Climate Change

It is pretty obvious that a climate change is happening on Earth since some decades. But what *exactly* is going on? Comprehensive informations on all aspects of climate change on highest scientific level are readily available in the reports[1] of the IPCC[2].

Reading those reports, however, is a quite tedious business. Therefore, I have compiled in this file on only 36 pages the most important informations on climate change such, that I do understand them myself, keeping with the motto "If I understand that, then everybody, gifted with a minimum of intelligence, will understand that as well." The informations come from the IPCC reports, and from many other sources I found in the net. Of course, I have included links to all of these sources so that readers who want more detailed, first-hand information on this or that point, can access it with a few mouse clicks.

[1] The IPCC reports can be downloaded here: https://www.ipcc.ch/

[2] The IPCC = Intergovernmental Panel on Climate Change has been established as a new institution of the United Nations in 1988 by the UNEP = United Nations Environmental Program and the WMO = World Meteorological Organization. By today (2025), 195 states are members of the IPCC.

On behalf of the IPCC, scientists compile the actual state of climate research, and assess the latest state of knowledge regarding the climate change. IPCC reports shall indicate the options available to policy-makers, clarify their respective implications, be neutral, policy-relevant, but not policy-prescriptive.

1. Measurement Results

1.1 Temperature

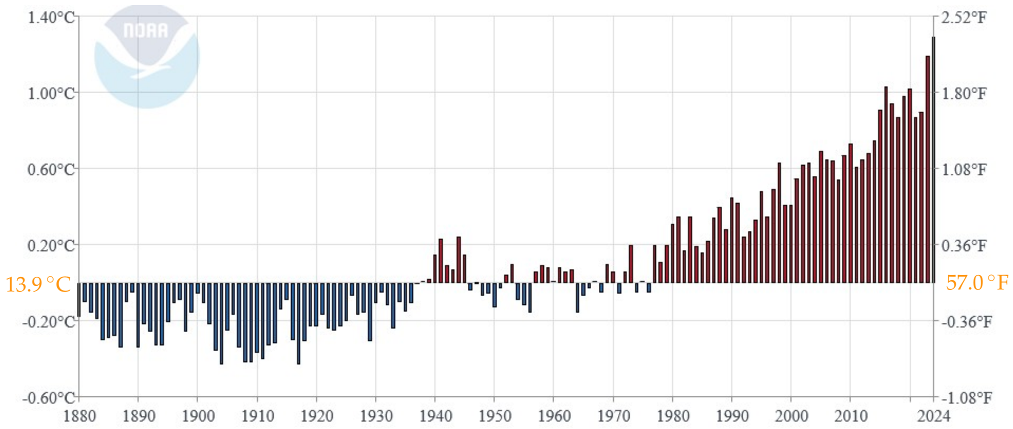

Fig. 1: Global surface temperature. Mean value over land and sea, mean value over the year. Graphic from [1].

The Earth's mean surface temperature in the 20$^{\text{th}}$ century, with the mean value computed over sea- and land-areas, has been 13.9 °C = 57.0 °F. The deviations from that reference value in the years 1880 through 2024 are indicated in fig. 1 .

The eleven years 2014 through 2024 have been the eleven warmest since the begin of regular temperature measurements. Record holder is 2024 with 1.29 °C above the 20$^{\text{th}}$ century mean value.

1.2 Melting Ice

Extension and thickness of the ice of 41 representative glaciers (listed here) in mountains on several continents is being monitored systematically since decades. While the ice volumes increase at times, the general trend everywhere is clearly downward.

In fig. 2 the mean cumulative loss of ice is indicated, which these glaciers in the respective regions have suffered relative to the 1976 value. The units

$$\begin{aligned} \text{m w.e.} &= \text{meter water equivalent} \\ 1000\,\text{kg}\,\text{m}^{-2} = \text{t}\,\text{m}^{-2} &= \text{tons per square meter} \end{aligned}$$

have identical meaning: They indicate the (measured or estimated) mass of the melted ice, divided by the glacier's area.

