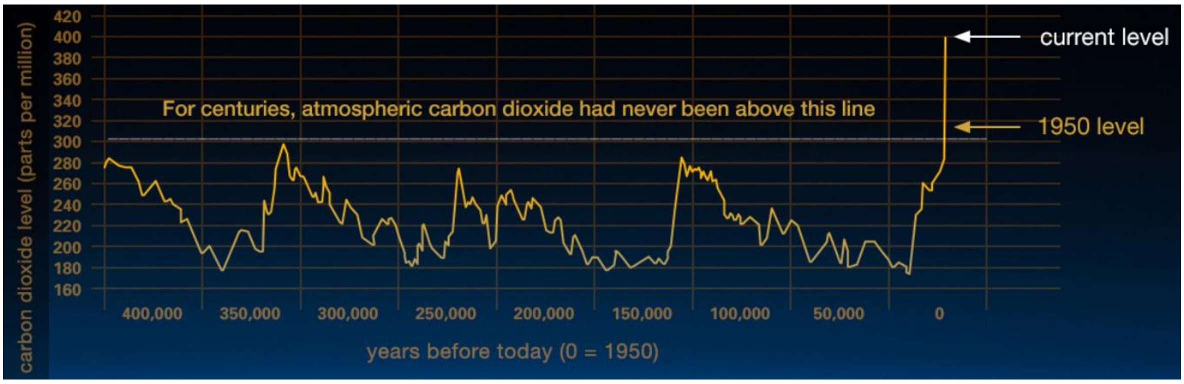


Figure 31 - Diagram of CO2 Concentration in the Atmosphere with Data from Current Measured Values and Reconstructions Using Ice Cores (Source: NASA - Global Climate Change; climate.nasa.gov/evidence/ called on 20.01.2019)

The main reason for this is that humans burn carbonaceous fossil fuels to produce usable energy, which releases carbon dioxide, among other things, when oxygen is supplied. Initially, this happened mainly in Europe and North America, later also in Russia, China, India and Brazil. In the last four generations, annual CO2 emissions have risen from 2 gigatons (1900) to 37.1 gigatons in 2017, the highest level ever recorded [8].

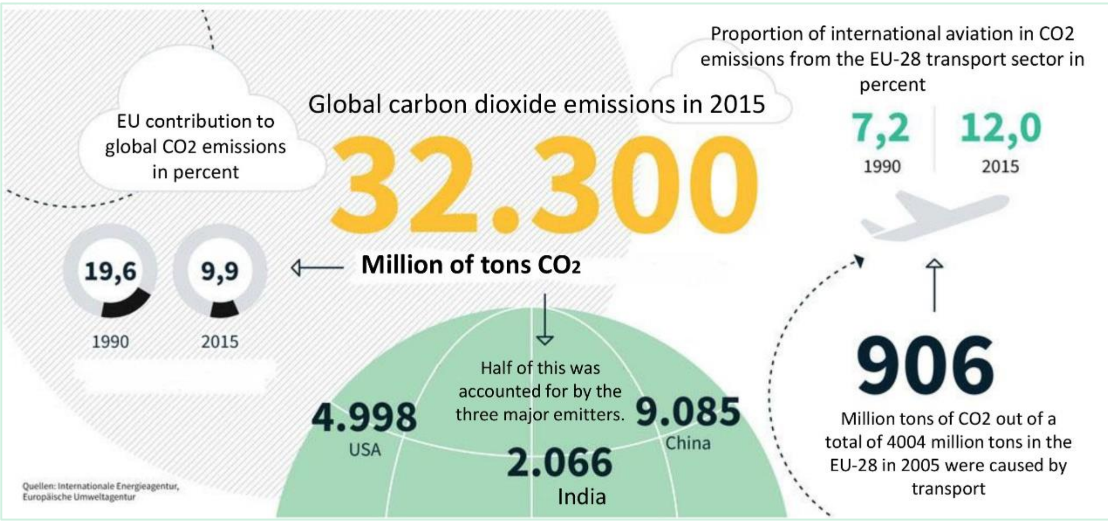


Figure 32 - Global Carbon Dioxide Emissions in 2015 (Credits: International Energy Agency, European Environment Agency)

---

9 ppm stands for parts per million, i.e. the number of CO_2 molecules per million molecules of dry air.

10 How do you know that? Drilling cores from a depth of more than 3 km were taken from the hundred-thousand-year-old ice of Antarctica. From the air bubbles it contains, conclusions can be drawn about the composition of the atmosphere in different eras of the Earth's history.

Figure 33 illustrates the global increase in carbon dioxide concentration over the past 150 years. The objection often raised by sceptics of anthropogenic climate change, stating that the fluctuations of sunspots with their increased radiation values would be responsible for the measurable rise in temperature over the last four decades, can be clearly contradicted. Solar activity is decreasing, while the temperature and carbon dioxide content of the atmosphere are increasing. Solar activity and global warming are decoupled, they even develop in the opposite direction.

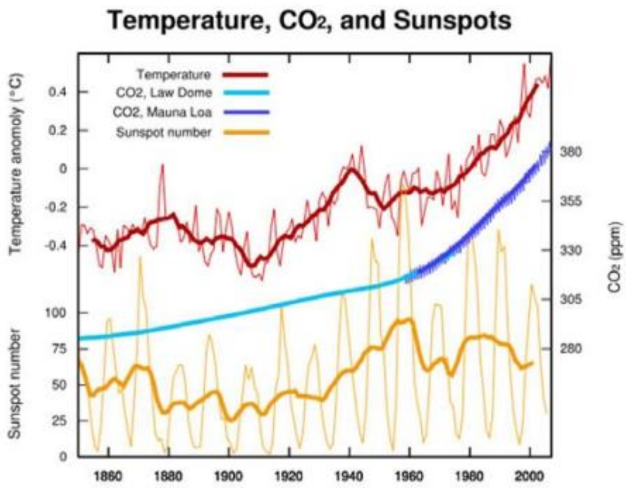


Figure 33 - Temperature and CO_2 increase (Source: ttp://en.wikipedia.org/wiki/Image:Temp-sunspot-co2.svg, called on 01.07.2021)

Methane (CH4) also plays a decisive role in the increased greenhouse effect. Compared to CO_2, it is more effective as a greenhouse gas by a factor of around 28 to 72 if we consider the effect over the next 100 or 20 years.[11] Since the industrial revolution, the methane concentration in the Earth's atmosphere has increased from around 700 ppb[12] to over 1800 ppb today [9]. 37 % of global methane emissions are directly or indirectly attributable to livestock farming [10] and today methane contributes around 16 % to the anthropogenic greenhouse effect [11]. This figure could soon rise sharply due to the thawing of the permafrost in Siberia and Canada (see "Water vapor and feedback effects" below). Methane is a short-lived greenhouse gas. Most of it oxidizes in the atmosphere within a decade to form carbon dioxide, which then warms the atmosphere further over a period of thousands of years.

Another greenhouse gas is nitrous oxide (N_2O), which has a 265 times higher greenhouse potential than carbon dioxide. In the Earth's atmosphere, the concentration of this gas has risen by about 20% since the Industrial Revolution and today contributes about 6% to the anthropogenic greenhouse effect [6]. The emission of N_2O occurs both naturally and in ways influenced by humans: In nature, N_2O is released by bacteria in soil, in water and in primeval forests. However, humans contribute to the increased release of this greenhouse gas by nitrogen-based fertilizers, the industrial production of chemicals, and by burning fossil fuels.

Fluorinated greenhouse gases also play a role. Unlike the gases mentioned above, they are not produced by natural processes, but were developed specifically for industry. Although their share of total greenhouse gas emissions from industrialized nations is very small, their effects should not be underestimated due to their long residence time in the atmosphere (possibly several thousand years) and their effectiveness as a greenhouse gas per molecule (12,000 to 25,000 times stronger than that of CO_2)

[11] In order to compare the harmfulness of greenhouse gases emitted over a certain period of time, they are each assigned a CO_2 equivalent (CO_2e), also known as global warming potential. Normally, a period of 100 years is assumed, in which case this factor is 28 for methane. If, on the other hand, a period of 20 years is assumed, i.e. a period in which we can still prevent the climate from tipping over, methane has 72 times the impact potential compared to CO_2 [43]

[12] ppb stands for parts per billion, i.e. parts per billion molecules of dry air

4.2. Feedback Effects

Activity 12

Increases in global temperature and climate change result in effects which themselves contribute to an amplification of their cause, i.e. can lead to a further increase in temperature. These are known as feedback processes. These feedback processes represent the actual "crux" of climate change. Something shifts and the climate system reacts with changes. The natural processes in the interplay of the atmosphere, the seas and oceans, the ice masses, and the biosphere have always taken place, even in times when there were no humans. Depending on the land mass distribution, volcanism and various astronomical parameters, the climate changed constantly - the change of the climate is therefore completely natural. In recent decades, however, the concentration of molecules with the ability to absorb heat radiation has been drastically increased by anthropogenic influences. In the middle of a networked, multi-layered and therefore complex natural event, humans change the boundary and initial conditions of the atmosphere through the extraction of fossil resources. Carbon, which was buried deep in the soil hundreds of millions of years ago, is first brought to the Earth's surface by coal, oil and gas extraction and then finally released into the atmosphere by combustion processes. Every natural system reacts to this gradual change through feedback effects quite naturally.

Some examples for these feedback processes are:

Water vapour in the atmosphere

Water vapour is the strongest natural greenhouse gas. However, it has only a very short residence time in the Earth's atmosphere, usually lasting only a few days and then returning to the Earth as rain (due to the higher absorption capacity of a warmer atmosphere, increasingly also as heavy rain). In total, its contribution to the natural greenhouse effect is about two to three times as high as that of CO_2. In contrast to CO_2, however, water vapour is not a direct cause of the human-induced increase in the greenhouse effect (the anthropogenic greenhouse effect is not caused by the increased emission of water vapour). However, due to the warming of the Earth's atmosphere by other greenhouse gases, more water evaporates and the hotter it gets, the higher the water vapour concentration in the atmosphere is[13]. An increased concentration of water vapor in the atmosphere increases the greenhouse effect, which in turn leads to higher global warming and so on [7].

Reduced albedo

Global warming leads to the melting of ice on the Earth's surface, for example in the Arctic Ocean. The sunlight is no longer reflected back into space by the glistening snow, but is lost in the depths of the polar seas or warms the exposed dark subsoil. The energy heats up the water or the ground and remains in the earth system, further driving global warming [12].

Melting of the Greenland ice sheet

In recent years, the loss of ice in Greenland has increased considerably due to glaciers flowing into the sea and increased melting in summer. As a result, the ice sheet, which in places is three kilometres thick, loses height in the long term. Its surface, which is now still in high and therefore cold layers of air, is sinking and is thus exposed to warmer temperatures. This in turn further intensifies the melting

[13] This effect can be observed, for example, in winter on poorly insulated window panes. As the warm and relatively humid room air cools down near the window, its capacity to absorb water vapour decreases and the water condenses on the glass pane.

process. In addition, the increased meltwater on the glacier bed accelerates the sliding of the ice masses into the sea like a lubricating film. The complete collapse of the Greenland ice sheet would cause a sea-level rise of 7 metres over centuries to millennia and of course also contribute to a reduction in albedo (see [13]).

Desertification of the Amazon rainforest

The rainforest is dependent on huge amounts of water that evaporate. A large part of the rainfall in the Amazon Basin comes from water that condenses back over the forest. The decrease in precipitation in a warmer global climate on the one hand, or the clearing of the forest on the other, could bring this cycle to a critical limit: The fewer forest areas evaporate water, the drier the region becomes and the less water is available to the forest. A conversion of the Amazon rainforest into a seasonal forest or grassland adapted to the dryness would also have fundamental effects on the Earth's climate: after all, about a quarter of the global carbon exchange between the atmosphere and biosphere takes place here. In the event of a loss, gigantic quantities of previously bound carbon would be released as CO_2, which, as a greenhouse gas, would further drive global warming (see [14]).

Decline of the Nordic coniferous forests

The Nordic coniferous forests cover almost one third of the world's forest area. With climate change, the stress caused by plant pests, fire and storms is already increasing significantly. At the same time, water shortages, increased evaporation and human use are affecting the regeneration of the forests. If the stress exceeds characteristic thresholds, they could be displaced by bush and grasslands. The disappearance of the forests would not only destroy the habitat of many animals and plants, but would also mean a massive release of carbon dioxide, which could contribute to accelerated global warming (see [12]).

Thawing permafrost

In the Siberian and Canadian permafrost soil, several hundred billion tonnes of carbon are probably stored at depths of more than three metres. They originate from organic material that was stored here during and since the last ice age. If the permafrost heats up, it releases huge quantities of carbon dioxide and methane, i.e. greenhouse gases, into the atmosphere (see [12]).

Attenuation of the marine biological carbon pump

The world's oceans absorb huge amounts of carbon - around 40% of the anthropogenic CO_2 emissions that have been produced to date have been removed from the atmosphere. Algae use a large proportion of this for growth. After dying off, they sink into the deep sea and thus store the carbon. This function could be limited by the warming and acidification of the water as well as more frequent oxygen depletion, so that more CO_2 remains in the atmosphere (see [15]).

Decrease in the absorption capacity of CO_2 in seawater

The temperature of the oceans is rising due to global warming. However, since the water's capacity to absorb carbon dioxide decreases with increasing water temperature, the CO_2 concentration in the atmosphere increases (see [16]).

4.3. Tipping points

Activity 11

Climate change entails processes that are self-reinforcing. These feedback processes occur when certain temperatures are exceeded. At these thresholds, small changes can cause the Earth's system to change to a qualitatively new state. This is known as a tipping point. "Tipping" means that these changes develop a dynamical process that can no longer be stopped and is therefore irreversible. The phenomenon of such tipping processes also plays a role for some feedback effects when viewed in isolation. This means that a progressive increase in temperature can lead to a cascade of mutually triggering tipping points ("domino effect"). Figure 34 shows the tipping point elements of the climate system.

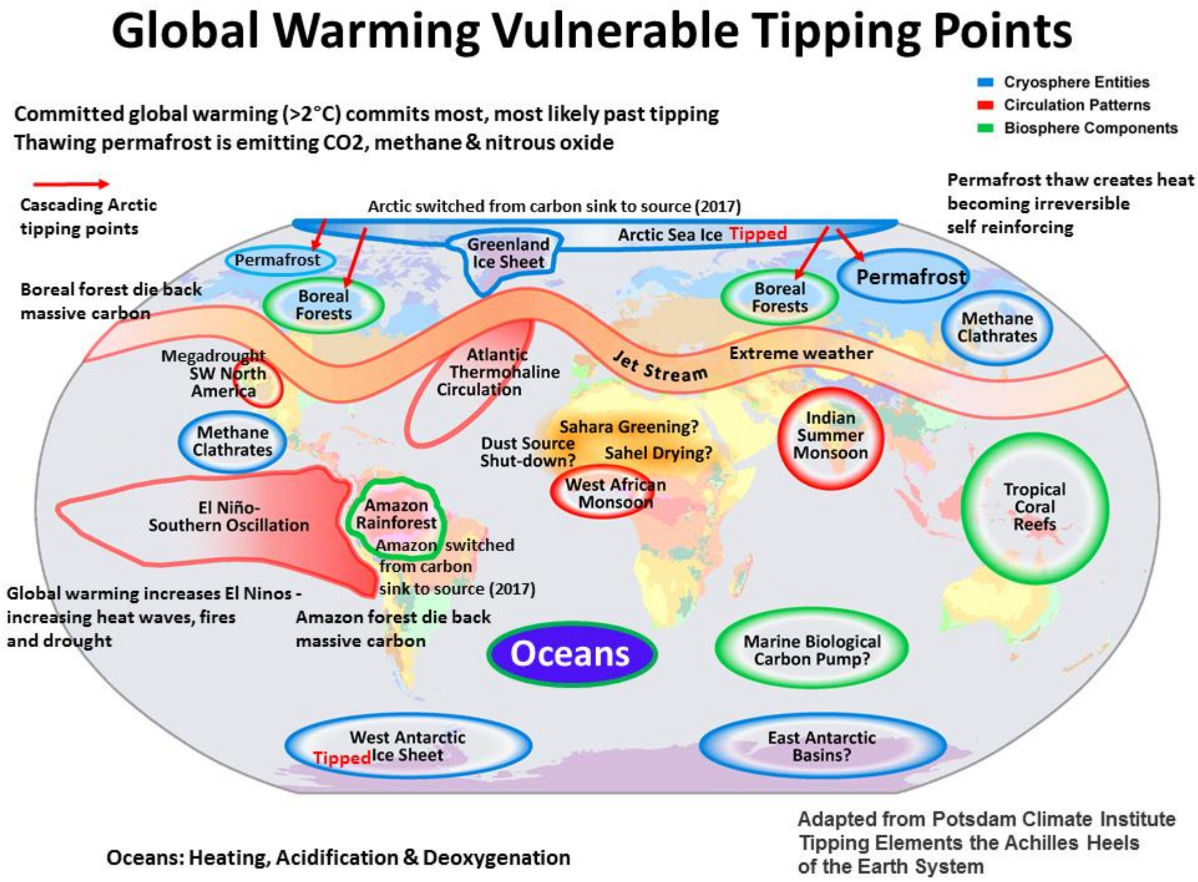


Figure 34 - tipping point elements of the climate system (Credits: Rahmstorf et al, 2019, PIK)

Chapter 5
Effects of Climate Change

5.1. Global Effects of Climate Change

As seen in the previous chapter, current global warming is the result of rising concentrations of carbon dioxide, methane, nitrogen oxides and other greenhouse gases, caused by humans with their actions and lifestyle. The increased greenhouse effect leads to changes in temperature, precipitation, cloud cover, snow cover, and the sea mirror, as well as to a significantly higher incidence of weather extremes of all kinds, e.g. long periods of drought, extreme precipitation, and increased atmospheric activity (storms). Some of these impacts are based on simple physical relationships, such as the rising sea level, the acidification of oceans or the albedo reduction. Others are complex, non-linear consequences, such as changes in sea currents with their impact on ecosystems, the habitability of Earth regions, and agriculture. In the following, the effects connected with water are discussed. Further consequences are shown in a table below.

The higher the temperature, the faster water evaporates. This leads to the feedback mentioned in the previous chapter. Due to the increased air humidity and the increased energy supplied to the atmosphere by condensation, the probability and strength of extreme weather events such as thunderstorms, hail and storms up to hurricanes is also increased (see [17]).

Activity 6

One of the risks posing a direct threat to humans is the rising sea level. Between 1993 and 2010, the consequences of the greenhouse effect led to an increase of 3.2 mm per year. In its 5th climate report from 2013, the Intergovernmental Panel on Climate Change (IPCC) predicts that sea levels will rise by 52 to 98 centimes by 2100 if greenhouse gas emissions continue unabated [9]. One reason for this increase is that water (like all liquids, solids and gases) occupies a larger volume at higher temperatures[14]. The share of this thermal expansion in rising sea levels is estimated at 30 to 55 % [18]. The rest is mainly due to melting continental ice, such as that of the Antarctic ice sheet or the glaciers in Greenland[15]. Current measurements conclude that the continental ice is degrading much faster than previously assumed: the melting of ice causes a sliding layer which forms between the ice and the ground. Thus resulting in huge areas of ice slipping into the sea [19].