One cubic meter ice melts to less than one cubic meter water, but not to much less (only the tip of the iceberg is visible above the water surface). Thus from the curve for Central Europe (i. e. the Alps), it can be read in rough approximation that a mountaineer, who climbs from the glacier up to the hut, must each year master the additional altitude difference of one meter, cf. fig. 3 on next page.

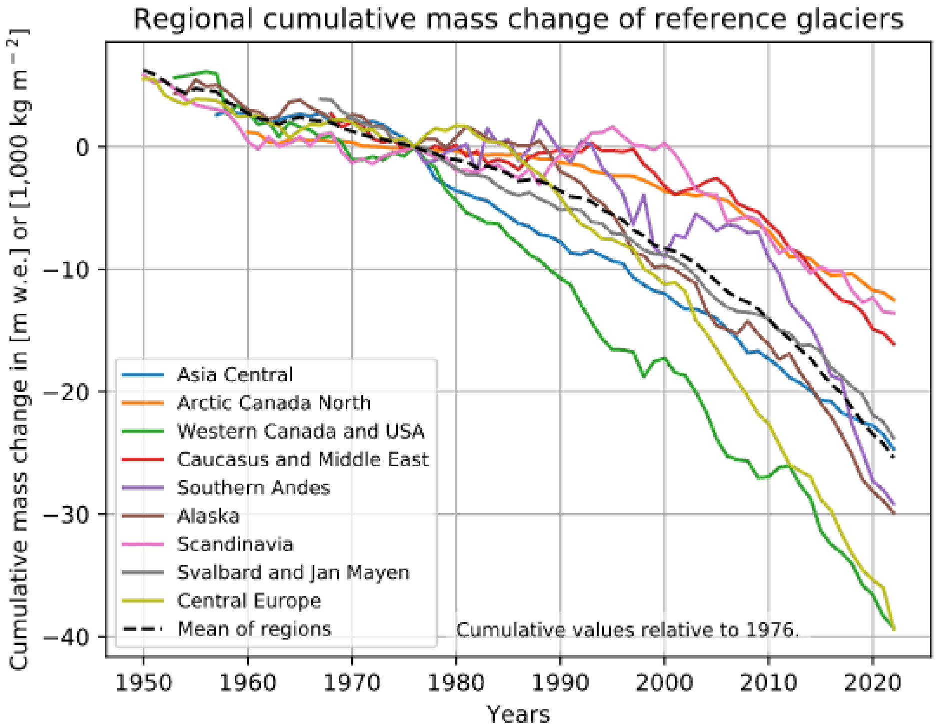

Fig. 2: Ice loss of 41 glaciers. Graphic from [2].

Fig. 3: The Concordia Hut above the Aletsch Glacier (Bernese Alps, Switzerland) by about 1880 and by March 2015.

In the years 2002 through 2015 the Earth's gravitational field has been evaluated with much higher precision than ever before by means of the two GRACE satellites. The measurement was based on this method:

The two satellites overflew each region of Earth dozens of times per year in 450 to 500 km height above surface. At any time, the second satellite followed the first at a distance of about 220 km along the same orbit. Each satellite was equipped with a special radar system, by which it monitored changes of distance to it's twin with an accuracy of 10 μm.[19,3]

When the satellites approached a region where the mass of the Earth was above average, then the front satellite was accelerated first, and the following satellite only slightly later, i. e. the distance between the satellites increased. When the satellites had passed the area with higher gravitation, then the front satellite was decelerated first, and only slightly later the following one, i. e. the distance between the satellites decreased

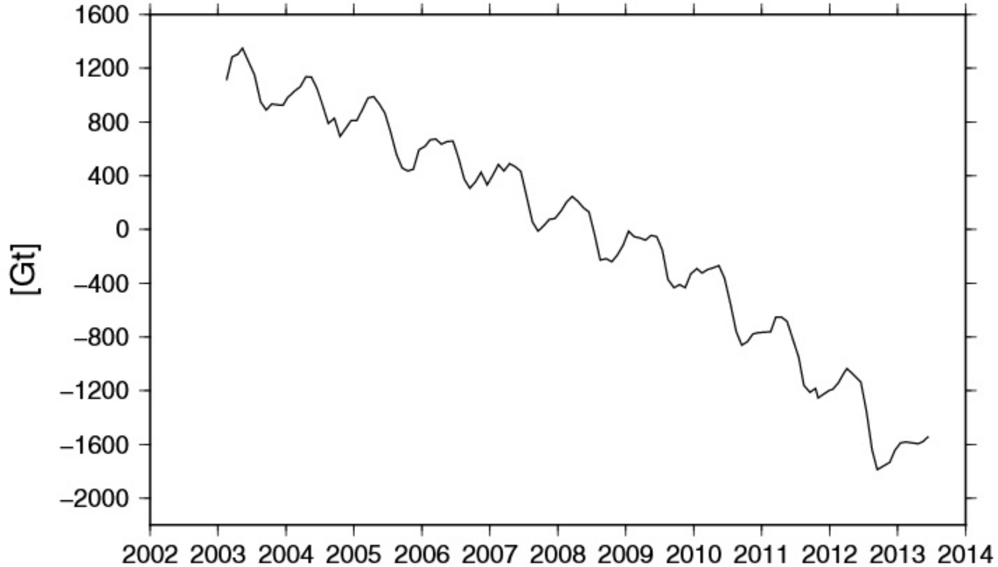

Fig. 4: Ice loss of Greenland, computed from GRACE data. Graphic from [3].

again. Thus the varying distance between the satellites was an indicator for the Earth's varying gravitational field.

When glaciers or the ice-caps of the Earth's poles melt down, then the meltwater distributes over the oceans. Hence the gravitation decreases, where the ice disappears. This could indeed be observed by means of the GRACE satellites.

The reduction of the Greenland ice cap as computed from GRACE data is displayed in fig. 4 in units of Gt = Giga-tons = billion tons (the zero-point of the vertical scale is chosen arbitrarily). The authors of [3] computed similar curves as well for Antarctica and for all other ice areas on Earth, and concluded these results:

	mass loss
Greenland	(278 ± 19) Gt/year
Antarctica	(92 ± 26) Gt/year
all other ice areas	(162 ± 10) Gt/year
sum	(532 ± 34) Gt/year

The authors remark, that the melting of 532 Gt of ice per year accounts

[3] No typo, but an engineering marvel!

for approximately half of the observed global sea-level rise.

Qualitatively, these results certainly are correct. But regarding the precise values, some caution may be advisable. The GRACE satellites measured — with 10 μm precision — the distance changes to their twins, and their position above Earth as determined by means of the GPS satellites, but nothing else. To compute from these two datasets the decreasing ice-load on some particular Earth area, not only a big lot of computer power is needed, but in addition some assumptions must be made, which are by no means trivial, and not beyond dispute amongst the experts.

One of the problematic factors of influence is called "Glacial Isostatic Adjustment" in the slang of geophysicists. The issue is sketched in fig. 5: The Earth is not a rigid sphere, but is subject to plastic deformations. That applies in particular for the outer part of the Earth mantle, which supports the approximately 30 to 60 km thick Earth crust (lithosphere). If the Greenland ice shield looses several hundred Giga-tons of weight each year, then the Earth surface below the ice will start to rise slowly. Qualitatively, this is obvious. But for an interpretation of the GRACE data some quantitative assumption must be made, and this is a *very* difficult question for geophysicists.

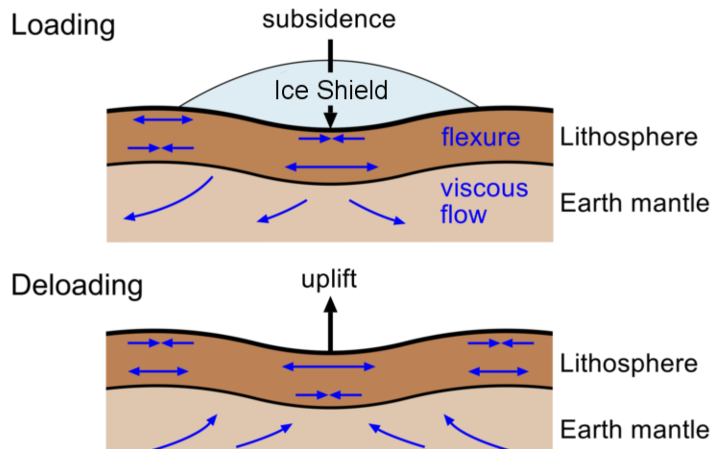

Fig. 5: Glacial Isostatic Adjustment. Graphic from [4].