The forecasts up to the year 2100 are just the beginning; this is shown by the comparison of temperature and sea level in recent geological history in Figure 35. The Greenland ice sheet binds an amount of water that, if it melted completely, would cause a global sea level rise of seven meters. If the West Antarctic Ice Sheet were to melt, sea levels would rise by 3.5 meters, and if the East Antarctic Ice Sheet (which has so far been considered largely stable) were to melt, sea levels would rise by more than 55 meters [7]

[14] Excluded from this, of course, is the density anomaly around 4 °C, which plays no role for our considerations.
[15] Melting sea ice, on the other hand, does not lead to an increase in sea level; see corresponding experiment in the climate kit

This would result in catastrophic flooding, especially for low-lying coastal regions and cities which include the world's most densely populated regions: 22 of the world's 50 largest cities are located by the coast, including Tokyo, Shanghai, Hong Kong, New York and Mumbai. In Bangladesh, 17% of the country's land area currently stands out of the water less than a metre - with a population of around 35 million. Other countries such as the island state of Kiribati are not expected to be habitable by 2050 and completely flooded by 2070. The Kiribati government is already taking steps to resettle the over 100,000 inhabitants.

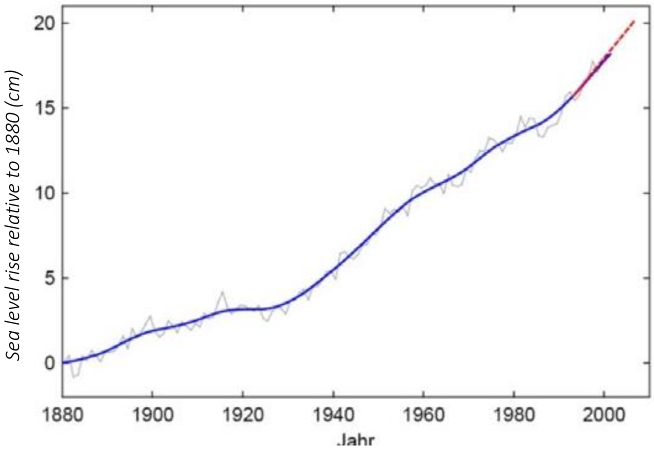


Figure 35 – Sea level rise relative to 1880 (Credits: Rahmstorf)

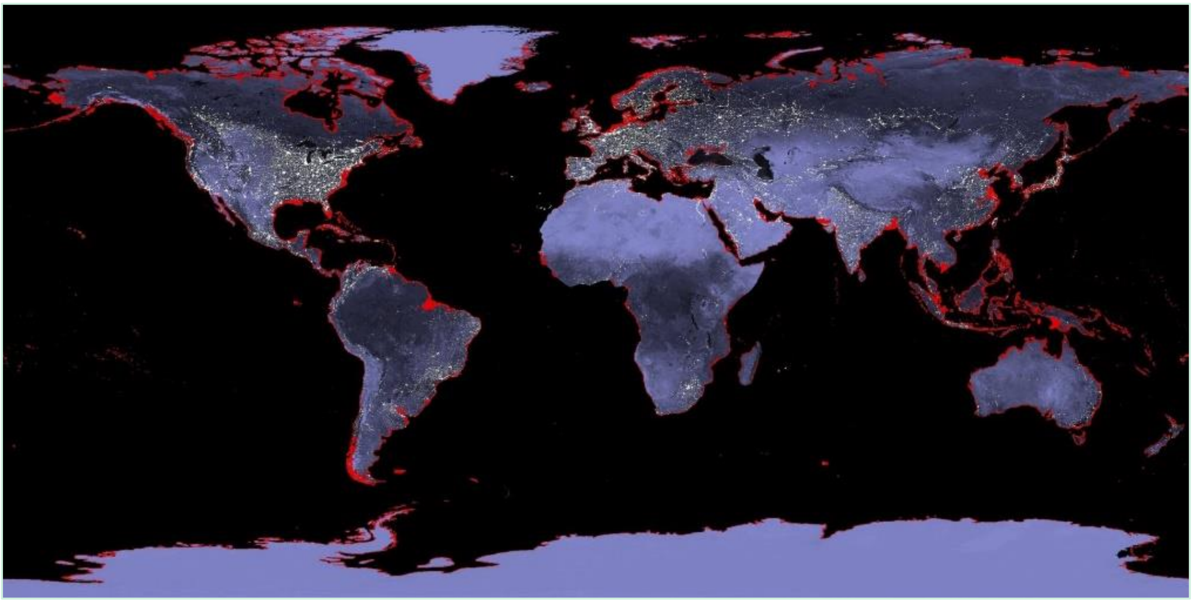


Figure 36 - Coastal Areas Affected by a Sea Level Rise of One Meter (Source: https://commons.wikimedia.org/wiki/File:6m_Sea_Level_Rise.jpg called on 27.05.2020)

Global warming also has extensive consequences for the water supply of many people. If the temperature were to rise by 4 °C, the melting of huge glaciers in the Himalayas would affect around a quarter of China's population and around 300 million people in India. In the Mediterranean region and in the southern regions of Africa, the drinking water supply would be severely restricted. Around two billion people worldwide would suffer the consequences of recurring droughts and dryness [20].

The following table examines further effects on the components of the Earth's climate system:

Component	Changes	Effects
Hydrosphere	Global warming leads to the thermal expansion of the oceans. Melting continental ice flows into the sea. The sea level rises.	Flooding of coastal areas and coastal cities; mass extinction of fish, algae and other marine animals, to some extent due to the rise in water temperature.
Atmosphere	Hot dry air increases erosion in some regions, while in others a higher water vapour content increases cloud formation and precipitation.	Extreme weather; heat waves with considerable damage to flora and fauna, and effects on humans; heavy rainfall with sudden floods.
Cryosphere	Melting ice and snow reduce the albedo (reflectivity).	More solar radiation is absorbed by the soil which leads to stronger global warming.
Biosphere	With global warming, plant and animal species become extinct (e.g. due to shifts in climate zones, changes in ecosystems, drought, forest fires).	Disappearance of CO_2sinks. Less CO_2 is absorbed by photosynthesis and transformed into O_2.
Pedosphere and Lithosphere	Unveiling of dark areas due to melting ice and snow.	Reduction of albedo, reinforced global warming.

Table 2 - Changes in the components of the climate system due to global warming (Credits: Scorza)

Overall, the consequences described are catastrophic: the environmental protection organization Greenpeace assumes that by 2040 at least 200 million people will have to leave their homes in order to survive and thus become climate refugees [21].

5.2. The Acidification of the Oceans

Activity 9

Perhaps it should be mentioned in this somewhat "apocalyptic" chapter that the capacity of water for the absorption of gases decreases with temperature. Today, the oceans still buffer over 90% of global warming through heat absorption (see hydrosphere on page 21) and carbon dioxide dissolution [22]. This will decrease in the future. Because of the difference in the partial pressure of CO_2, the atmosphere exchanges CO_2 with the ocean. The partial pressure corresponds to the proportion of CO_2 the total pressure within a gas mixture. If the pressure of carbon dioxide in the Earth's atmosphere is higher than the partial pressure in the ocean, the surface water of the ocean binds carbon dioxide. However, the partial pressure of CO_2 in seawater is strongly dependent on temperature: the warmer the water, the higher it is. This means that a warmer ocean can absorb less carbon dioxide from the atmosphere than an ocean with a lower temperature. In other words, an increase in the temperature of the oceans leads to a higher concentration of CO_2 in the atmosphere.

In the Earth's atmosphere, CO_2 does not react with other gases. In seawater, this is different: the dissolved carbon dioxide forms compounds and carbonic acid (H_2CO_3), for example, is formed:

$$CO_2 \ + \ H_2O \ \rightleftharpoons \ H_2CO_3 \ .$$

The carbonic acid is split into oxonium ions (H_3O^+) and hydrogen carbonate ions (HCO_3^-) by the following reaction:

$$H_2CO_3 \ + \ \ H_2O \ \rightleftharpoons \ H_3O^+ + \ HCO_3{}^- \ ,$$

which in turn can react further under energy supply to oxonium ions and carbonate ions ($CO_3{}^{2-}$):

$$HCO_3{}^- \ + \ H_2O \ \ \rightleftharpoons \ H_3O^+ + \ CO_3{}^{2-}.$$

We can see: The more CO_2 is dissolved in water, the more oxonium is formed, i.e. the more acidic the oceans become.

The dissolved carbon dioxide is involved in a further equilibrium. It influences the formation or solution of lime ($CaCO_3$):

$$CaCO_3 \ + \ \ CO_2 \ + \ H_2O \ \rightleftharpoons \ Ca^{2+} \ + \ \ 2\,HCO_3{}^-$$

If the concentration of carbon dioxide increases, the equilibrium is shifted to the right side, so that less lime is formed or existing lime is even dissolved. Thus less lime is available as building material for the skeletons and shells of mussels, snails, sea urchins, corals etc.

Chapter 6 Climate Change in the Classroom: Understanding and Acting.

6.1. The Urgency of Action

At the Paris Climate Change Conference (COP21), countries agreed to limit global warming to well below 2 °C, preferably to 1.5 °C. This is the only way we can reasonably avoid triggering the cascade of tipping elements (see section 4.3) and making large parts of the Earth uninhabitable for us in the long term. In order to comply with this upper limit, greenhouse gas emissions must be reduced as soon as possible, because the later the reversal starts, the less time remains (see Figure 45).

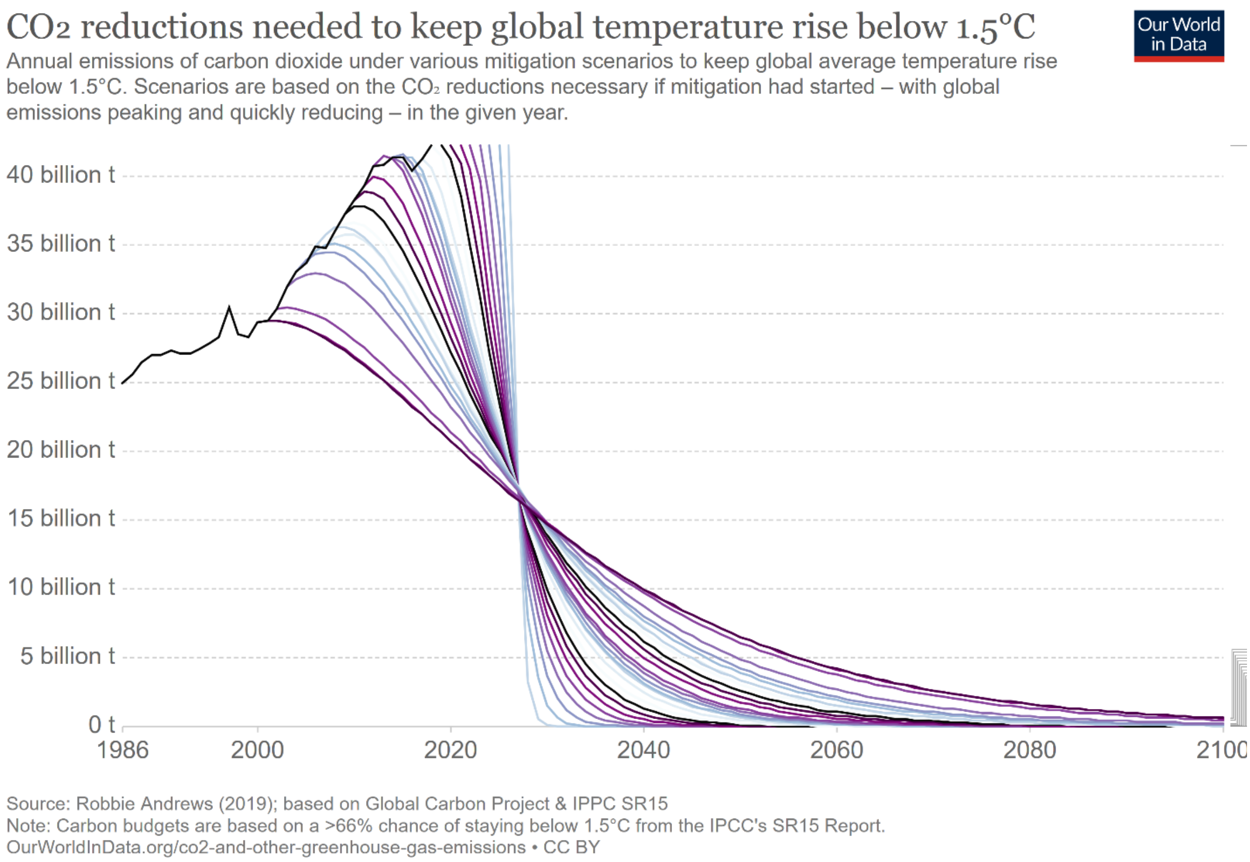


Figure 45 - Emission Scenarios for Achieving the Paris Climate Targets. The figure assumes that the total amount of CO_2 still to be emitted is limited to a fixed amount through the use of fossil fuels. This is why one runs into the "integral trap" if one does not start in time. Since one has already carelessly used a lot of the available CO_2 quota, one must make even more effort in the future to avoid the "Hothouse Earth" path. *(Source: Spiegel Online; The Global Carbon Project, Nature, Rahmstorf)*

In 2020, the remaining amount needed to achieve the 1.5-degree target has already shrunk to 420 billion tons. If all known fossil energy reserves of natural gas, oil and coal were used, this would release around 5,400 billion tons of CO2. The aim must therefore be to leave these raw materials underground and convert our energy supply to renewable energies!

It is clear that the global community must become greenhouse gas neutral in the second half of the century if this goal is to be achieved. However, the global consumption of coal, natural gas and oil continues to increase, despite the climate protection efforts of some countries. In many cases, economic interests and a lack of pricing for climate-damaging emissions[16] are preventing the implementation of the climate agreement.

Activity 11

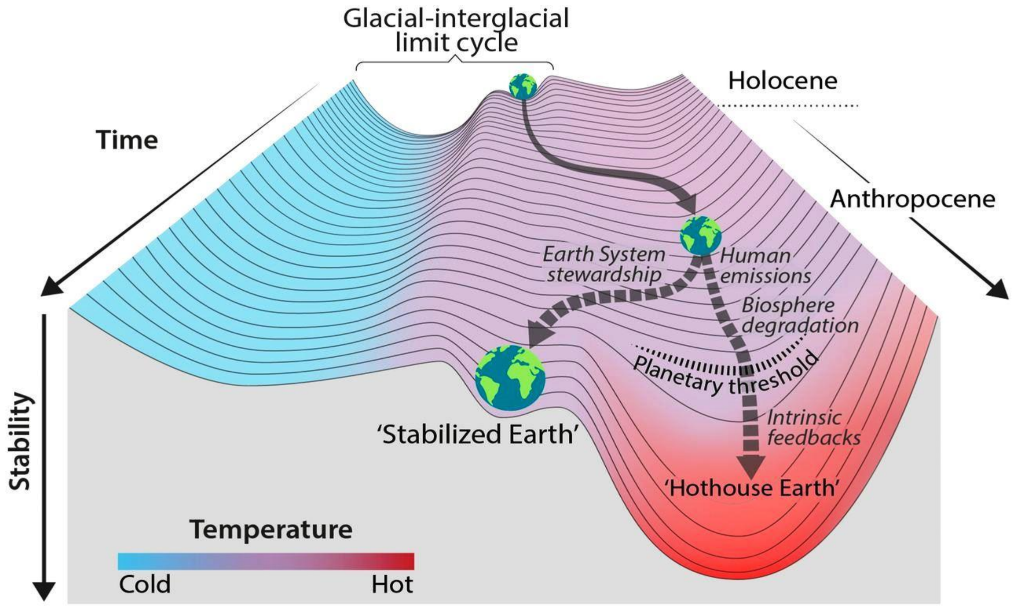


Figure 46 - Trajectories of the Earth System in the Anthropocene. Due to Human Impact, the Earth is close to a Dangerous Tipping Point (Credits: Steffen et al.).

If we take these decisions seriously, we will have very little time to stabilize the Earth's climate and prevent the activation of tipping points, from which the climatic conditions on Earth would drift into chaos through feedback effects.

Will Steffen, Joachim Schellnhuber et al make this clear in Figure 46: During the last 1.2 million years of the Earth's history, relatively cold and warm phases alternated in a cycle of about 100,000 years (glacial-interglacial limit cycle). Currently the earth is on the way to a diabolic hot period ("Hothouse Earth"), caused among other things by human greenhouse gas emissions and the destruction of the biosphere (e.g. deforestation). If the Earth exceeds the planetary load limit at about two degrees on this path, the path can no longer be changed due to feedback processes (see Section 4.2). According to Steffen et al, however, the path to an Earth on a stable way requires a fundamental change in the role of humans on the planet - but a determined and rapidly implemented reduction of greenhouse gas emissions is not sufficient for this. Improved forest, agricultural and soil management to store carbon, the preservation of biodiversity and technologies to remove carbon dioxide from the atmosphere and store it underground can also play an important role.

So how can teachers motivate pupils to actively combat climate change? Before we turn to concrete proposals, we would like to briefly ask: Why does knowledge about climate change does not play a role in everyday life for many? What ethical values do people possess? Which of these should they use for successful climate protection? And what psychological barriers prevent people from acting?

[16] The Federal Environment Agency has calculated the costs of climate damage. For 2016, this results in a value of 180 €/t CO2 equivalents. In 2030, the amount is 205 €/t CO2 equivalents [51].

6.2. Energy transition

In order to achieve the goal of the Paris Climate Agreement, no more than approximately 400 gigatons of additional CO_2 may be released into the atmosphere worldwide as of now (2021) [33]. Figure 47 shows the situation for Germany:

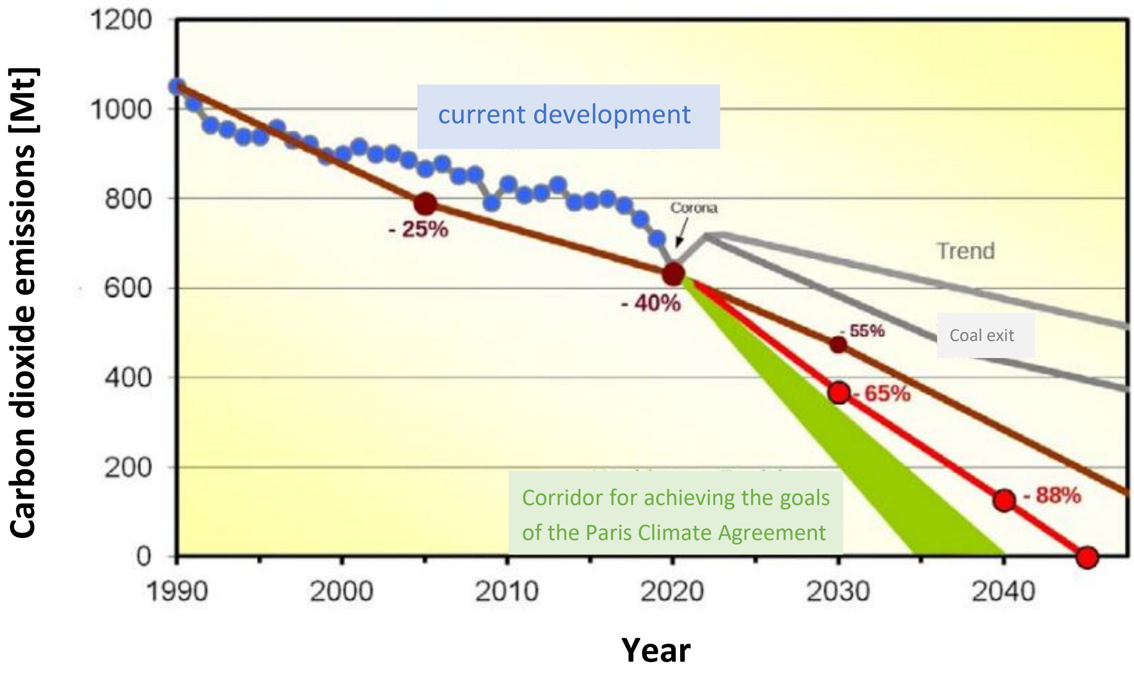


Abbildung 47 – Development of German CO2 emissions, comparison of the Paris climate target with the German targets and the extrapolation of our CO2 emissions (data: Federal Environment Agency)

The annual measured and projected CO2 emissions for the period 1990 to 2048 are shown. The reduction path for achieving the 1.5 °C goal assumes that we will succeed in establishing an energy supply entirely without the fossil fuels natural gas, oil and coal by 2040. This necessary reduction path is significantly more ambitious than the plans of the German government. Following the decision of the German Constitutional Court in May 2021, which declared the Climate Protection Act unconstitutional in parts because it did not take sufficient account of the interests of future generations, the German government has adjusted the goals upward. The goals are now in line with those of the European Union. However, to achieve the 1.5-degree goal of the Paris climate agreement, the goals would have to be more ambitious. And there is still a large divergence between the goals now set and the projected trend in our CO_2 emissions. There is still a lack of concrete plans and guidelines from the German government as to how these goals can be achieved.

One thing is certain: If we abandon the use of fossil fuels in the future, they will have to be replaced by energy generated from renewable sources. And even if the sensible potential for biomass, geothermal energy and solar thermal energy is exhausted, electricity from photovoltaic (solar cells) and wind power plants will have to cover most of our energy needs in Germany in the future. With the current energy consumption in Germany of approximately 3,500 TWh[17] per year [34] this is impossible! It is therefore imperative that the energy transition goes hand in hand with savings and efficiency enhancements [18]. Figure 48 assumes that electrical power generation will be increased to the necessary level of approximately 1,300 TWh per year by 2040 in order to meet the total energy demand, which is significantly reduced compared to today, and to replace fossil fuels.

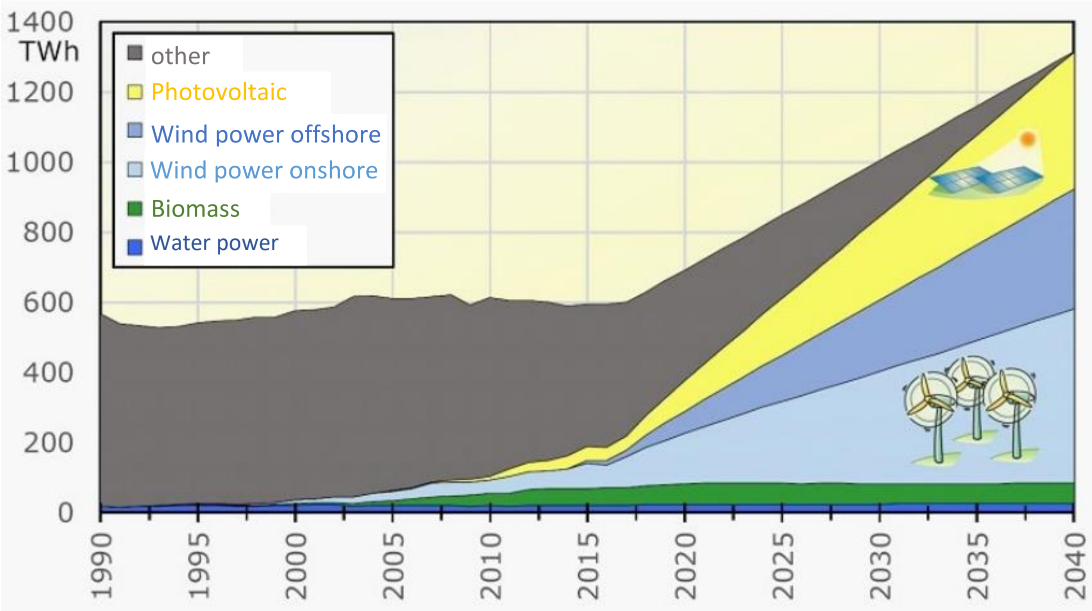


Figure 48 – Development of renewable electricity generation and electricity consumption in Germany by 2040 to achieve a climate-neutral energy supply, taking into account savings and efficiency measures (Credits: V. Quaschning [39])

At the present time (2020), the share of renewable energies is only approximately 14 % of Germany's total energy demand. The increase in renewable energy generation will be achieved mainly through increased expansion of the established technologies of wind power and photovoltaics, the expansion of which must be accelerated significantly: An addition of 10 GW per year (wind power) and 20 GW per year (photovoltaics) is necessary.[19] Legal regulations must support such a rapid expansion!

Security of supply at times when there is no wind and it is dark will be ensured by the large-scale introduction of battery storage and power-to-gas/liquid technologies.

If the phase-out of fossil fuels is to succeed by 2040, the new acquisition or installation of old technologies based on fossil fuels must be avoided at an early stage, taking into account the expected service lifetime. For example, cars with internal combustion engines, which have a service life of around 15 years, would no longer be permitted after 2025.

[17] This is the total German primary energy consumption. This includes, for example, the energy demand of oil heating, car traffic and industry in Germany.

[18] Examples of efficiency improvements: 1. A car with an internal combustion engine requires 65 kWh/100 km due to the low engine efficiency. The same car needs 20 kWh/100 km with a battery powered electric motor. ([49], p. 22) 2. Space heating & hot water (approximately 32% of energy consumption in Germany 2014): By using electric heat pumps, two to three times the thermal energy for heating rooms and water can be taken from the environment as is used in the form of electrical energy for pumping (reverse refrigerator principle). ([49], p. 15)

[19] The output results from the retrievable power multiplied by the service life. Photovoltaics can supply electricity for approximately 950 hours per year in Germany. For wind energy, the annual operating hours are approximately 2,500 hours for onshore locations and approximately 4,500 hours for offshore locations..

We know what we have to do:

1. *We must significantly reduce our energy requirements and make efficient use of the energy we do use!*
2. The energy we use must not be based on the burning of fossil fuels!

Since the topic of renewable energies and energy transition, i.e. the future renunciation of the use of fossil fuels, is central to the fight against climate change, a separate handbook with accompanying student activities will focus on this in the near future. Subscribe to the mailing list on our website and we will keep you up to date!

6.3. Social psychology and climate protection

by Gabriel Appl Scorza

We now turn to the psychological obstacles that, according to various psychological studies, prevent people from taking action and discuss ways of overcoming these obstacles.

PSYCHOLOGICAL OBSTACLES

A. Psychological distance

For many people, the causes and consequences of climate change seem distant, almost intangible. This so-called psychological distance is made up of various factors: spatial, temporal and social distance, as well as the degree of uncertainty. To counteract the great psychological distance in the case of climate change, it is necessary to draw attention to the local consequences of climate change: We feel these effects here and we feel them now.

What to do? In class, discuss the immediate effects on the students' own lives, on their family, their social environment and their environment. Since the consequences of climate change often remain invisible in cities due to the infrastructure and less available nature, it is worthwhile to visit a farm or forester, for example, and interview them. As a rule, small villages are much more exposed to weather extremes, which is why it would also be possible to conduct research on flooding in communities in the immediate vicinity.

B. Climate anxiety and perceived self-efficacy

The immediate effects of climate change are not pleasant and can even be frightening. In some cases, great fear can be paralysing, especially if it is accompanied by a feeling of not being able to change anything. However, if students feel they can make a difference through their they can make a difference through their behaviour, i.e. experience self-efficacy, then even negative emotions can be can have a positive effect on action. The pupils therefore need to understand how they can act concretely and which climate-protecting behaviours are really effective and which are less so.

What to do? Work out different climate-protecting actions with the pupils and assign them to the categories "effective" and "limited effective" (see section 6.4).

C. Responsibility diffusion

Another hurdle that is closely related to perceived self-efficacy is the so-called responsibility diffusion. Beliefs such as: "I can't make a difference through my behaviour anyway, because everyone else will carry on regardless", can lead to climate awareness not leading to climate-friendly behaviour. When this thinking is widespread and responsibility is passed on to others, collective passivity results. The key lies *in groups and their very specific dynamics*. In a group, for example a school class or even groups within the school class, it is possible to demand appropriate behaviour by establishing norms, such as protecting the environment - especially if the group is important for the person. At the same time, the group also creates a local reference system for responsibility, which counteracts the diffusion of responsibility.

What to do? Design group work and also longer *group projects* on the topic. It would be important that the projects not only take place within the school, but also connect the outside world with the school, making it easier for the students to transfer what they have learned into their everyday life.

POSITIVE FRAMING

Show the students the ways in which they can efficiently protect the climate in their everyday lives. Now, when it comes to concrete actions or changing old behaviours, it is important to frame the *messages positively*. For people, losses weigh about twice as much as gains - that's why we don't want to draw attention mainly to the renunciations, but right away to the alternative action.

What to do? Instead of "drive less", "cycle more and stay healthy". This can at the same time bring into focus other gains that come with the new behaviour, such as in this case more exercise. Other examples would be:

- ✓ Buy fresh, regional products that are richer in vitamins than imported goods.
- ✓ Set the heating on low so that your mucous membranes stay moist. This protects against germs!
- ✓ Become a (part-time) vegetarian. It's healthy!
- ✓ Buy things carefully that you really need and that you will enjoy for a long time!
- ✓ Only invest your money in projects that help other people and are good for nature!

TRANSFORMATIVE ENGAGEMENT:
THE CHANCE TO MAKE A DIFFERENCE!

Transformation means changing social structures through active action. The concept of "transformative engagement" therefore means initiating change through personal commitment and action. Originally derived from the UNESCO education program "Teaching and Learning Transformative Engagement" (see bibliography), we have applied it here to climate change.

What is meant by "transformative engagement"?

Transformative engagement happens on two levels:

1. The process that students go through towards internally motivated climate engagement
2. The impact of students' engagement on established institutions and norms

The process of transformative engagement at school

In the following, we describe point one: the process that students go through towards internally motivated climate engagement. This is subdivided into several sub-processes at UNESCO:

1. Perception of a gap - ideal vs. status quo

Transformative engagement often begins with the perception of the existence of a gap between reality and what is considered the ideal state.

In relation to climate change, this would be the discrepancy between the preservation of our planet as an ideal state and the current reality, i.e. the status quo, in which many economic, political and individual actors continue to conduct "business as usual", i.e. the continuation of climate-damaging processes and behaviours without changing anything. This can lead to an "awakening", the realization that change is urgently needed.

2. Internalization

Such moments of 'awakening' are often accompanied by cognitive dissonance or emotional turmoil, prompting students to engage in critical thinking or self-reflection. Questions may arise such as:

How can it be that so little is happening when the facts are so clear?

What can I do to play my part?

What do I perhaps need to do differently than before?

This internal realization can then lead to the students actually taking active action and thus bringing the internal change to the outside world.

3. Take action

Not all experiences and moments of 'awakening', [...] result in the implementation of an action or behavioural change in the learner. There are some facilitating factors that can trigger action. These include:

Empathy

In addition to the cognitive approach to learning content, the socio-emotional approach is also of great importance, especially when it comes to taking action. Empathy allows students to deal with the reality of a situation or problem and then *build a deeper emotional connection to it*, which at the same time makes the relevance to their own lives clear.

Self-efficacy

In addition to knowing that something needs to be done, it is particularly relevant to know and feel *that you can contribute something yourself*.

Tipping moments

In addition to empathy and self-efficacy, so-called tipping moments are of great importance, in which students can translate all their cognitive, emotional and social observations into a challenging action. This happens above all when young people are *given a concrete and feasible opportunity* to use their knowledge and social commitment to bring about change. *Belonging to a group* can act as a catalyst here. For example, the news report "Corona - 80 million babies without a vaccine" makes us sad, but there is nothing we can do about it. However, when pupils learn that, in the event of a 100% energy transition in Germany, energy consumption must nevertheless be reduced, they feel addressed and able to actively participate.

6.4. Concrete action for students

Article by Thomas Hensel and Moritz Strähle

After 65 million years, life on our planet is experiencing a mass extinction for the sixth time. The dramatic difference to the previous times:
this time no meteorites or volcanic eruptions are responsible, but the emission of greenhouse gases by humanity ...

Every human being living today has the responsibility to keep the earth habitable! NOW is the time to fight for life on this planet!
Lack of Knowledge or denial can not be accepted as an excuse!

But where and how do you start with climate protection in the most effective way? You can use these five points, which are explained in further detail below, to guide you:

1. Have fun with climate protection!
2. Knowledge is power - get informed!
3. Maximize the climate-protecting effect of your actions!
4. Get political!
5. Join forces!

"The environmental and social consequences, as well as the financial and economic consequences, of unchecked climate change are far more devastating than those of the Covid-crisis could have been. By contrast, the consequences we would all have to draw for our actions to address the climate crisis would be far less radical."

Prof. Dr. Volker Quaschning on the consequences and limitations of the Covid-crisis compared to the climate crisis [35]

1. Have fun with climate protection!

You can do a lot to protect the climate and the environment - it's best to start with something YOU enjoy doing: Maybe you'd like to prepare by watching a documentary on climate change?[20] Perhaps you're interested in cooking? Then set yourself the challenge of cooking as climate-friendly and tasty as possible next month - with as little meat and animal products as possible, but with seasonal vegetables and other ingredients with as short a transport route as possible.

You are sporty or want to be and your parents drive you or you still drive to school? Then switch to public transport, the bike or a mix of both!

However you start: Be creative and have fun! Then you will automatically become a role model for friends and parents - maybe someone will join in soon!
And once you've started taking action, you're sure to think of more things YOU can do to fight for the preservation of the Earth's diversity and beauty!

2. Knowledge is power - get informed!

Stay informed - documentaries, movies, books, newspaper articles, podcasts and media counters on the web offer first-class opportunities to stay in the picture. We have put together a great selection for you on our website at https://klimawandel-schule.de/en/event/concrete-action-students.

Well-informed people do not get carried away by every trend and greenwashing[21] and pay attention to lobbyism and fake news. How to recognize fake news? First of all by the sources: any "truth portals"

[20] We have compiled many entertaining, exciting and informative documentaries, short films, videos, etc. for you on our website: www.klimawandel-schule.de/

[21] Greenwashing refers to when companies portray their image or that of their products as being "greener" and more sustainable than it actually is. For example, when a green leaf and the word "eco" are printed on plastic packaging. Or when a large German energy company advertises in a video with a giant planting wind turbines - although at the time of broadcasting only 0.1% of the company's electricity came from wind power.

instead of scientific sources are quoted. By researching science portals (you can also find an overview here: https://klimawandel-schule.de/en/online-sources-and-books) you will get reliable information. Soon you will understand further connections and develop a greater and greater awareness of what is actually at stake, who is lying and who is deceiving.

3. Maximize the climate-protecting effect of your actions!

Which measures bring the most benefits? To answer this question, we will first introduce you to the SER-principle and highlight a typical carbon footprint.

BASIC TOOLS:
SAVINGS, **E**FFICIENCY AND **R**ENEWABLE ENERGIES (SER)

Savings[22]

To consume little and live economically is the simplest, cheapest, fastest and first measure!

True to the motto less is more: drive fewer kilometers by car, travel less far on vacation, buy new things less often, but buy high-quality, durable favorite pieces that you can use for a long time. Whether clothing, electrical equipment or furniture: What is not being produced, does not lead to CO2 emissions!

Think of saving money as a creative alternative that can also save you a lot of money:

- ✓ Minimalism can be very liberating!
- ✓ Don't let advertising tell you what you need!
- ✓ Repair, share, lend and borrow!
- ✓ Eat much less meat and other animal products! But high-quality, regional, seasonal and fresh food and which contains a lot of healthy nutrients.

EFFICIENCY

The less energy you use to achieve a certain goal, the more efficient you are!

To achieve the goal of "lighting my room," using an LED lamp is a very efficient option compared to using light bulbs or setting up candles. To achieve the goal of "keeping my body warm", putting on a sweater is much more energy efficient than turning up the heat.

Further examples: In a fully occupied car, each passenger consumes only approximately one-fifth of the energy compared to driving alone, so they act five times as efficiently! SUVs[23] are so inefficient because the very high dead weight must be constantly accelerated and braked. So, in addition to

---

[22] Consuming less is an important step - if not the most important. Through clever advertising, companies manage to increase production and at the same time the demand for scarce raw materials almost every quarter. Around 50 years ago, the Club of Rome described the economic and, above all, ecological dangers very accurately in its work "The Limits to Growth". Today, we would need almost three earths if all of the world's inhabitants lived as consumer-oriented a life as we Germans do.

[23] On paper, SUVs are paradoxically very efficient. A 2-ton SUV produces fewer emissions than four 0.5-ton compact cars. Comparing a car with four cars by total weight is totally illogical and a distortion of reality - but it makes a good sales argument. And since the automotive industry earns a lot of money with large cars and has a certain influence, the values are given in this way.

using bicycles, pedelecs[24] , electric mopeds, and public transit, fully-occupied small cars with little dead weight are efficient ways to get around.

An absolute elephant among the measures towards more energy efficiency is the insulation of one's own home! Efforts to do this are currently heavily subsidized by the state.

Other ways to avoid climate-damaging emissions with efficient technologies are, for example, refrigerators and other electrical appliances with an energy efficiency class A[25]; but you will certainly find many more possibilities!

RENEWABLE ENERGIES

In Germany, as well as worldwide, the demand for electrical energy has been steadily increasing in recent decades [36]. On one hand, this is due to our abundance-oriented lifestyle: Today we own 5 times more objects than 40 years ago. The second reason for the increasing demand for electrical energy is related to the fact that modern technologies such as heat pumps, heating systems, e-mobility and also industry increasingly rely on electricity[26]. It is therefore fundamental for all climate protection goals to cover the electricity demand not via fossil energy sources, but via renewable sources such as sun and wind.
Thanks to the high technical standard of today's photovoltaic and wind power plants, this form of energy generation is now not only much lower in emissions, but also cheaper. Germany's third-largest energy company EnBW, for example, is investing almost 100 million euros in the country's largest solar park - and doing so without any government subsidies.

The graph on the right shows the emissions caused in grams per kilowatt-hour of electrical energy, depending on the energy generated, if plant construction, energy distribution and plant disposal are included. The generation of one kilowatt-hour of electrical energy in a wind power plant emits 25 grams, i.e. 0.025 kg of CO2, whereas the generation in a coal-fired power plant emits approximately one kilogram, therefore 40 times as much! [37]

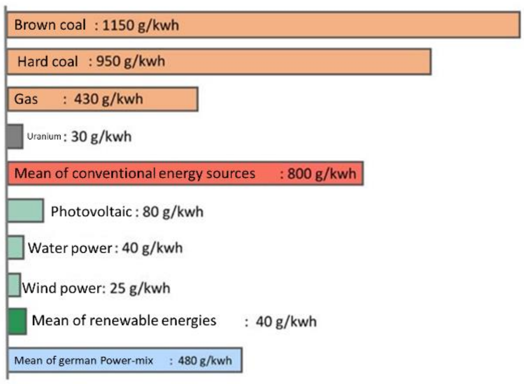


Figure 49 – CO2-Emissionen nach Energieträgern, Stand 2017 (Quelle: Naturwissenschaften Europa Verlag

Switching to real green electricity in your home is very easy to implement, very effective and should therefore be one of the first steps!
100% green electricity is sold by companies that do not operate coal or nuclear power plants and does not cost much more than conventional electricity.

24 Pedelec: electric bicycle that provides pedal assistance up to a speed of 25 km per hour.

25 The energy efficiency classes have changed in March 2021. The "plus classes" A+ to A+++ no longer apply. Now there are divisions from A to G, with A now being the most energy-efficient.

26 In the context of Germany's planned greenhouse gas neutrality, energy-intensive industries such as steel and chemicals in particular will have to convert their production processes - i.e. away from fossil fuels such as coal, oil and gas to hydrogen from green electricity. The chemical industry alone would currently require one seventh of Germany's electricity production as a result of this conversion. [53]

Obtaining domestic heat from renewable sources such as from a heat pump has even more impact on climate protection. According to expert opinions [38], [39], we will need four to five times more photovoltaic systems and four to five times more wind power systems in the next few decades to meet the Paris climate targets. The expansion and acceptance of photovoltaics and wind depend very much on regulatory frameworks. Thus, it is especially important to get involved politically - get informed!