1.3 Sea Level Rise

Since the the 18th century, tide gauges are used to measure the sea level height in the Northern Hemisphere; Southern Hemisphere measurements started in the late 19th century. Only since few decades, satellite altimetry has been established as a new measurement method. The both methods are not exactly equivalent: Tide gauges measure the height difference between the sea level and a fix point at the coast (i. e. on land), while satellites move on an orbit at known distance from Earth center, and measure the distance between sea level and their orbit. For that reason, measurements with satellites are also called geocentric measurements.

In fig. 6 the global mean values of tide gauge measurements from 1880 through 2010 are displayed. The mean values were computed by three different methods;[4] consequently there are three different curves with different shaded uncertainty margins. By and large, however, the result is unique: The global mean value of tide gauges rose in these 130 years by 29 cm , i. e. on average by

$$+2.2\,\text{mm}/\text{year}\,.$$

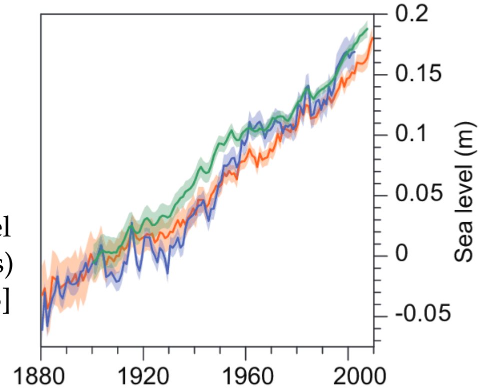

Fig. 6: Mean global sea level (tide gauge measurements) Graphic from [5, Chapter 13]

If the oceans were calm lakes, then they would adjust within short time to identical sea level everywhere. Reality is quite different: Locally different solar irradiation, melting ice, the smaller density of warmer water, the higher density of water with higher salinity, the tides (caused by the gravitation of moon and sun), different depths and different coastal forms of the oceans, storms, and many further factors, set huge sea currents in motion, which again cause regional different heights of sea level.

[4] In computation of the global mean values, various tide gauges at different harbors clearly must be weighted differently, because e. g. a gauge at the Pacific is representing much more sea surface than a gauge at the Baltic Sea. But how the statistical weights shall be fixed in detail is not at all obvious. For that reason, there are different curves in fig. 6 with different shaded uncertainty margins, even though all curves bear on the same basic data.

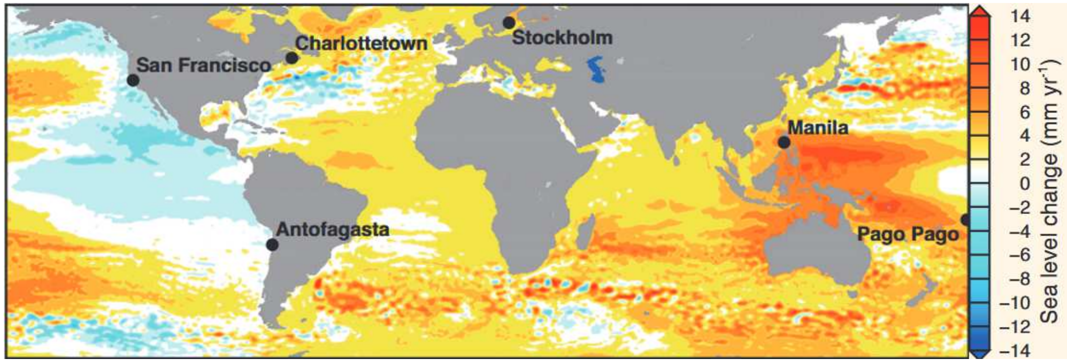

Fig. 7: Mean change-rates of the geocentric sea level 1993 – 2012 . Graphic from [5, Chapter 13].