MORE ACCURATE ANALYSIS FOR **S**AVINGS: THE CO2 FOOTPRINT:

Your personal carbon footprint shows how much CO_2[27] your actions cause (and where you can save CO_2). You can calculate your personal CO_2 footprint in just a few minutes using various CO_2 calculators on the Internet, e.g. at www.uba.co2-rechner.de (German Federal Environment Agency) or at www.fussabdruck.de (Brot für die Welt)[28].

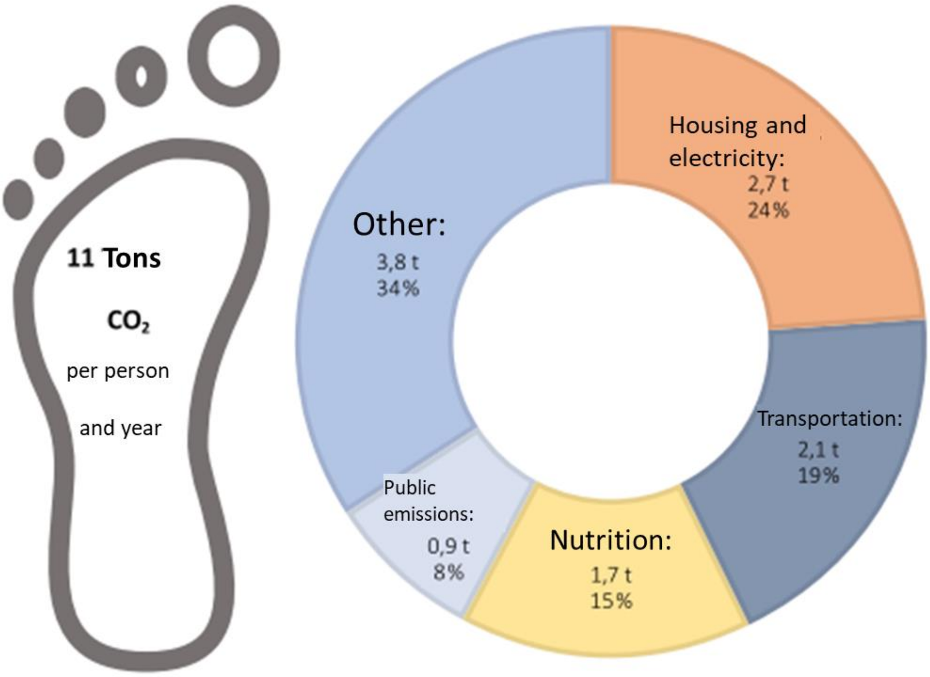


Figure 50 – CO_2 footprint of an average German (data: Federal Environment Agency).

The composition of the carbon footprint of an average German is shown in Figure 50. The five major areas shown here will be examined in more detail below:

(A) Consumption: 3,8 Tons

The purchase of all kinds of goods and services contribute to about a quarter of carbon dioxide emissions. Cell phones, clothing, entertainment electronics, household furniture and appliances, decora-

---

[27] CO2, along with methane, laughing gas and a number of other gases, is the greenhouse gas which, in total, has the greatest effect on climate change. Thus, in the following text, CO2 is referred to symbolically, although other greenhouse gases are also involved, depending on the example.

[28] When creating your OWN CO2 footprint, you calculate YOUR CO2 emissions in five major areas. Furthermore, you can use the CO2 calculator to learn specific tips for all areas and develop a feeling for which of YOUR measures saves how much CO2.

tions, packaging, sporting goods, and so on: For all these products to end up in your hands, the following steps are usually necessary: raw material extraction, production, transport, storage, marketing, shipping - only to end up as waste at some point[29].

In addition, services such as the delivery of shoes in different sizes with free returns or streaming and communication services[30] may be convenient and inexpensive and often seem indispensable - but they sometimes come at a high price for the climate and the environment. S for saving is the magic word here! By not buying **object* you can reduce your footprint quickly and easily! If you really need **object**, however, one can buy it certainly on various classified portals second-hand and thus often cheaper and CO_2-cost-free! And if you don't find it there, there are now many companies and manufacturers that produce CO_2-neutral and sustainable - but beware of greenwashing (see above)!

(B) Housing and electricity: 2,7 Tons

Around a quarter of the energy required in Germany per year and the resulting emissions are attributable to private heating, air conditioning[31] , generating hot water and electricity [40]. Heating our living spaces accounts for the largest share of this, as the dark blue sector in the figure below clearly shows. Replacing old oil heating systems with a modern and sustainable heating system and insulating older apartments and houses can therefore significantly reduce the footprint of all residents at the same time! Since this is so crucial to achieving Germany's climate goals, the government is currently subsidizing such measures with large sums (KfW-funding)!

Private households: Energy consumption 2017 in %

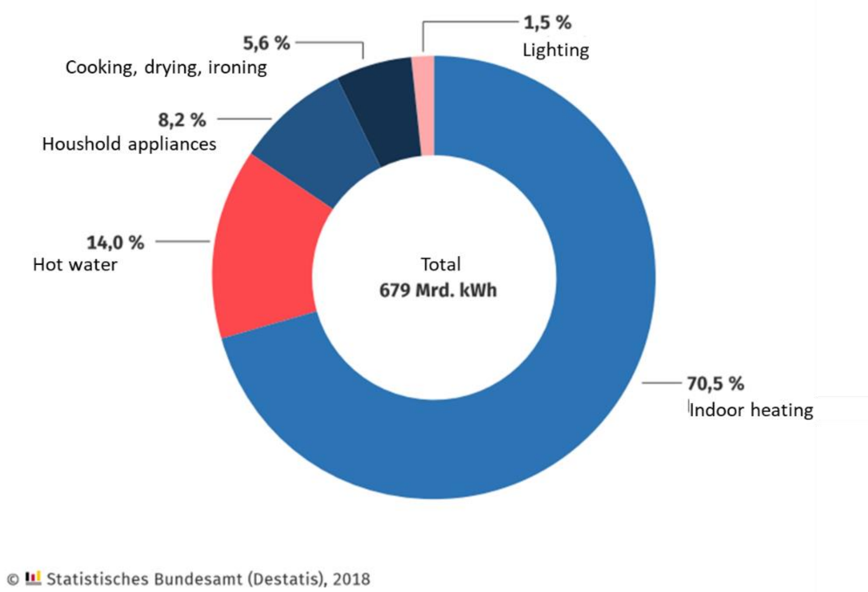


Figure 51 – Source: Federal Statistical Office Destatis, 2018

[29] Gray energy is the technical term for the amount of energy a product generates before and after its actual use.

[30] All online services of our entertainment electronics cause about 2% of the national CO2 emissions - as much as the entire German air traffic [54]. This statement can only be understood if one imagines the amount of servers and computers working worldwide to be able to watch a simple YouTube video. All these server rooms and computers have to be cooled a lot constantly - and cooling requires proportionally even more energy than heating.

[31] Cooling requires far more energy than heating living spaces. Fortunately, virtually no air conditioning systems are installed in German homes, which means that this application causes virtually no emissions in private households. However, the situation is different in office buildings or in warm regions such as California or Dubai.

The recommended room temperature, which is also considered healthy, is 18 °C in the kitchen, toilet and bedroom and 20 °C in the living room[32]. So it's better to wear one more layer of clothing and thus reduce your footprint. The savings potential for lighting, on the other hand, is comparatively small.[33]

Regardless of whether hot water is produced via an electric boiler or heated electrically: Switching to a genuine green electricity provider is probably one of the measures with the best cost-benefit ratio - an average four-person household can save well over a ton of CO_2 without any effort!

(C) Mobility: 2,1 Tons

Different means of transportation differ significantly in their CO2 emissions - this news is nothing new. The following table provides an overview of which means of transport causes how much CO2. The direct emissions are shown in grams per kilometer traveled per passenger. For car, e-car and e-scooter, one passenger was assumed. The values are a rounded average from various sources such as the European Environment Agency, Utopia, ADAC or the Federal Environment Agency.

Means of transportation	Air-plane	Car	E-Car	Train	Bus	Tramway	E-Scooter	Pedelec	Bicycle
grams of CO_2 per km and per person	300	200	75[34]	50	50	15	5	2	0

As already mentioned on the topic of efficiency on the previous pages, these average values vary significantly depending on the installed drive technology, vehicle weight and number of passengers! Furthermore, not every train runs on green electricity yet, which results in a comparable emission value as with the bus.

However, the greatest CO_2 savings are achieved by avoiding traveling long distances as much as possible. A vacation in Germany, as many experienced in Covid-Summer of 2020, means less travel stress for the time being, can be a lot of fun and saves more than 7 tons of CO_2 compared to a flight to Bali - per person!

(D) Nutrition: 1,7 Tons

There is unimagined potential in the category of nutrition. If we consider only the emissions caused in this country, then every German citizen causes on average about one fifth of his emissions through his nutrition - an average of 2 tons of CO_2 per year. And this figure is more than doubled if we consider the pollutant emissions caused by us outside Germany for the cultivation and production of our food!

---

[32] One degree of temperature reduction saves between 5% and 10% of heating energy or emissions, depending on the insulation and type of heating.

[33] The Federal Environment Agency has compiled further tips online for reducing the footprint in this area: www.umweltbundesamt.de → Environmental tips for everyday life → Heating building → Heating and room temperature https://www.umweltbundesamt.de/umwelttipps-fuer-den-alltag/heating-building/heating-room-temperature#our-tips.

[34] For electric cars, the range extends from 25 to 125 grams of CO_2/km. The lower value results from 100% wind power and the upper value from the current German electricity mix. If you now add the emissions from vehicle production to the direct emissions, all the values in the table above increase - for a conventional car by an average of 20 grams of CO2/km and for electric cars by an average of 50 grams of CO_2/km.

Depending on the study, livestock production is responsible for 20 % to 50 % [41] of all widespread greenhouse gas emissions.!

How does this huge proportion come about?[35] Farm animals need a lot of feed. Soy is often fed as "concentrated feed", which cannot be grown in Germany in these quantities and therefore does not appear in the national emissions balance. Especially in South America, huge areas of rainforest are cleared in order to plant soy and then transport the protein-rich beans across the globe with renewed CO2 emissions. Since meat processing in other European countries is often cheaper, this is also followed by a considerable energy requirement for cooling and transport. The methane gas emitted by cows is also far more harmful to the climate than CO2, and the production of mineral fertilizer for animal feed production also requires considerable energy.
Did you know that cattle kept on pasture produce only half as much methane as those kept in large barns?

Clear conclusion: Reducing the consumption of meat and dairy products is a very effective climate protection measure!

Second adjusting screw: Use regional and seasonal organic ingredients! Organic farming requires only about half the amount of energy of conventional farming. In the case of non-regional and non-seasonal foods, superfluous emissions are caused by the long transport routes: 100 g of asparagus from Chile cause 1.7 kilograms of CO_2 emissions through transport alone, while 100 g of asparagus from our own region at asparagus season cause only 0.06 kg!

(E) Public emission: 0,9 Tons

CO_2 emissions from this sector are generated by all public facilities - i.e. mainly by the electricity and heating requirements of museums, hospitals, schools, etc. Savings are therefore not immediately feasible, but they are not impossible either. The organization Solar für Kinder, for example, supports schools in building a solar system on their own school roof or in the neighborhood - nothing is impossible and asking costs nothing![36]

And as with all things that affect the public, change in the area of public emissions will only happen if engaged citizens (like you?!) point out grievances and push local government.

Now that you know the five major areas of action (A to E), focus on a few concrete actions with great potential, using your personal carbon footprint as a guide.

[35] Follow the reasoning of J.S. Foer in the appendix of his 2019 book "Wir sind das Klima"

[36] Info at www.solarfuerkinder.de

Before we move on to point 4, "Get political!", here are two important thoughts on capital investment and the opportunity to compensate:

THE CHANCE OF COMPENSATING

Not all emissions can be avoided. For unavoidable emissions, the idea of
of "offsetting" was invented. In general, offsetting should only take place in addition to personal climate commitment and not as an indulgence for climate sins. The idea behind it:

Offset platforms such as Atmosfair, Klima-Kollekte or Primaklima invest in projects to avoid CO2 (e.g. protection and renaturation of moorland and peat soils[37]) or to save CO2 (e.g. more efficient cooking stoves to prepare food in developing countries). However, the compensation price here can vary considerably depending on the provider - and unfortunately also whether the promised compensation effect is actually achieved. An extremely informative article on the subject of CO2 compensation was published in November 2020 on Deutschlandfunk Kultur. [42] If you are unsure about choosing a carbon offset project, the recommendation of the German Federal Environment Agency (Umweltbundesamt), which rates projects with "Gold Standard" according to the guidelines of the Intergovernmental Panel on Climate Change, can help.

CAPITAL INVESTMENT

Even if there are probably not yet large sums in your savings account, this point is important for the future and perhaps also for the discussion with your parents! Because where you invest your savings and with which pension insurance you later enter into a contract, you have yourself in hand! There are banks, investment opportunities and insurance companies that are committed to sustainability, public welfare aspects, climate and social justice and still offer comparable interest rates and good benefits. To exaggerate, it would be fatal for one's own CO2 balance to live ecologically the whole year and in return to promote coal mining consciously or unconsciously with thousands of Euros via shares. There are already banks and investment funds that are really serious about environmental protection and sustainability. Search the Internet for the term "ESG criteria" as a basis of assessment for a sustainable investment.

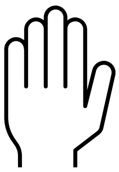
[37] CO2 and methane avoidance potential: Source Europabuch: Peatlands in rainforests threaten to dry out. If this happens to the peatlands in the Congo Basin with the size of half of Germany, this would have fatal consequences for/on the climate. There would be an additional emission of 30,000 Mt CO2, which would correspond to the national CO2 emission of the last 40 years.

CONCLUSION:

The association *3 fürs Klima* suggests three sensible steps to maximize the climate-protecting effect of your own actions::

- ✓ Reduce your *footprint*
- ✓ *compensate* the remainder
- ✓ and increase your *handprint*!

If you make your footprint as small as possible and offset the rest of your emissions, you're well on your way - but you're far from reaching your goal!



Now it's time to make your *handprint* as big as possible! Unlike your footprint, which you can reduce to a maximum of zero, your handprint has the potential to grow to infinity by taking other people along with you on your journey and convincing them with enthusiasm.

Teenagers and children have a much greater influence on their parents, other adults and society than they realize. Use this influence and confront adults with facts and arguments!

- ? Why could it even come to this, that we are threatened with a climate catastrophe today?
- ? What did your parents do about climate protection when they were your age?
- ? What are they doing today?

Have the courage to talk to friends and family about environmental and climate protection - even about topics such as investing money and planning vacations!

And with the enlargement of your handprint, we now come to the last two topics: " Get political!" and "Together we are strong!"

5 Get Political!

Politics is only for politicians? Cooking is only something for cooks? Of course not! Legal regulations affect everyone and are so effective primarily because of their broad impact: Even with drastic behavioral changes and decisive action, we cannot prevent the world from becoming a and decisive action, as long as our measures are limited to the personal sphere. our measures are limited to the personal sphere!

Did you know that in 2012 the German state spent around 57 billion euros of taxpayers' money in the form of environmentally and climate-damaging subsidies? (Report of the Federal Environment Agency, [43].) Thus, among other things, coal mining and the automotive industry were subsidized, and air travel was supported with 12 billion euros (i.e., over
250 € per taxpayer and year)! You think that the money, which is available to our society through taxes, can be used more sensibly? Then get involved, show your opinion and become political![38]

Legal regulations are necessary, for example to tax kerosene and thus to price flying in a way that is appropriate to its harmfulness to the climate. Examples such as compulsory seat belts in cars, compulsory helmets for motorcyclists or the Non-Smoker Protection Act[39] show that legal regulations that are initially perceived as restrictive are extremely useful and become part of everyday life after only a short time. And as the last few years in particular have clearly shown, political pressure from the population is enormously important for this.

This is how you can get started:

- ✓ Analyze the party programs before the next election with regard to their commitment to climate protection and discuss them with friends and relatives!
- ✓ Check how these parties have pushed or hindered climate protection during the past years: You should judge them by their actions, not by their fine words.
- ✓ Signatures for climate and environmental protection can have a big impact. Successful examples from the past include referendums against species extinction and the referendum for non-smoker protection in Bavaria in 2009.
- ✓ For example, you can find your elected representatives via www.abgeordnetenwatch.de. Contact them and get involved - they were elected to represent YOU!
- ✓ With your participation in demonstrations YOU point out grievances to the ruling parties and address demands for improvement!
- ✓ Join a party! This way, you can help shape things yourself, take responsibility and experience how politics and legislation work in Germany and how you can become part of the decisions yourself.

[38] Incidentally, "politics" means nothing other than "concerning the general public"

[39] In 2009, the ÖDP, a political party in Germany, initiated the referendum "For real non-smoker protection!". Around 14% of eligible voters cast their vote in favor of this initiative, leading to the referendum "Non-smoker protection". In 2010, the majority of the 3.5 million voters cast their ballots in favor of the decision, which introduced a ban on smoking in restaurants without exceptions.

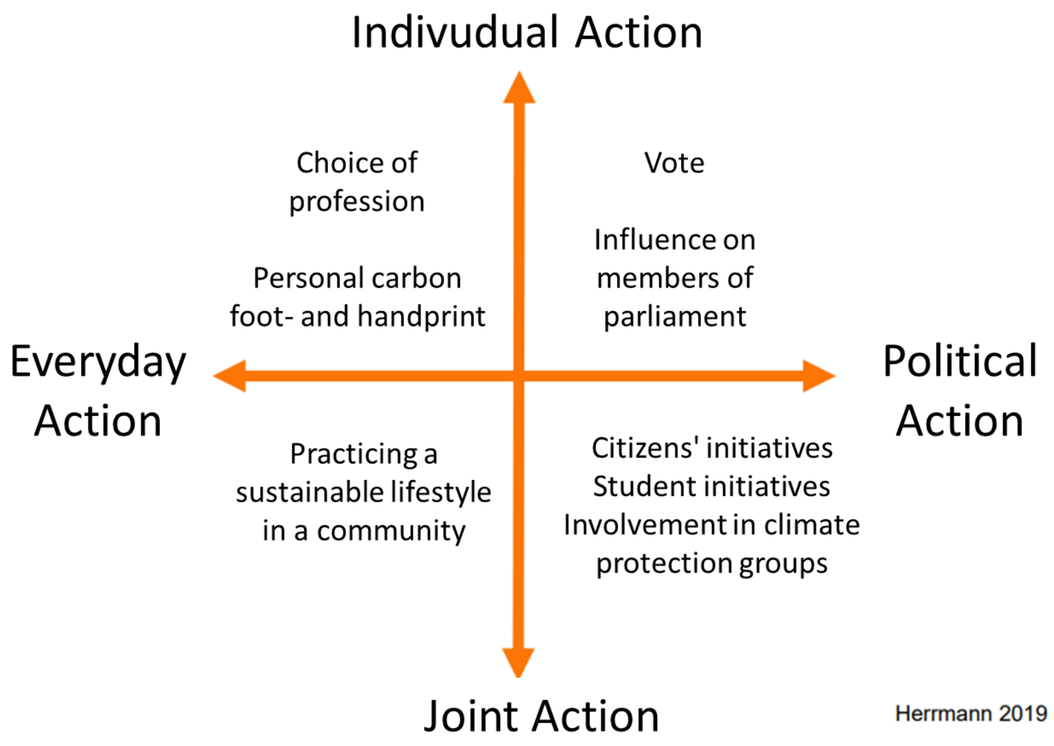
6. together we are strong!