The change-rates of the geocentric sea level, as deduced from satellite measurements in the years 1993 – 2012 , are represented in fig. 7 by colors. This result tallies well with the global mean value of about +2 mm/year as derived from tide gauge measurements, but obviously there were very large regional differences. In the eastern Pacific, at the west coasts of both Americas, the sea level was even falling, while it raised nowhere else as rapidly as in the western Pacific, north and east of Indonesia.[5]

This result is superposed by countless local special effects; two examples are displayed in fig. 8 . The Stockholm tide gauge was falling

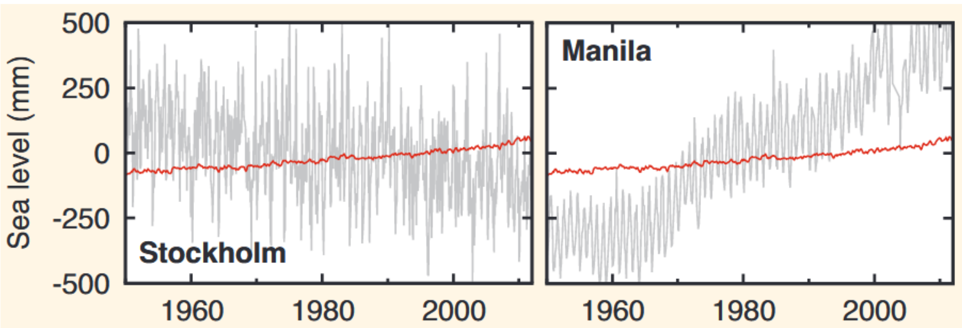

Fig. 8: Local tide gauge (gray) and global mean value (red) of sea level height. Graphic from [5, Chapter 13].

slowly, but constantly, even though in fig. 7 the Baltic Sea is color-coded in yellow, i. e. the geocentric sea level rise in that region was approximately matching the red line. The authors of [5, Chapter 13] suggest this explanation: During the last ice age, which ended 8 000 years ago, Scandinavia had been covered for 12 000 years by an ice shield of about 1 km thickness. When that shield melted down, the land started to rise as sketched in fig. 5 , and that rise is still ongoing by today. Thus the Stockholm tide gauge was not falling because the sea level was falling, but because the land was rising.

At the Philippine coast the geocentric sea level was rising rapidly according to fig. 7 , but the Manila tide gauge was rising even faster. According to [5, Chapter 13] this is a result of land subsidence caused by intensive groundwater pumping.

A global mean value can as well be derived from the geocentric sea level as measured by satellite altimetry. In fig. 9 the result is displayed.

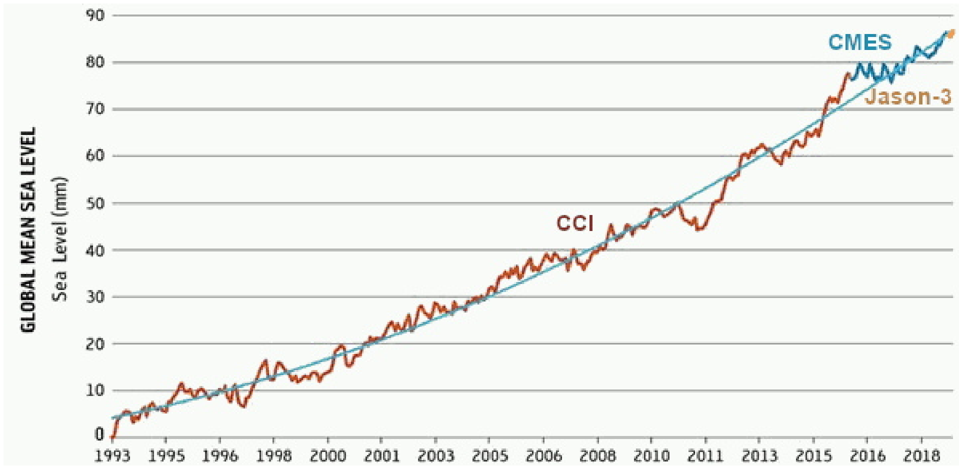

Fig. 9: Global mean value of the geocentric sea level. Graphic from [6].