You won't be able to save the world on your own, and sticking to goals you set yourself is much harder without the motivation of a group. Therefore: Join together! Thus you increase your effectiveness and your action receives the necessary perseverance!

Want to see some examples?

- ✓ Set up a climate protection working group at your school!
- ✓ Set climate challenges among your friends!
- ✓ Ask your teachers to address the topic of climate protection in class!
- ✓ Join local environmental or climate protection organizations! Together, your political influence will also grow![40]

The diagram below shows different areas (and just a few examples) that you can use to increase your carbon handprint. Notice, that individual action in everyday life only represents a small part of your influence - so distribute your energy across all four fields!



[40] First contact points can be NGOs such as Greenpeace, BUND, WWF or NABU, but also non-profit associations.

All good so far?! Then let's get started! Here are five challenges for you to start with:

Challenge 1: *Watch two documentaries and read a book on climate change!*

Challenge 2: *Reduce your consumption of meat and dairy products: Meat only in the evening! Or even better: Meat only one day a week at the most.*

Challenge 3: Ask your parents some of the following questions:

"How did you get involved in climate protection when you were my age?"
"What is your contribution today to keeping our planet livable?"
"What kind of electricity provider do we have?"
"What kind of heating system did we install?"
"Is our house well insulated?"
"Why don't we have solar on our roof?"

Challenge 4: *Call your bank, health insurance or pension company and ask where they invest your money. For example, can you make sure it's not invested in coal mining?*

Challenge 5: Join the climate protection working group at your school! There is no Club about Climate Protection? Then start a climate protection working group with your friends!

Chapter 7 Exploring Climate Change with the Climate Kit

The student activities presented below are part of the climate suitcase developed at the Faculty of Physics at LMU Munich.

Figure 52- Experiments from the Climate Kit

The activities in the climate kit are designed to be used by pupils from the eighth grade onwards.

> The following descriptions of the activities in the climate kit are ideas for implementation and not ready-made copy templates or worksheets!
> We provide editable versions of the descriptions on the website for adaptation to individual teaching situations.
> **www.klimawandel-schule.de**
> You can also find suggested solutions, answers to content-related questions and other materials relating to the activities in the climate kit here.

The climate kit is licensed under the following Creative Commons License: CC BY-NC-SA 4.0.



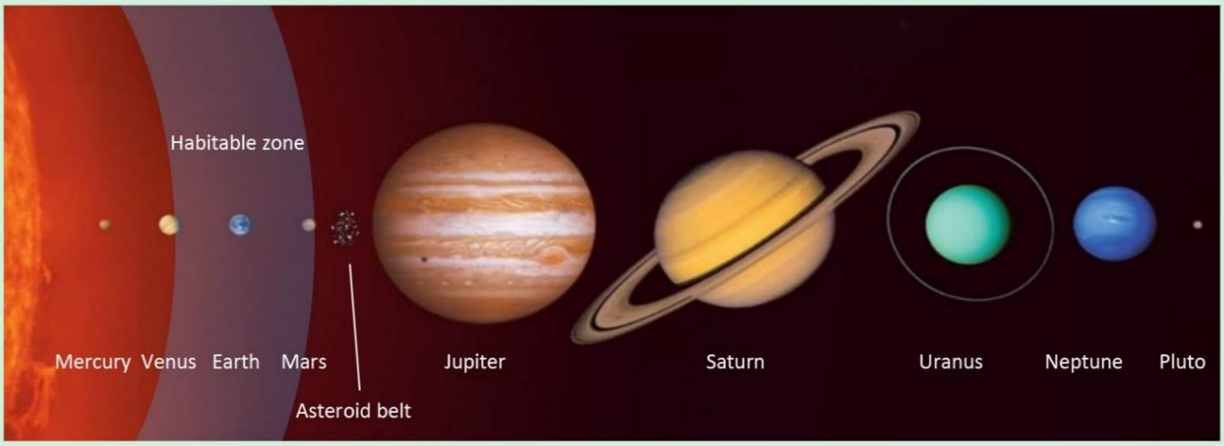

Cecilia Scorza

Activity 1 - The Earth in the Solar System

What makes our Earth a habitable planet?

Background:

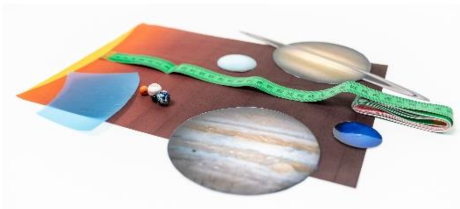
The Earth, like Mercury, Venus, and Mars, is one of the inner rocky planets of the Solar System. The inner rocky planets are followed by the asteroid belt (with about 650,000 asteroids) and the four gas giants Jupiter, Saturn, Neptune and Uranus as well as many dwarf planets such as Pluto. Around all stars, and thus also around our Sun, there is a so-called habitable zone - an area where water can exist in liquid form. The Earth and Mars are situated in the habitable zone, but only the Earth is habitable. Why?



The planets of our solar system in scale. The distances between the planets, however, are shown here clearly too small! (Credits: Scorza)

Materials:

- ✓ Background image with an outline of the Sun
- ✓ Planet models made of wood (rocky planets) 1
- ✓ Laminated gas planets, cut out individually (green Folder + 1)
- ✓ Habitable zone (blue transparent film) 1
- ✓ Measuring tape 1

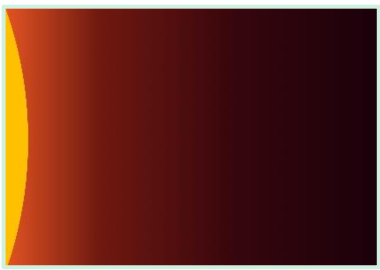


Materials for the activity

Implementation:

Part 1: Where is the Earth located in the Solar System?

The distance from the Sun to the Earth is about 150 million km (this distance is defined as the *Astronomical Unit* (AU)). In our model, we compress this distance to 10 cm. The radius of the bright yellow disc thus corresponds to 1 AU. The habitable zone in our Solar System model is represented by the 6 cm^2 blue transparent film.



Detail of the Sun (Credits: Scorza)

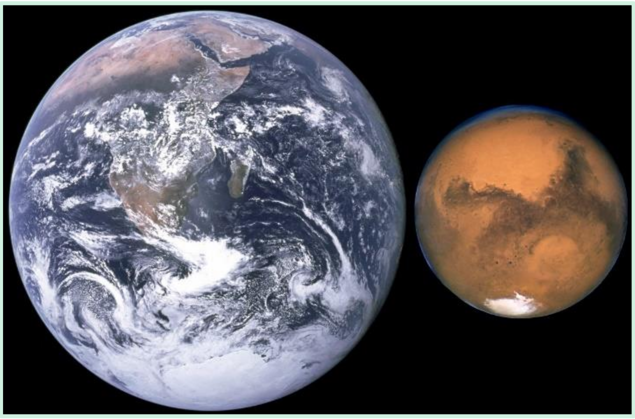
→ Enter the distances of the planets to the Sun and the position of the habitable zone into the table.

Planet	Distance from the Sun in AU	Distance in the model in cm
Mercury	0.4	
Venus	0.7	
Earth	1.0	10
Mars	1.5	
Jupiter	5.2	
Saturn	9.5	
Uranus	19.2	
Neptune	30.1	
Habitable zone (inner edge)	0.85	

→ Place the light-yellow disc on the floor and place the planetary spheres, the habitable zone, and the gas giants at the correct distance along a line on the floor.

Note: The sizes of the planets and the sun are much too large compared to the distances in this model! It would be correct to place the Earth more than 100 m away from the sun. However, the scale of the planets and the sun in relation to each other is correct.

Part 2: What role does mass play in the habitability of the Earth?



Comparing Earth and Mars (Credits: NASA)

? Where is the Earth model located in relation to the habitable zone?

? Now place Mars on the spot of the Earth. Discuss whether Mars would then be habitable. Compare the mass of Mars ($6.4 \cdot 10^{23}\ kg$) with that of the Earth ($5.9 \cdot 10^{24}\ kg$) and consider how the density of a planet's atmosphere is related to its mass (and gravity). Think of our Moon ($m = 7.35 \cdot 10^{22} kg$). Is there an atmosphere there?

Moritz Strähle and
Cecilia Scorza

Activity 2 – The Earth is irradiated

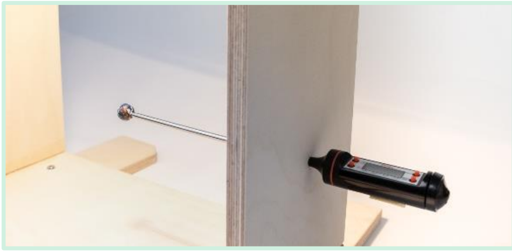
Part 1: Why is the Earth not getting hotter and hotter, even though it is constantly exposed to the Sun?

Background:

When a cool body is heated by supplying radiant energy, the body itself irradiates more and more energy in the form of thermal radiation. At some point, it absorbs the same amount of energy per second as it irradiates itself - it is then in *radiative equilibrium* and has reached the *equilibrium temperature.* Like all planets in the Solar System, the Earth is irradiated by the Sun. Is the Earth in radiative equilibrium?

Materials:

- ✓ Spotlight
- ✓ Small wooden Earth globe 2
- ✓ 1 digital thermometer
- ✓ Stopwatch



Caution! Very hot radiator: risk of burns!

Implementation:

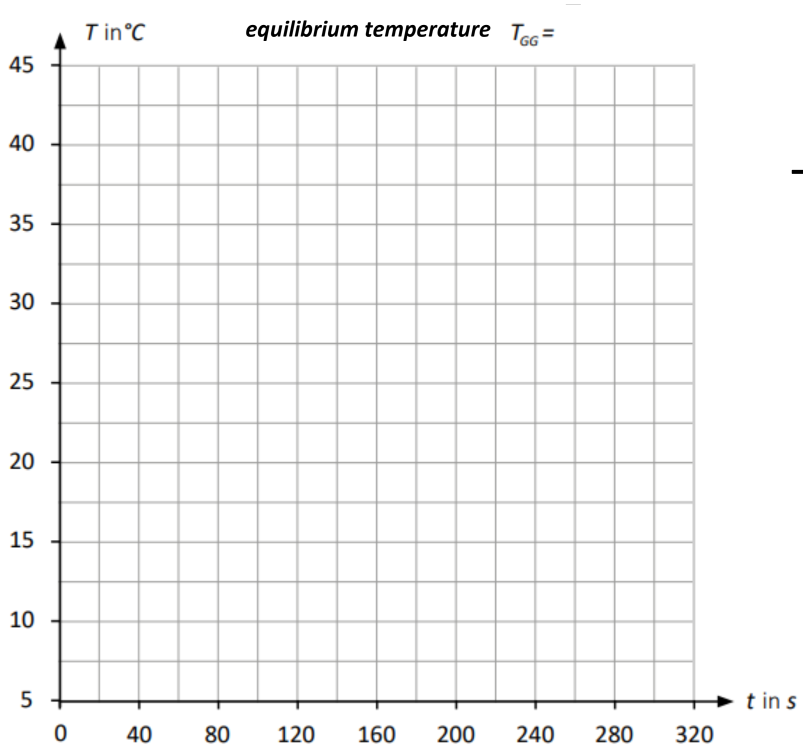
→ Do not plug the cable into the socket yet! Insert the reflector bulb into the socket of the protective cage and then insert the closed protective cage into the corresponding holder in the frame.

→ Take the Earth model and insert the digital thermometer into the small opening on one side. Place the earth directly under the radiator so that it is irradiated with the highest intensity.

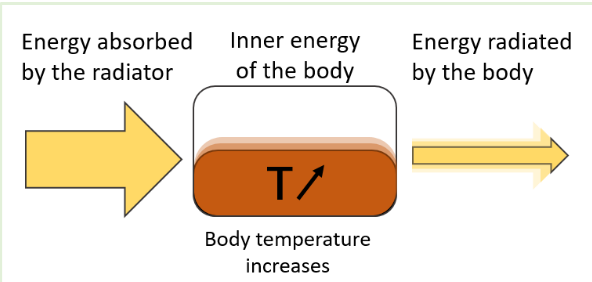
→ Measure the temperature of the Earth every 30 seconds and note the results in a table.

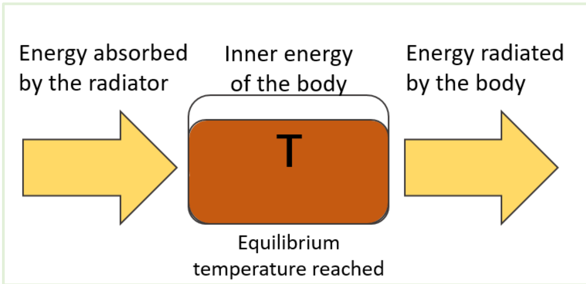
Time s	0	20	40	60	80	100	120	140	160	180
T in °C										
Time s	200	220	240	260	280	300	320	340	360	380
T in °C										

→ Display the results graphically in the diagram:

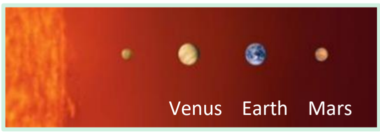


→ "The warmer a body is, the more thermal radiation it emits!" Given this context, discuss the measurement result and explain why the temperature of the model earth does not continue to rise. Use the following two illustrations for the discussion and interpretation. Use the terms *equilibrium temperature* and *radiative equilibrium*.





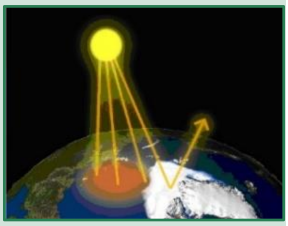
? Venus is closer to the Sun than the Earth. What would happen to the temperature on Earth if it were moved to the location of Venus (or Mars)?



Part 2: What role do ice surfaces play in the temperature of the Earth?

Background:

Bright surfaces on the Earth, such as ice and snow, reflect the incident light of the Sun more strongly than, for example, water or the ground. This reflectivity of a surface is called *albedo* α (lat. "white"). For the Earth applies $\alpha = 0{,}3$. This means that 30 % of the incident radiation energy is reflected and does not contribute to heating. The loss of white space due to global warming has devastating effects on the Earth's climate.



Albedo of the Earth

Materials:

- ✓ Spotlight
- ✓ 2 paper bodies (printed as rock or ice surface) 2
- ✓ 2 digital thermometers
- ✓ Stopwatch

Experiment on the Albedo

Caution! Very hot radiator: risk of burns!

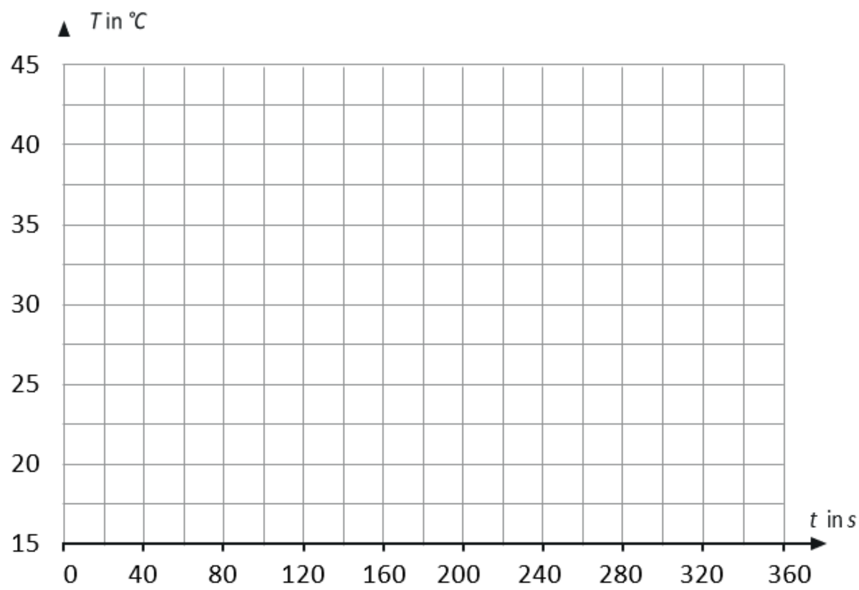
Implementation:

→ The two thermometers are inserted into the folded paper bodies. One represents the rocks under a melted glacier, the other an intact ice surface. Both test bodies are placed under the switched-on spotlight so that they are irradiated with the same intensity.

→ Measure the temperature of the two paper bodies every 30 seconds and note the results in the table.

Time in s	0	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	320	340	360
Temperature dark in °C																			
Temperature white in °C																			

→ Display the results graphically in the diagram. Use different colours.



→ Discuss your results and explain the different temperature curves. Use the terms *albedo*, *equilibrium temperature* and *radiation equilibrium.*

? Discuss the effects of melting ice and glaciers on the temperature of the Earth Draw a figure in which you use arrows to show the gradual effects of melting ice and glaciers on the Earth's temperature.

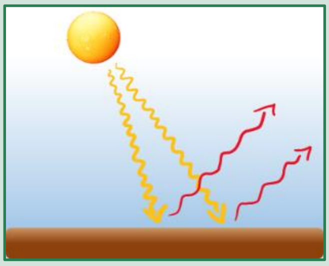
Activity 3 – The Earth, a Radiating Planet

Part 1: Can we make the heat radiation of the Earth visible?

Cecilia Scorza and Moritz Strähle

Background:

Energy is transported from the Sun to the Earth via electromagnetic waves. The largest part of solar radiation consists of short-wave electromagnetic waves (the light visible to us), which reach the ground almost without hindrance from the atmosphere, where they are then absorbed to a large extent. The ground of the Earth then radiates this received solar energy as heat radiation in the form of *long-wave infrared radiation* towards space. In total, the earth absorbs as much solar energy as it radiates into space as thermal radiation - it is in *radiative equilibrium*. The heat radiation of the earth is invisible to us. Can it be made visible and can it be researched?



Short wave solar radiation (yellow) and long wave infrared radiation (red). (Credits: Scorza, Strähle)

Materials:

✓ Thermal imaging camera

Implementation:

Not only earth, but all bodies radiate heat! The warmer a body is, the more intense the heat radiation. A thermal imaging camera "translates" this heat radiation into visible light so that it can be seen on the display.

→ Observe people with and without glasses with the thermal imaging camera. What can you observe? Which parts of the face are warmer, which colder?

→ Heat radiation can also be felt! Feel carefully next to a cup of warm tea or another hot body; also observe with a thermal camera.

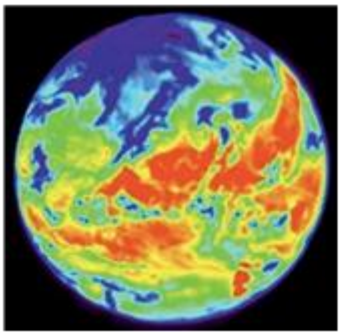
→ Rub your palms firmly together for five seconds and then press them on the table for five seconds. After removing your hands from the table, look at the contact surface with the thermal imaging camera. Explain how the image is created and why it disappears again. Rub the floor with your feet. What do you see?

? Make a connection between the fading of your handprint and the radiant surface of the Earth. Why doesn't the Earth cool down more and more?

? Look at the following pictures a) of the Earth and b) of the Sun. Can you guess what is shown in picture c)?

a) Earth

b) Sun



c) ?

Part 2: Which materials are transparent to visible light, which to infrared radiation?

Background:

Visible light and infrared radiation have different properties. Some materials are transparent to infrared radiation (IR radiation) but not to visible light. Other materials absorb (i.e. trap) infrared radiation and allow visible light to pass through without hindrance. We explore these properties ourselves!

Materials:

- ✓ Thermal imaging camera
- ✓ Black garbage bag, paper
- ✓ air-filled balloon, water-filled balloon
- ✓ Petri dish made of glass or glasses
- ✓ Paper and book

Various materials for exploration of IR radiation

→ Use your hand as an infrared radiator and your eyes or the thermal imaging camera to examine the permeability of different materials and complete the table:

Material	Permeable for IR radiation	Permeable for visible light
Glass		
Black bag		
Paper		
Air-filled balloon		
Water-filled balloon		
Textbook		
Cling film		

? The greenhouse gases in the atmosphere allow visible light to pass almost without hindrance. However, they absorb infrared radiation. Which of the above explored materials also exhibits these properties?

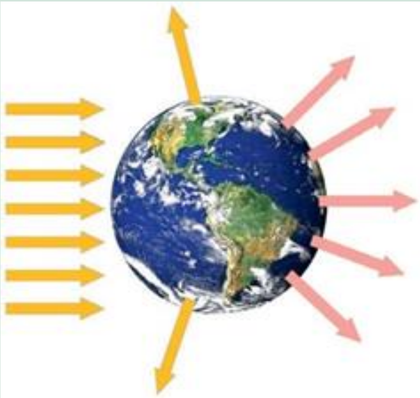
Klimawandel
verstehen und handeln

Activity 4 – The Keys of the Earth’s temperature

What influence do greenhouse gases have on the Earth's temperature?

Moritz Strähle and Cecilia Scorza

Hintergrund:



The earth is irradiated by the sun and radiates itself

The sun only ever irradiates the daytime side of the earth, but on average the earth's surface is irradiated by the sun with 340 W/m^2 ("watts per square meter") over the course of a day. Approx. 30% of the solar radiation is reflected back into space, e.g. by ice and white clouds; the remaining energy is absorbed by the ground and emitted again in the form of invisible thermal radiation (in the infrared range). The amount of energy radiated in a certain period of time is equal to the amount of energy input - the earth is in radiation equilibrium.

In physics, there is a law that describes how much energy a body radiates per m^2 of its surface per second at a certain temperature T, the Stefan-Boltzmann law. The diagram on the next page shows the relationship. Boiling water, for example, emits approx. 1100 joules of energy in the form of thermal radiation per m^2 and per second. The radiation intensity I is therefore 1100 W/m^2 (watts per m^2).
As can be seen in the Stefan-Boltzmann diagram, the hotter a body is, the more intensely it radiates, and this is proportional to the fourth power of its temperature. If the temperature of a body is doubled, it radiates 2^4 = 16 times more energy per second! We can now use this law to estimate the average temperature on an earth without an atmosphere!

Materials:

- ✓ Three short arrows ④ and four long arrows (DIN A3 folder)
- ✓ Eight labels and four numerical values ④
- ✓ Two DIN A3 sheets: Earth with and without atmosphere (DIN A3 folder)

Part 1: What would be the average temperature on an earth without atmosphere?

Implementation:

→ Placing arrows: Place the light grey bordered arrows and the light grey labels on the sheet "Earth without atmosphere" to match the background text.

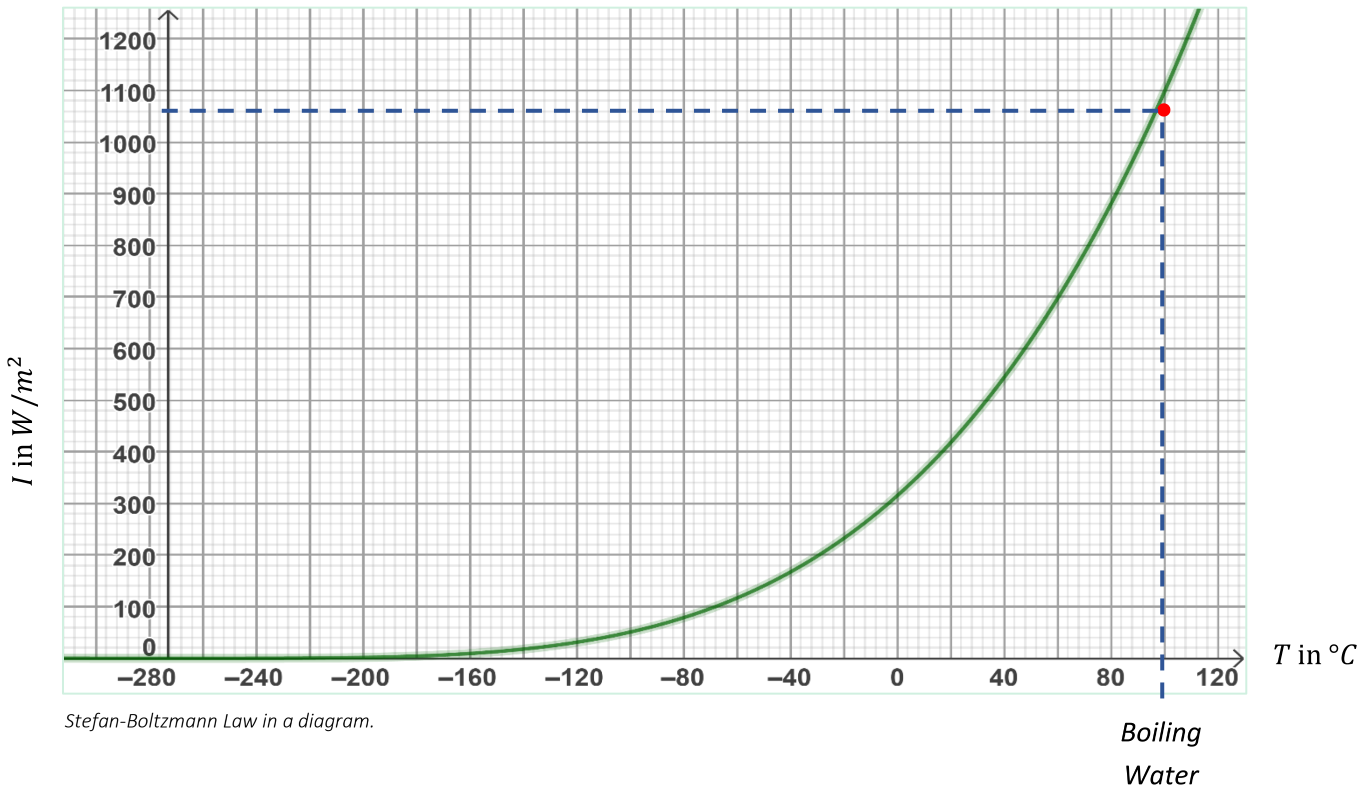
→ In the diagram on the next page, you will find a graphical representation of the Stefan-Boltzmann law. We will now try to get familiar with it! First complete the missing temperature values in the table (estimate) and then enter them into the diagram. Now read the values of the corresponding radiation intensity of these objects in the diagram and complete them in the table as well. Follow the example of boiling water.

Object	Temperature °C	Intensity W/m^2
Boiling water	100	1100
Human body		
Ice cubes		

→ If you have placed and assigned the arrows and labels correctly, you will know that, on average, the Earth absorbs $238\,\frac{W}{m^2}$ of solar radiation and radiates this energy away again (radiation equilibrium). Now use the diagram inversely to determine the average temperature of an earth that radiates infrared radiation with this intensity and enter it in the diagram accordingly.

? Interpret the result and compare it to reality: Is it possible to align the average temperature of the Earth you have determined with your experiences? What is the reason for this?

? Not an easy additional question: Do you have any idea why it would be much colder on an earth without an atmosphere?



Stefan-Boltzmann Law in a diagram.

Part 2: What temperature on Earth does the natural greenhouse effect cause?

Background:

Without an atmosphere, it would be very cold on Earth. But how does our atmosphere ensure pleasant temperatures on Earth? The light of the Sun can pass the atmosphere almost without hindrance. Moreover, we assume that the Earth's surface is irradiated by the Sun on average with $340\frac{W}{m^2}$, 30% of which is directly reflected back into Space and the rest is absorbed by the Earth's surface. In the following, we assume that 76% of the heat radiation emitted by the heated surface of the Earth is absorbed by the atmosphere; the rest (24%) goes unhindered into Space. The atmosphere heated by this absorbed heat radiation now in turn also radiates heat radiation - half towards Space, the other half towards the ground.

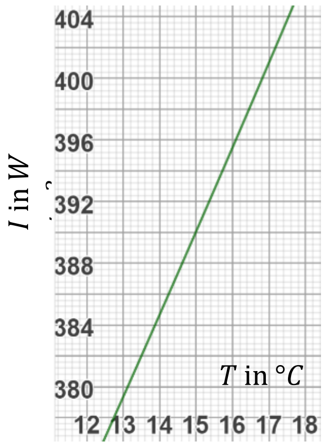

Earth with atmosphere

Implementation:

→ Laying arrows: Study the background text and lay out the light grey and dark grey bordered arrows on the "Earth with atmosphere" sheet.

→ The atmosphere is thus (in addition to the Sun) a second source of radiation, which (with our assumptions) emits radiation with an intensity of $147\frac{W}{m^2}$ towards the ground. This energy is now additionally absorbed by the ground, which radiates again with greater intensity. What is the value of this radiation intensity and what is the temperature of the ground for this? Use the diagram on the right, which is an enlargement of the diagram above.

Hint: Add up the two radiation intensities absorbed by the earth.



Part 3: How strong is the anthropogenic greenhouse effect?

Background:

The natural greenhouse effect ensures pleasant temperatures and that life can exist on Earth at all! But now humans come into play: Due to the strong emission of greenhouse gases such as carbon dioxide or methane, an increasing proportion of the Earth's infrared radiation is absorbed by the atmosphere.


Greenhouse gas emissions

? In the following example, we assume that the atmosphere absorbs slightly more radiation from the Earth: 78% instead of 76%. As a result, it heats up more and therefore also radiates with higher intensity. In this case, this would correspond to an *additional* $6\frac{W}{m^2}$. What is the average temperature for the Earth with this additional energy source, that irradiates the Earth?

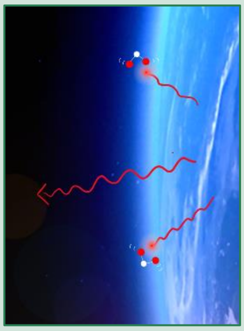
Info: The Intergovernmental Panel on Climate Change (IPCC) uses computer models to provide scenarios (possibilities) for the future climate. The scenarios vary from RCP 2.6 to RCP 8.5, with the figure indicating an additional radiation intensity of $2{,}6\frac{W}{m^2}$ *respectively* $8{,}5\frac{W}{m^2}$ *from the atmosphere towards the Earth's surface.*

Activity 5 – The Effect of Greenhouse Gases

What effect do greenhouse gases have on the Earth's temperature?

Background:

The Earth's atmosphere consists mainly of nitrogen (78%) and oxygen (21%). Greenhouse gases such as carbon dioxide (0.04%) and methane (0.0002%) are only present in trace amounts, but nevertheless have a major impact! The molecules of the greenhouse gases absorb the invisible infrared radiation emitted by the Earth's surface and thus vibrate. This oscillation energy is then transferred to particles in the environment in the form of kinetic energy - the atmosphere warms up! What happens to the temperature of the atmosphere when people release large quantities of CO_2 into the atmosphere by burning fossil fuels?



Absorption of IR radiation by greenhouse gases

Part 1: Can CO_2 "intercept" invisible infrared radiation?

Model experiment for greenhouse

Materials:

- ✓ Ceramic infrared radiator
- ✓ Tin, stopper, cling film and rubber bands
- ✓ Wooden block for plugging in and holding rubbers
- ✓ Digital thermometer ⑤
- ✓ Erlenmeyer flask with stopper and tube
- ✓ Soda, citric acid and water

Caution! Very hot radiator: risk of burns! Chemicals: Wear safety goggles!

Preparation:

→ Place the ceramic infrared radiator with the wooden holder on the folded-up feet of the wooden frame and push the wooden holder for the cardboard tube into the two holes as far as it will go (see picture). This should represent the radiant earth and not the sun.

→ Close the large openings of the cardboard tube with cling film and household rubbers and then attach the cardboard tube to the wooden holder with rubbers so that the distance between the infrared radiator and the can is 8 cm.

→ Insert the thermometer into the small hole in the middle (so that the tip is in the middle of the tube) and seal the other two holes (CO2 inlet and air outlet) with a plug each.

→ Switch on the infrared emitter. While the emitter is heating up, read the background text carefully and match the parts of the experiment (left) to their equivalents in reality (right)

Air in the can	*Additional greenhouse gases*
Ceramic infrared radiators	*Earth's atmosphere with normal CO_2 concentration*
CO_2 produced in the Erlenmeyer flask	*Earths ground*

Wait until the temperature in the can no longer changes within 30 seconds and you can assume that the equilibrium temperature has been reached (approx. 27 °C). This can take up to 25 minutes if the radiator has not yet been heated up.

➞ As soon as the equilibrium temperature is reached, CO_2 is added to the cardboard tube in the next step (execution).

➞ Possible previous experiment during the waiting time: Produce CO_2 in an Erlenmeyer flask (mix a teaspoon each of sodium bicarbonate and citric acid with a little water) and then pour the gas over a burning candle. What properties of CO_2 can you observe with this experiment?

Implementation:

➞ Start the experiment when the equilibrium temperature is reached. Make a note of this before you continue!

➞ Now produce CO2 and pour it into the can:

Mix two teaspoons each of baking soda and citric acid in an Erlenmeyer flask (still without water)

➞ Remove the two small stoppers from the can.

➞ Then push the tube through one of the holes, add approx. 30 ml of water to the acid and soda mixture and quickly place the large stopper with tube on the Erlenmeyer flask!

➞ Swivel the Erlenmeyer flask slightly so that the CO2 is directed into the can. This should take about one and a half minutes.

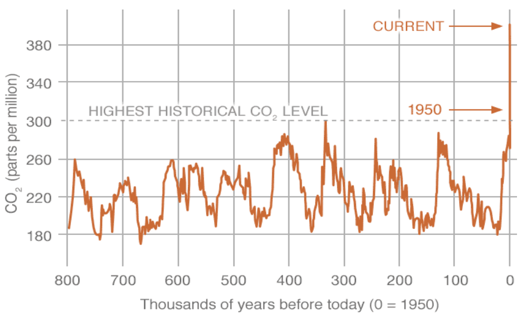
➞ Then remove the tube from the can again and at the same time quickly close the two holes with the small plugs.

(The CO2 concentration in the can is now greatly increased, much higher than it is on earth. This is necessary because the cardboard tube is only a few centimetres long, but the atmosphere is several kilometres thick).

➞ Observe the measured temperature over the next few minutes and wait until an equilibrium temperature is reached again. Note its value and compare it with the previous temperature.

Task:

? The CO_2 concentration in the atmosphere is measured in parts per million (ppm). It thus indicates how many molecules of CO_2 one million molecules of dry air contain. Search the Internet for "NASA CO_2" and search for the current CO_2 concentration in the atmosphere. Also compare with the historical values of the last 800,000 years in the figure there.



? What has led to the observed greenhouse gas concentration since the 19th century? How is the experiment related to these data? Summarise your findings in two sentences.

Part 2: Infrared radiation is intercepted

In addition to measuring the temperature in the can, the radiation that passes through the can can be measured (transmission).

Materials:

- ✓ same materials as above
- ✓ thermal imaging camera with static

Caution! Very hot radiator: risk of burns! Chemicals: Wear safety goggles!

Experiment: Absorption of heat radiation

Preperations:

- → For this experiment, carefully open the protective cage (risk of burns!) so that there is no grid between the infrared emitter and the cardboard tube. Mount the thermal imaging camera on the stand so that the heat radiation hits the measuring opening of the thermal imaging camera through the cardboard tube and the target cross is on the heat emitter.
- → Addition for thermal imagers with fixable temperature scale (e.g. FLIR C3-X): Set the temperature scale to manual, fix the upper limit (maximum temperature of the heat emitter) and then set the lower limit approximately 20°C below it.

Implementation:

- → Wait until the temperature remains constant (as above) and then observe the temperature reading (and visible image, if applicable) of the thermal imaging camera as CO_2 is poured into the cardboard tube.

Task:

- → Interpret the result! Note that a thermal imaging camera calculates the temperature of an object using the emitted thermal radiation (see Activity 4 - Stefan-Boltzmann law).

Part 3: Why do greenhouse gases in the atmosphere heat up the Earth's surface?

Materials:

- ✓ Ceramic infrared radiator
- ✓ Petri dish out of glass
- ✓ Wooden clip
- ✓ Thermal imaging camera

Absorption model atmosphere

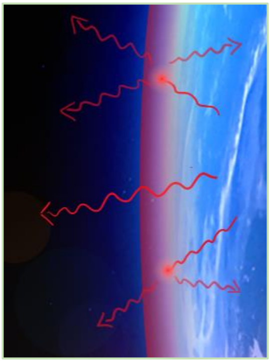
Re-radiation model atmosphere

Implementation:

- → The Petri dish out of glass in the following experiment acts like a very dense greenhouse gas atmosphere that absorbs almost all the infrared radiation from the Earth's surface (infrared radiator). Observe the infrared radiator from the front with the thermal imaging camera, first without the glass plate and then push the glass plate in between with the help of wooden clip (left picture). Observe for about one minute and then write down your observations.

→ Now look (directly afterwards) at the glass plate from the surface of the Earth (right picture). The effect observed here in the model experiment is a further crucial element in understanding the greenhouse effect. Explain it by putting the sentence blocks in the right order:

- ☐ It is heated up by absorbing radiant energy.
- ☐ The greenhouse gas CO_2 absorbs the heat radiation emitted from the Earth.
- ☐ This additional source of radiation heats up the Earth's surface.
- ☐ The heated gas itself now radiates infrared radiation in all directions, including towards the Earth.



Reflection of IR radiation by the atmosphere

Activity 6 – The Rise in Sea Level

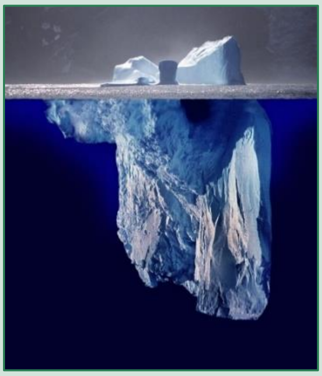
How does climate change lead to a rise in sea level?

Cecilia Scorza
and Moritz Strähle

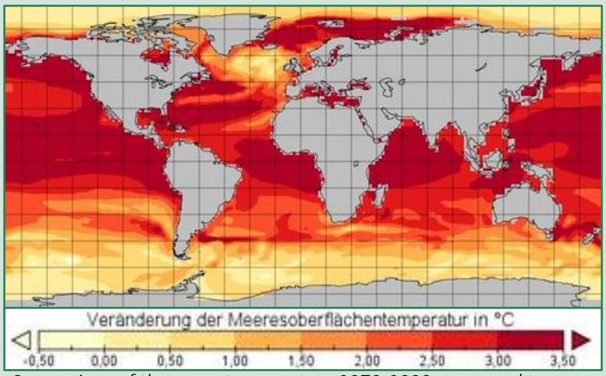
Background:

Due to global warming, large masses of ice are currently melting on land, such as the Greenland ice sheet or glaciers in the Alps. The water temperature of the oceans is also rising. This also means that icebergs floating in the water are melting faster.

Glaciers on Greenland (Source: Wikipedia)



Photomontage of an iceberg (Credits: Uwe Kils)



Comparison of the mean temperature 2070-2099 compared to 1961-1990 in scenario RCP8.5 (source: wiki.bildungsserver.de)

Materials:

- ✓ Radiant heaters in the protective cage or sunlight
- ✓ Two 150ml beakers
- ✓ Ice cube penguin and polar bear
- ✓ Two flat pebble stones ⑥
- ✓ Water-soluble felt-tip pen
- ✓ Erlenmeyer flask
- ✓ Rubber stopper with glass tube

Experiments on sea level rise

Caution! Very hot radiator: risk of burns!

Experiment 1: Is sea level rising due to melting icebergs?