[5] A special case is the Caspian Sea, which is not connected to the oceans. It's water level fell in the period 1993 – 2012 extremely fast, with −14mm/year . In the previous decades it rose extremely fast at approximately same speed, and it had already fallen with extreme speed prior to that. The experts could not yet agree on an explanation.

Obviously the speed of sea level rise is permanently increasing; by now the rate is more than 4 mm/year according to the light-blue trend line. It is a small comfort, however, for the endangered island states in the southern Pacific, that the mean global sea level rise is not as fast as locally in their region.

These explanations are suggested in [5, chapter 13, table 13.1] for the observed sea level rise:

	contribution 1993 – 2010	%
ice melt	1.46 mm/year [6]	50
thermal expansion	1.1 mm/year [6]	37
extraction from ground-water and reservoirs	0.38 mm/year [6]	13
sum	2.94 mm/year	100
measured rise	3.2 mm/year	

Thus about 50 % of sea level rise is caused by ice melt. 37 % are caused by the expansion of warming water. And not less than 13 % of the sea level rise is caused by ruthless exploitation of the fresh-water reservoirs of this planet — in my view a particularly disturbing fact.

1.4 Greenhouse Gases

By a net of globally distributed stations (indicated in fig. 11) the concentrations of various greenhouse gases in the air are regularly monitored. The global mean value of the measured concentrations of CO_2 are displayed in fig. 10 in red color.[7] The unit ppm = parts per million indicates the number of CO_2-molecules per 1 million of all air molecules. Regular changes each year are clearly visible: The CO_2 concentration increases in (northern hemisphere) winter, and decreases again in (northern hemisphere) summer,[8] but never returns to the previous value. Instead the minimum and maximum values are always a little bit higher than in the previous year.