→ Place the stones in one of the beakers. Fill up this beaker so that only the first stone is under water and fill the other the other with approx. 80 ml of cold water. Then place one ice cube on the stones, let the other one float in the other beaker and place the beakers under the spotlight. Mark the water level with the water-soluble felt pen instantly! Continue with the next experiment.

Experiment 2: Is the sea level rising due to the warming of the water?

→ Fill the flask with water and close it with the rubber stopper and glass tube so that the water in the tube is halfway up and no air bubbles form (some tests may be necessary).

→ Mark the level with the water-soluble felt pen and heat the water in the flask with your hands for a few minutes. Watch the ice cubes while doing so.

→ Write down your observations in both experiments and describe in a short summary why sea levels are rising (and why they are not) due to global warming. Also refer to the pictures in the background text and the results of the experiments.

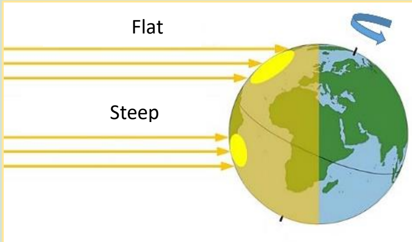
Activity 7 – Climate Zones and Climate Change

How do the Earth's climate zones develop and what impact does climate change have on their expansion?

Cecilia Scorza
and Moritz Strähle

Background:

The climate zones of the Earth are created by the difference in intensity of solar radiation depending on the geographical latitude. Near the equator, the angle of incidence of the Sun's rays is relatively high all year round and at certain times even perpendicular to the Earth's surface. With increasing geographical latitude, the Sun's rays reach the Earth's surface at an increasingly flat angle, so that the irradiated energy is distributed over a larger area (see figure).



Angle of incidence of the Sun's rays in relation to the geographical latitude
(Source: denkwerkstatt-physik.de)

The seasons are created by the inclination of the Earth's axis of 23.5° relative to the orbital plane of the Earth around the Sun, the so-called ecliptic. Thus, the northern hemisphere tends to tilt towards the Sun in summer and away from it in winter. (In the figure, the northern hemisphere is in winter.)

Part 1: How do climate zones develop?

In this experiment you will learn about the relationship between the angle of incidence of the Sun and the climate zones and how climate change affects them.

Materials:

- ✓ Radiant heaters in the protective cage on the frame
- ✓ Solar cell with fan 7

Caution! Very hot radiator: risk of burns!


Angle of incidence and intensity

Implementation:

→ Take the solar cell with the connected fan. The speed of rotation indicates how high the incident light intensity is. The spotlight represents the Sun.
Caution! Do not touch the sensitive surface of the solar cell, but hold it from the side!

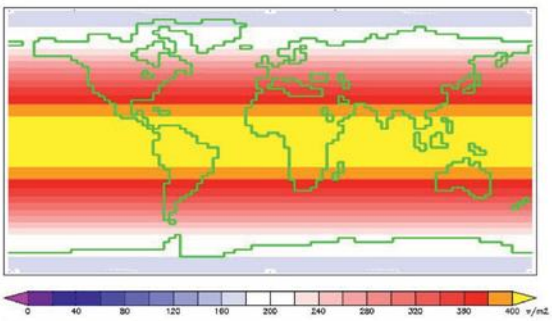
→ Switch the spotlight on and align the solar cell on the opposite edge of the wooden frame in the direction of the spotlight.
Caution! Do not touch the radiator - risk of burns!

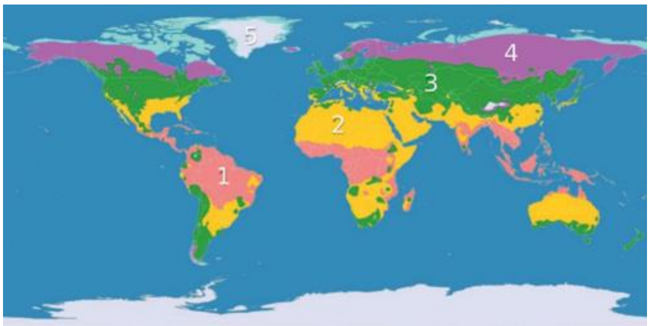
→ Now change the inclination angle of the solar cell and make a qualitative note of the rotation speed for the following angle positions:
Rotation speed at 90°: 45°: 0°:

→ Summarise the test result in one sentence.

Evaluation:

The left figure shows the annual mean value of solar radiation at the top of the atmosphere in the unit W/m^2. The right figure shows the division of the Earth into our five main climate zones.





Left: Annual mean solar radiation top atmosphere;
Right: Genetic climate classification (Source: left: Wiliam M. Conolley; right: Wikimedia)

→ Assign the following climate zones to the numbers 1 to 5 and give approximate values of the average solar radiation for each zone: Subpolar zone, Subtropical zone, Temperate zone, Polar zone, Tropical zone.

→ Briefly explain the relationship between the left and right figures above

Number	Climate zone	Climate zone Average solar radiation in W/m^2
1)		
2)		
3)		
4)		
5)		

Part 2: Impacts of climate change on climate zones and ecosystems

Follow the QR Code and read the article on the consequences of climate change on climate zones and the animals living there.

Evaluation:

→ Describe the consequences of climate change on the Earth's climate zones.

? What are the consequences of climate change on animal habitats and what problems does it pose?

→ *Future scenario:* Outline a possible global distribution of climate zones in 2100 in the silent world map below. Colour the climate zones according to the marking in Fig.2.

Activity 8 – The Oceans as a Climate Buffer

How do the oceans protect us from even greater climate change?

Cecilia Scorza
and Moritz Strähle

Background:

About two-thirds of the Earth's surface are covered with liquid water and this has an impact on the Earth's climate. This is because water is a very effective heat store: A certain mass of water can absorb significantly more energy per Kelvin temperature increase than, for example, the same mass of air. For example, one kilogram of water heats up with an energy supply of $4.2\ kJ$ at $1\ K$. Water therefore has a *heat capacity* of $4{,}2\frac{kJ}{kg\cdot K}$. Air and dry Earth, on the other hand, have a heat capacity of approx. $1\frac{kJ}{kg\cdot K}$. Thus, about one kilojoule is enough to warm up one kilogram of these substances by $1\ K$.

The man-made greenhouse effect provides the Earth's surface with additional energy. How does the water in the oceans affect global warming?

Our blue Earth (NASA)

Materials:

- ✓ Balloon filled with water
- ✓ Candle and match

Water-filled balloon over a candle

Implementation:

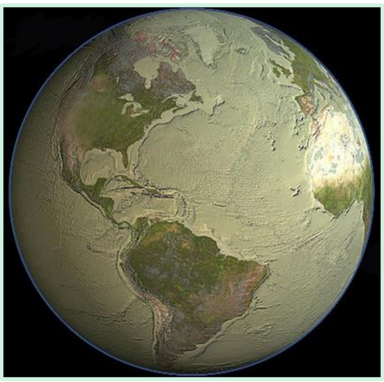
→ How close do you dare to hold the water-filled balloon over the candle? Approach the flame slowly!

→ Touch the balloon from below after some time. Has it warmed up a lot?

Evaluation:

→ Read the background text and explain your observations.

→ The man-made greenhouse effect adds extra energy to the atmosphere. Explain why without our oceans the impact would be even more drastic than it already is today. Which of these two Earths would have a higher surface temperature?



Dry Earth (Credits: Cook, Nieman, USGS)

The blue pearl (Credits: NASA)

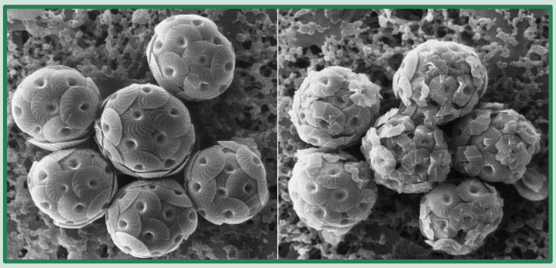
Activity 9 – The Acidification of the Oceans

Why does CO_2 make the oceans acidic and what are the consequences?

Pascal Eitner, Markus Vogelpohl, Clemens Bröll and Markus Nielbock

Background:

Measurements of the pH value in the oceans show an increasing acidification of the water. If the content of the greenhouse gas CO_2 in the Earth's atmosphere rises (for example due to the burning of fossil fuels), it will also increasingly be dissolved in seawater, where it chemically reacts to carbonic acid ($H_2O + CO_2 \rightleftharpoons H_2CO_3$). This has fatal consequences for the life of algae and animals living there, which are not adapted to the increasingly acidic environment. In addition, the shells of calcareous algae, for example, become thinner (see figure) and corals lose their calcareous skeleton. The CO_2 fixing of the oceans is decreasing overall.



Calcareous algae: on the left side today's ocean, on the right side ocean with high CO_2 content. [Source: IFM-GE-

Materials:

- ✓ Two 50 ml beakers
- ✓ Universal indicator with pH-value chart 9
- ✓ Citric acid, sodium bicarbonate and water
- ✓ Erlenmeyer flask with rubber stopper and tube

Experimental setup

Caution! Chemicals: Wear safety goggles!

Implementation:

→ Pour 20 ml of water into a beaker and add approx. four drops of the indicator until the solution becomes clearly discoloured.

→ Note the pH value of the solution.

→ Mix half a teaspoon each of citric acid and sodium bicarbonate in the Erlenmeyer flask and then carefully add approx. 20 ml of water from the second beaker. Pass very little (important for activity 10) of the CO2 with the tube (only a few "bubbles") into the water until the solution turns yellow. Then remove the tube.

→ Describe the result of the experiment in one sentence.

Do not pour away: You need the solution in the second beaker for activity 10!

Evaluation:

Answer the following questions with the help of the background text for Experiment 1 and with an internet search under the QR code shown on the right:

? To what extent do oceans seem to contribute to a slowdown of the man-made greenhouse effect?

? What consequences does acidification of the oceans have for its creatures?

Activity 10 – Release of CO_2 by the oceans

Why does ocean warming increase global warming?

Pascal Eitner, Markus Vogelpohl, Clemens Bröll and Markus Nielbock

Background:

The oceans have a dual role in tempering global warming: On the one hand, they store heat and, on the other, they absorb CO_2 from the atmosphere. However, when the temperature of the water increases, these buffers lose their effect: Warm water absorbs less heat as the temperature difference with the environment becomes smaller, and it can also dissolve less CO_2. It even releases it again at higher temperatures! Acidification also leads to the dissolution of lime, which releases additional CO_2 into the atmosphere. The water vapour, which is produced to a greater extent as a result of the increased water temperatures, is as a greenhouse gas much stronger than CO_2 and thus leads to an additional increase in the greenhouse effect.

Materials:

- ✓ Approx. 20 ml of the acidic solution (from Activity 9)
- ✓ Two 50 ml beakers
- ✓ Tea light candle and matches 9
- ✓ pH-value table 9

Caution! Chemicals: Wear safety goggles!

Experimental setup

Implementation:

→ Distribute the acid solution over the two small beakers and put one of the beakers aside for later comparison.

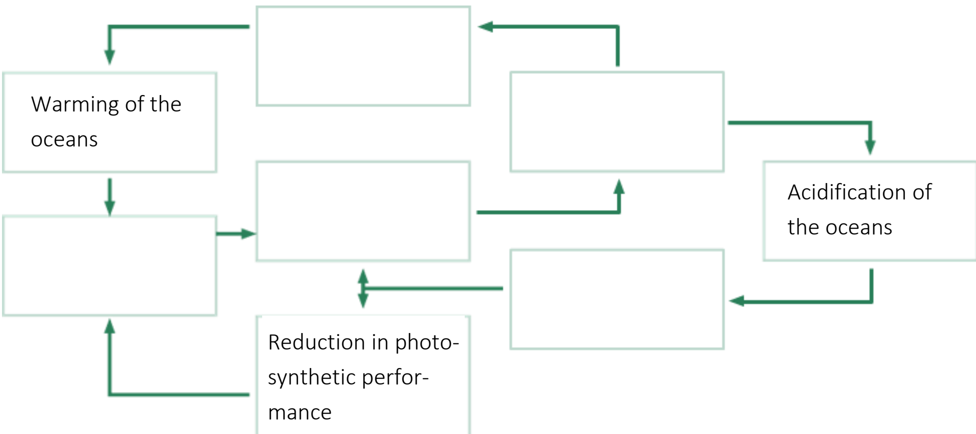
→ Heat one of the two beakers with acid solution over the tea light for about three to four minutes until you can make a clear observation.

→ Observe the colour change and after some time note the pH values of the two solutions.

Evaluation:

→ Complete the following flowchart with the given text blocks and link it to the experiment. Which aspects of the experiment correspond to reality and which do not?

Death of calcifying organisms; reduced CO2 absorption capacity; intensification of the greenhouse effect; increased CO2 concentration in the atmosphere; release of CO2



Activity 11 – Tipping Points: When the Climate Changes...

Klimawandel
verstehen und handeln

Rudolf Pausenberger and Moritz

Will climate change at some point be unstoppable?

Background: Feedback and tipping points

When "tilting" with a chair, you can get yourself into a tilted position by pushing yourself against a table - the more you push, the more you can tilt. If you stop pressing against the table, you return to your starting position. But woe betide you if you push yourself off just a little too much...

Unfortunately, the Earth's climate system behaves in a similar way and could irrevocably collapse in the near future if even one gigatonne too many greenhouse gases are emitted.

Materials:

- ✓ Connected wooden rails
- ✓ Wooden frame
- ✓ Metall rod 11
- ✓ Table tennis ball 11
- ✓ Sliding weight 50g 11
- ✓ Sachet 11
- ✓ 12 nuts (M6) 11

Experimental setup for modelling the tipping points in the Earth's climate system

Preparation:

→ Place the wooden element on the table in front of you with the engraving facing upwards.

→ Insert the 4 wooden spacers into the upper holes of each of the four pairs of holes.

→ Insert the screws into the holes below the wooden spacers. Screw them tight with the nuts.
Caution: On the other side of the scale, the wood chopper is inserted between the wooden elements.

→ Place the second wooden element on top with the engraving facing upwards.

→ Insert the long rod through the large hole in the middle of the wooden construction. Fasten the construction to the wooden frame with this rod. Then attach the bag to the wooden hook by folding it over.

→ Place the tennis ball on top of the construction and balance it by holding the large nut (running weight) with the help of the paper clip on the spike rail. Now you can start experimenting.

Analogy:

- The position of the ball symbolizes the state of the earth's climate and how stable it is. In the starting position the earth's climate is in a relatively stable position.
- The scale at the top corresponds to the increase in the Earth's average temperature compared to today.
- Each nut that is placed in the bag corresponds to the emission of 40 Gt of CO2, the global emission due to fossil fuels within one year.

→ Now emit greenhouse gases by placing a nut in the bag and observe how the temperature on the earth rises a little

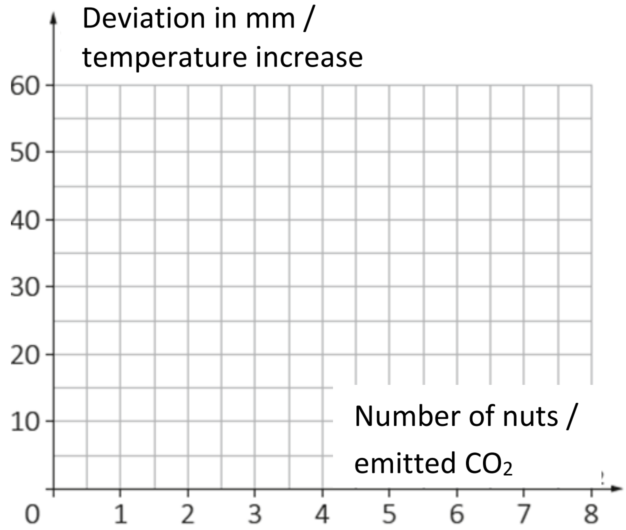
Experiment 1: Small cause, small effect

The relationship between the inserted nut and the position x of the ball is now to be examined more closely:

→ Place eight nuts one after the other in the container and enter the rest position of the ball in the diagram. How far is it from the beginning rest position at the end? *Note: If you think the ball is stuck, give it a light push and let it settle down again.*

→ The ball is still on the left. Now take the nuts out of the container one by one (CO_2 is removed from the atmosphere) and mark the rest positions with a pen of a different colour and enter the values in the same graph.

? What is the mathematical relationship in this experiment taking measurement errors into account?



The devastating forest fires of 2019/20 in Australia have released approx. 30 Gt of CO2 were released. They were the result of an unusually long drought.

? *What options are there to remove CO2 from the atmosphere?*

Forest fire (Source: Pixabay.de)

Experiment 2: Small cause, big effect

→ We now examine the tipping point at which the system changes to another state.

→ Guess, without trying, from which position the ball will roll to the other side and how many nuts this corresponds to.

→ Check your assumption in the experiment. Gradually put nuts into the container until the air conditioning system tilts.

→ Now remove the added CO_2 from the Earth's atmosphere again (remove nuts from the bag).

→ Answer the following questions for evaluation:

? Where is the actual tipping point compared to your estimated one?

? Does the drastic rise in temperature decrease when the added CO_2 is removed from the atmosphere?

Tipping points are crucial to the catastrophic dynamics of climate change: When a tipping point is triggered, it is not immediately noticeable in reality, but a process is set in motion that is no longer reversible! An example: The ice on the Arctic Ocean reflects sunlight. If parts of the ice melt, more solar energy can warm the sea because of the lower reflection. The remaining ice then melts more quickly. At some point, the vicious circle can no longer be stopped. As in the game of dominoes, there is a cascade of tipping points in the Earth's climate system. One can trigger the next one at a time, making the temperature increase incalculable.

The Potsdam Institute for Climate Impact Research (PIK) scientifically addresses such tipping points. Search under "PIK tipping elements" (QR-Code) for more tipping points.

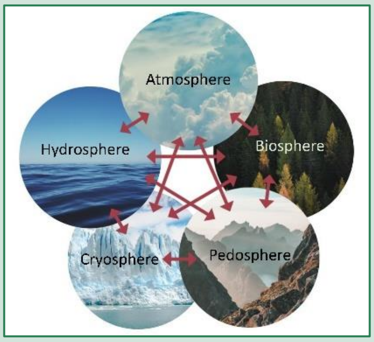
Activity 12 – Tipping Points: Achilles' Heel in the Climate System

Klimawandel verstehen und handeln

Cecilia Scorza

What are tipping points and how are they connected?

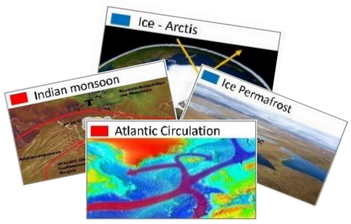
Background:



The Earth's global climate system is determined by the *interaction* between the main components of the climate system: hydrosphere (water), atmosphere (air), cryosphere (ice and snow), pedosphere and lithosphere (soil and rock) and the biosphere (living organisms). Global warming sets processes in motion that influence and change these different elements in different ways. Some of these processes are *self-reinforcing: For example*, global warming leads to increased evaporation of water; and since water vapour is a greenhouse gas, it increases the temperature of the atmosphere, which in turn leads to increased evaporation of water. Because of these *self-reinforcing feedback processes,* when a certain threshold is exceeded, the Earth's climate system can enter the uncontrollable state of a hot period. This is known as a *tipping point*. "Tipping" fmeans that these changes, as they become more and more self-reinforcing, will then be unstoppable or irreversible. The environmental effects of tipping points are far-reaching and could endanger the livelihoods of many millions of people.

Materials:

✓ 14 cards each: Illustrations (A) and explanations (B) of the tipping points 12



Implementation:

On the world map, tipping points and the affected parts of the climate system are shown in different colours:

Ice bodies Flow Systems Ecosystems

→ Place the 14 cards with the illustrations of the tipping points (A) on the table and sort them by colour. Lay out the cards with the explanations and questions about the tipping points (B) on the right side.

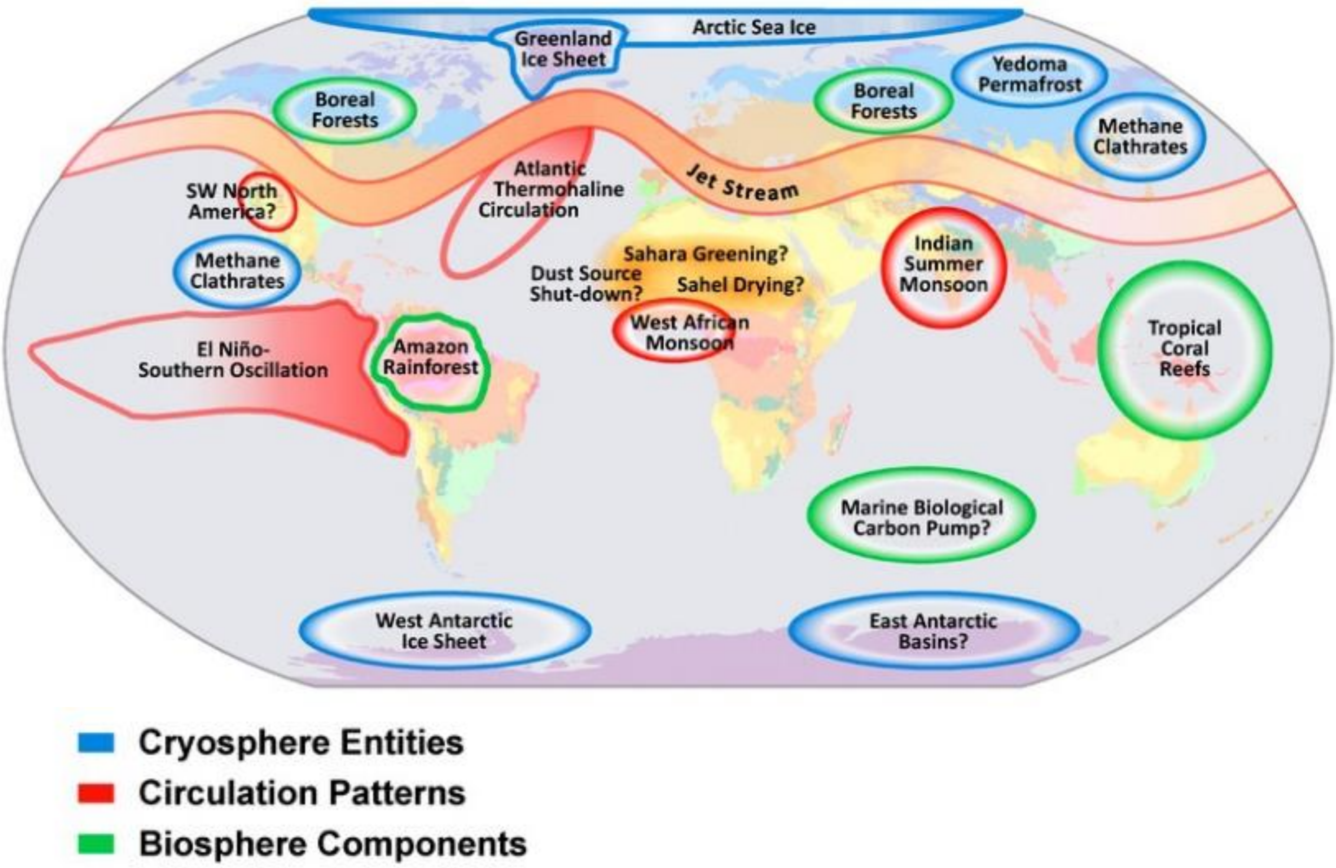
→ Match the cards (B) with the corresponding cards (A) and form the cor-responding pairs.

→ Look at the world map again and answer the following questions with the help of the pairs of cards:

a) How does climate change alter the cryosphere (ice)?

b) How are the flow systems changing as a ¬result of cli-mate change?

c) How are ecosystems changing as a result of climate change?



Geographical classification of tipping elements in the Earth's climate system (Source: PIK, 2007)

Literature

[1] R. M. Ramirez und L. Kaltenegger, „A Volcanic Hydrogen Habitable Zone,“ The Astrophysical Journal Letters, 1 März 2017.

[2] G. Kopp und J. L. Lean, „A new, lower value of total solar irradiance: Evidence and climate significance,“ Geophysical Research Letters, Bd. 38, Nr. 1, Januar 2011.

[3] „Wiki Bildungsserver,“ Hamburger Bildungsserver, 3 Dezember 2013. [Online]. Available: https://wiki.bildungsserver.de/klimawandel/index.php/Albedo_(einfach). [Zugriff am 27. Mai 2020].

[4] Trenberth, Fasullo and Kiehl (2009): Earth’s global energy budget. In: Bulletin of the American Meteorological Society, basiert auf Kiehl and Trenberth 1997.

[5] P. D. Jones, M. New, D. E. Parker, S. Martin und I. G. Rigor, „Surface air temperature and its changes over the past 150 years,“ Reviews in Geophysics, Bd. 37, Nr. 2, p. 173–199, 1999.

[6] P. T. Doran und M. K. Zimmerman, „Examining the Scientific Consensus on Climate Change,“ Eos, Bd. 90, Nr. 3, pp. 22–23, 2009.

[7] S. Rahmstorf und H. J. Schellnhuber, Der Klimawandel: Diagnose, Prognose, Therapie, München: C.H. Beck, 2018.

[8] „EU Science Hub,“ [Online]. Available: https://ec.europa.eu/jrc/en/news/global-fossil-co2-emissionsincreased-2017. [Zugriff am 27. Mai 2020].

[9] T. F. Stocker, D. Qin und e. al., „Climate Change 2013,“ Cambridge University Press, New York, 2013.

[10] „Umweltbundesamt,“ [Online]. Available: https://www.umweltbundesamt.de/themen/bodenlandwirtschaft/umweltbelastungen-der-landwirtschaft/lachgas-methan. [Zugriff am 21 09 2020].

[11] „The NOAA Annual Greenhouse Gas (Index),“ NOAA, [Online]. Available: https://www.esrl.noaa.gov/gmd/aggi/aggi.html. [Zugriff am 21.09.2020].

[12] T. M. Lenton, J. Rockström, O. Gaffney, S. Rahmstorf, K. Richardson, W. Steffen und H. J. Schellnhuber, „Climate tipping points – too risky to bet against,“ Nature, Bd. 575, pp. 592–596, 2019.

[13] „Wiki Bildungsserver,“ Hamburger Bildungsserver, 10. September 2020. [Online]. Available: https://wiki.bildungsserver.de/klimawandel/index.php/Gr%C3%B6nl%C3%A4ndischer_Eisschild. [Zugriff am 21.09.2020].

[14] „Scinexx,“ MMCD NEW MEDIA GmbH, 20. Dezember 2004. [Online]. Available: https://www.scinexx.de/news/geowissen/wird-der-amazonas-regenwald-zur-steppe/. [Zugriff am 21.09.2020].

[15] „Wiki Bildungsserver,“ Hamburger Bildungsserver, 02. Dezember 2015. [Online]. Available: https://wiki.bildungsserver.de/klimawandel/index.php/Kipppunkte_im_Klimasystem. [Zugriff am 21.09.2020].

[16] „Wiki Bildungsserver,“ Hamburger Bildungsserver, 5. Dezember 2013. [Online]. Available: https://wiki.bildungsserver.de/klimawandel/index.php/Kohlenstoff_im_Ozean. [Zugriff am 21.09.2020].

[17] D. Coumou, S. Rahmstorf und weitere, „A decade of weather extremes,“ Nature, 2012.

[18] X. Chen, X. Zhang, J. Church, C. S. Watson, M. King, D. Monselesan, B. Legresy und C. Harig, „The increasing rate of global mean sea-level rise during 1993–2014,“ Nature Climate Change, Bd. 7, pp. 492–495, 2017.

[19] P. Christoffersen und M. B. et. al., „Significant groundwater contribution to Antarctic ice streams hydrologic budget,“ Geophysical Research Letters, Bd. 41, Nr. 6, pp. 2003–2010, 2014.

[20] B. Schinke, S. Harmeling, R. Schwarz, S. Kreft, M. Treber und C. Bals, „Globaler Klimawandel: Ursachen, Folgen, Handlungsmöglichkeiten,“ Germanwatch, Bonn, 2011.

[21] C. Jakobeit und C. Methmann, „Klimaflüchtlinge,“ Universität Hamburg, Hamburg, 2007.

[22] J. A. Church, N. J. White, L. F. Konikow, C. M. Domingues, J. G. Cogley, E. Rignot, J. M. Gregory, M. R. v. d. Broeke, A. J. Monaghan und I. Velicogna, „Revisiting the Earth's sea-level and energy budgets from 1961 to,“ Geophysical Research Letters, Bd. 38, Nr. 18, pp. 1944–2007, 2011.

[23] „Beobachteter Klimawandel,“ Umweltbundesamt, [Online]. Available: https://www.umweltbundesamt.de/themen/klima-energie/klimawandel/beobachteter-klimawandel. [Zugriff am 21.09.2020].

[24] „Klimafolgen: Handlungsfeld Wasser, Hochwasser- und Küstenschutz,“ Umweltbundesamt, 04.09.2013. [Online]. Available: https://www.umweltbundesamt.de/themen/klima-energie/klimafolgen-anpassung/folgen-des-klimawandels/klimafolgen-deutschland/klimafolgen-handlungsfeld-wasserhochwasser#wasserverfugbarkeit-und-hitze. [Zugriff am 21.09.2020].

[25] „Klima-Report Bayern 2015,“ Bayerisches Staatsministerium für Umwelt und Verbraucherschutz, München, 2015.

[26] B. f. Naturschutz. [Online]. Available: https://www.bfn.de/themen/biotop-und-landschaftsschutz/moorschutz/moore-entstehung-zustand-biodiversitaet/moortypen.html. [Zugriff am 20.10.2020].

[27] D. G. f. M.-. u. T. e.V., „Was haben Moore mit dem Klima zu tun?,“ 2009

[28] H. Höper, „Freisetzung klimarelevanter Gase aus deutschen Mooren,“ Telma, Bd. 37, pp. 58–116, 2007.

[29] A. u. M. D. Freibauer, „Moor unter: Klimaschutz“ Politische Ökologie, Bd. 30, pp. 98–105, 2012.

[30] „klimawandel-meistern.bayern.de,“ Bayerisches Staatsministerium für Umwelt und Verbraucherschutz, [Online]. Available: https://www.klimawandel-meistern.bayern.de/moorschutz.html. [Zugriff am 20.10.2020].

[31] M. &. K. M. Drösler, „Klimaschutz durch Moorschutz – im Klimaprogramm Bayern (KLIP 2020/2050),“ Anliegen Natur, Bd. 42, Nr. 1, pp. 31–38, 2020.

[32] W. Steffen, J. Rockström, K. Richardson, T. M. Lenton, C. Folke, D. Liverman, C. P. Summerhayes, A. D. Barnosky, S. E. Cornell, M. Crucifix, J. F. Donges, I. Fetzer, H. Schellnhuber und weitere, „Trajectories of the Earth System in the Anthropocene,“ Proceedings od the National Academy of Sciences of the United States of America, Bd. 115, Nr. 33, pp. 8252-8259, 2018.

[33] H. D. Matthews et.al., An integrated approach to quantifying uncertainties in the remaining carbon budget, Communications Earth & Environment, 2, 2021, DOI: 10.1038/s43247-020-00064-9

[34] Umweltbundesamt, „https://www.umweltbundesamt.de/,“ [Online]. Available: https://www.umweltbundesamt.de/daten/energie/primaerenergieverbrauch [Zugriff am 11.7.2021].

[35] P. D. V. Quaschning, „Was kollabiert noch alles nach Corona?,“ [Online]. Available: https://www.y-outube.com/watch?v=6V-C5q4VxEI. [Zugriff am 17.03.2021].

[36] Umweltbundesamt, „Umweltbundesamt.de,“ 12.11.2020. [Online]. Available: https://www.umwelt-bundesamt.de/daten/energie/energieverbrauch-nach-energietraegern-sektoren. [Zugriff am 17.03.2021].

[37] Umweltbundesamt, „www.probas.umweltbundesamt.de,“ [Online].

[38] „Energieszenarien,“ Sonnenenergie, Nr. Dezember 2020, 2020.

[39] P. D. V. Quaschning, „volker-quaschning.de,“ [Online]. Available: https://www.volker-quaschning.de/datserv/ren-Strom-D/index.php. [Zugriff am 17.03.2021].

[40] BMWI, „Energiedaten: Gesamtausgabe,“ 2019.

[41] J. A. Robert Goodland, „Livestock and Climate Change,“ http://templatelab.com/livestock-and-cli-matechange/, 2009

[42] R. B. Fishman, „Schlechtes Gewissen, gutes Geld und faule Kompromisse,“ Deutschlandfunk Kultur, 24.11.2020. [Online]. Available: https://www.deutschlandfunkkultur.de/co2-kompensation-schlechtesgewissen-gutes-geld-und-faule.976.de.html?dram:article_id=488040 . [Zugriff am 17.03.2021].

[43] Umweltbundesamt, „Umweltschädliche Subventionen in Deutschland 2016,“ 2016.

[44] R. Goodland und J. Anhang, „Livestock and climate change,“ World Watch, Bd. 22, pp. 10–19, No-vember 2009.

[45] J. Swim, P. Stern, T. Doherty, S. Clayton, J. Reser, E. Weber, R. Gifford und G. Howard, „Psychology's contributions to understanding and addressing global climate change,“ American Psychologist, Bd. 66, Nr. 4, p. 241–250, 2011.

[46] „Am 15. März ist CO2-Tag: Deutschland am Limit,“ Zukunft Erdgas e.V., 2020. [Online]. Available: https://zukunft.erdgas.info/ueber-zukunft-erdgas/experten-leistungen/kommunikation/kampagnen/co2-budget-deutschland.

[47] „Treibhausgas-Emissionen in Deutschland,“ Umweltbundesamt, 06 07 2020. [Online]. Available: https://www.umweltbundesamt.de/daten/klima/treibhausgas-emissionen-in-deutschland. [Zugriff am 22.09.2020].

[48] „Was haben Moore mit dem Klima zu tun?,“ Deutsche Gesellschaft für Moor- und Torfkunde e.V., 2009.

[49] V. Quaschning, „Sektorkopplung durch die Energiewende,“ Hochschule für Technik und Wirtschaft, Berlin, 2016.

[50] V. Quaschning, „volker-quaschning.de,“ [Online]. Available: https://www.volker-quaschning.de/grafi-ken/index.php. [Zugriff am 12.10.2020].

[51] Umweltbundesamt, „CO2-Bepreisung in Deutschland,“ 2019.

[52] C. u. S. C. Buchal, Klima – Die Erde und ihre Atmosphäre im Wandel der Zeiten, Wilhelm und Else He-raeusStiftung, Helmholtz-Gemeinschaft Deutscher Forschungszentren, 2010.

[53] G. Schröder, „Energiewende in Gefahr – Deutschland braucht mehr grünen Strom,“ Deutschlandfunk Kultur, [Online]. Available: https://www.deutschlandfunkkultur.de/energiewende-in-gefahr-deutschland-braucht-mehr-gruenen.976.de.html?dram:article_id=481356. [Zugriff am 17.03.2021].

[54] ZDF, 28.11.2019. [Online]. Available: https://www.zdf.de/nachrichten/heute/klickscham-wie-viel-co2-emails-und-streaming-verusachen-100.html.

Further literature references

Bals, C. (2002): Zukunftsfähige Gestaltung der Globalisierung. Am Beispiel einer Strategie für eine nachhaltige Klimapolitik.In: Zur Lage der Welt 2002. Fischer Verlag.

Bals, C. et al. (2008): Die Welt am Scheideweg. Wie retten wir das Klima? Rowohlt Verlag

Dincere, I. (2018): Comprehensive Energy Systems, Elsevier Verlag.

Levke, C., Rahmstorf, S., Robinson, A., Feulner, G., Saba, V. (2018): Observed fingerprint of a weakening Atlantic Ocean overturning circulation.In: Nature [DOI: 10.1038/s41586-018-0006-5]

Church, J. und White, N. (2006): A 20th century acceleration in global sea-level rise.In: Geophysical Research Letters, Vol. 33, L01602

Hupfer, P. (1998): Klima und Klimasystem.In Lozan, J.L., H. Graßl und P. Hupfer: Warnsignal Klima. Wissenschaftliche Fakten, Hamburg, S. 17–24.

IPCC (2007a): Climate Change 2007 – The Physical Science Basis.

http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents

IPCC (2007b): Climate Change 2007 – Impacts, Adaptation and Vulnerability. http://www.ipcc-wg2.org/

IPCC (2007d): Klimaänderungen 2007: Zusammenfassungen für politische Entscheidungsträger.

http://www.proclim.ch/4dcgi/proclim/de/Media?555.

IPCC (2007e): Climate Change 2007. Synthesis Report. Contribution of Working Groups I, II and III to the Fourth

Assessment Report of the Intergovernmental Panel on Climate Change.

http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm.

Jonas, H. (1984): Prinzip Verantwortung, Suhrkamp Verlag.

Lenton, T.M. et al. (2008): Tipping Elements in the Earth‘s Climate System.In: PNAS, Vol. 105.

Lesch, H. und Kamphausen, K. (2016): Die Menschheit schafft sich ab – Die Erde im Griff des Anthropozäns, Komplett-Media

Rahmstorf, S. und Katherine Richardson, K. (2007): Wie bedroht sind die Ozeane? Fischer Taschenbuch Verlag.

Rahmstorf, S. und Schellnhuber, H.J. (2018): Der Klimawandel: Diagnose, Prognose, Therapie. Verlag C.H. Beck.

Schüring, J. (2001): Schneeball Erde. Spektrumdirekt.

Seifert, W. (2004): Klimaänderungen und (Winter-)Tourismus im Fichtelgebirge – Auswirkungen, Wahrnehmungen und Ansatzpunkte zukünftiger touristischer Entwicklung, Universität Bayreuth.

Swim, J. K., Stern, P.C., Doherty, T. J., Clayton, S., Reser, J. P., Weber, E. U., Gifford, R., Howard, G. S. (2011): Psychology's contributions to understanding and addressing global climate change. American Psychologist, Vol 66(4), May–Jun 2011, 241–250.

WBGU (2007): Welt im Wandel – Sicherheitsrisiko Klimawandel. Hauptgutachten. Berlin. http://www.wbgu.de/wbgu_jg2007.html.

Literaturhinweise zu Abschnitt 6.4

Fritsche, I. & Masson, T. (2014). Adherence to climate change-related ingroup norms: Do dimensions of group identification matter? European Journal of Social Psychology, 44, 455–465

Bishop, B., Leviston, Z., & Price, J. (2014). Imagining climate change: The role of implicit associations and affective psychological distancing in climate change responses. European Journal of Social Psychology, 44, 441–454

Leach, C. (2008). Group-Level Self-Definition and Self-Investment: A Hierarchical (Multicomponent) Model of In-Group Identification. Journal of Personality and Social Psychology, 95(1), 144–65

Bertolotti, M. & Catellani, P. (2014). Effects of message framing in policy communication on climate change. European Journal of Social Psychology, 44, 474–486

Fielding K., Swim J. & Hornsey M. (2014). Developing a social psychology of climate change. European Journal of Social Psychology, 44, 413–420 (2014)

UNESCO Publication Teaching and learning transformative engagement UNESCO, https://en.unesco.org/themes/119915/publications/all