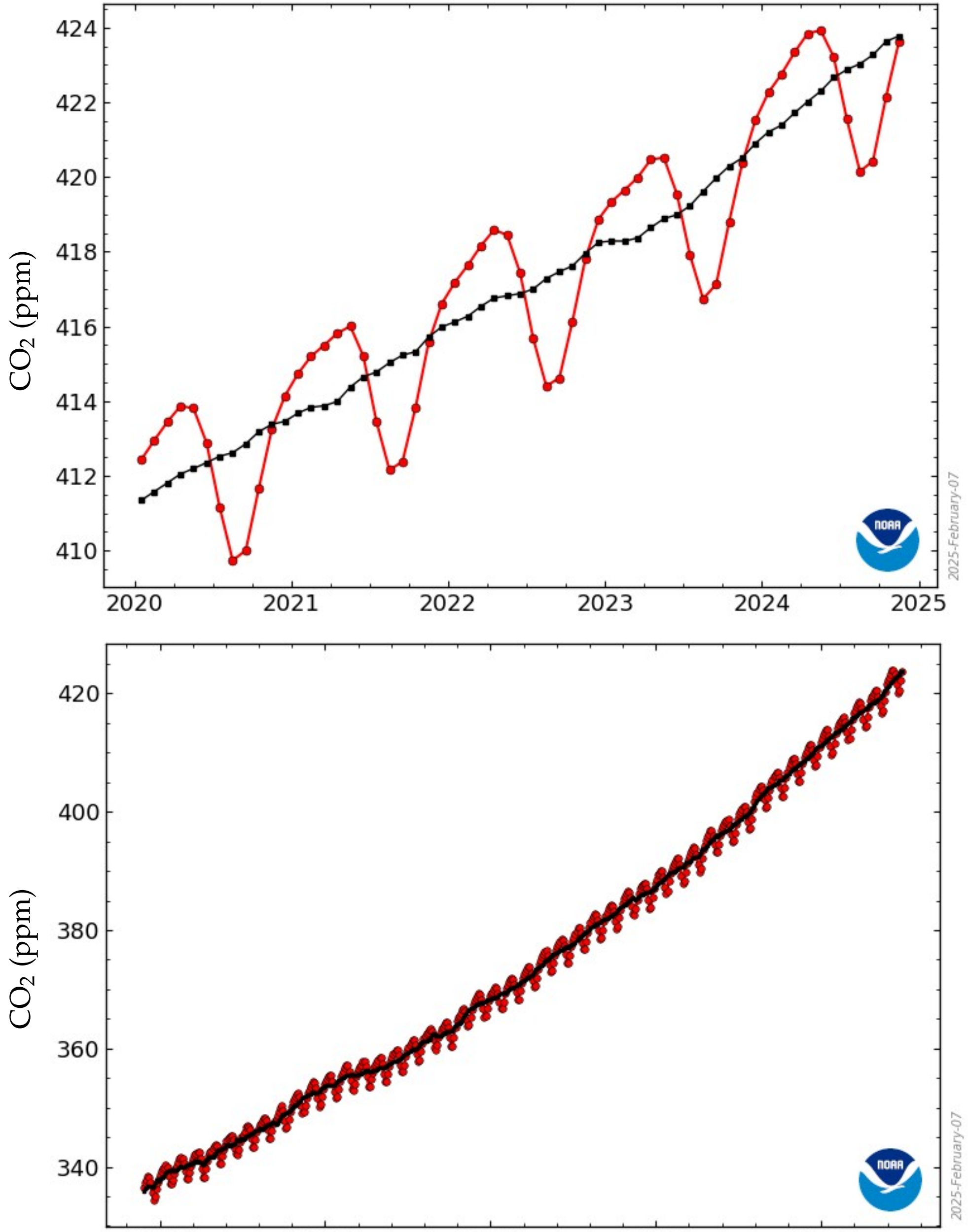

Fig. 10: Mean global CO_2 concentration since 2019 (top) and since 1980 (bottom). Graphic from [7].

[6] This is the mean value of several evaluations.
[7] The black points are floating averages; simply ignore them.
[8] see section 4.1 for an explanation

The global mean values of CH_4 concentration are displayed by red dots[7] in fig. 12, the global mean values of N_2O concentration by red dots[7] in fig. 13. The unit ppb = parts per billion indicates the number of CH_4- resp. N_2O-molecules per 1 billion of all air molecules.

From 1999 to 2006 the CH_4 concentration was almost constant, but by now it is again increasing as rapidly as before 1990. The increase of N_2O concentration continues unabated.

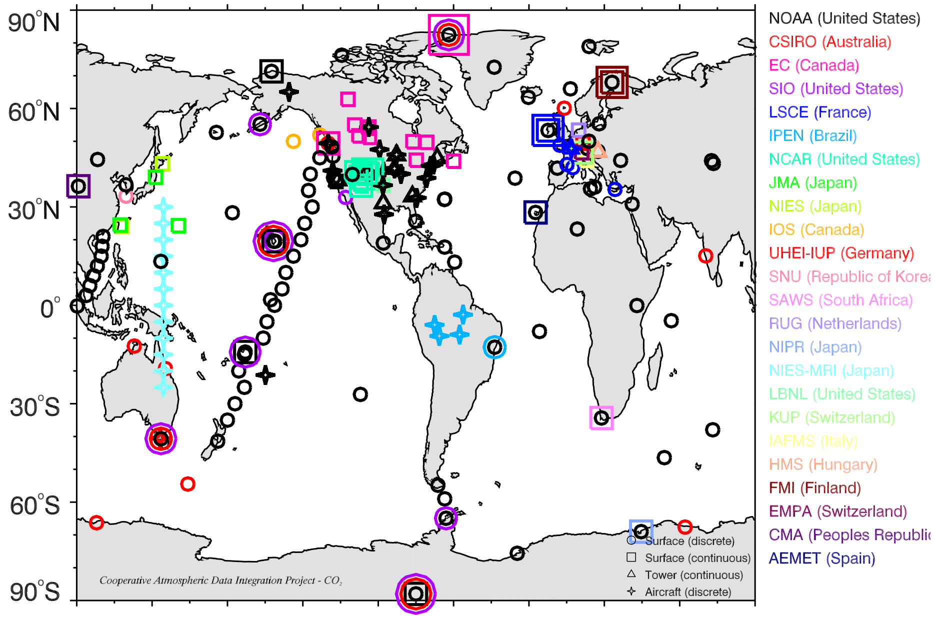

Fig. 11: Stations, where concentrations of greenhouse gases are regularly monitored. Graphic from [7].

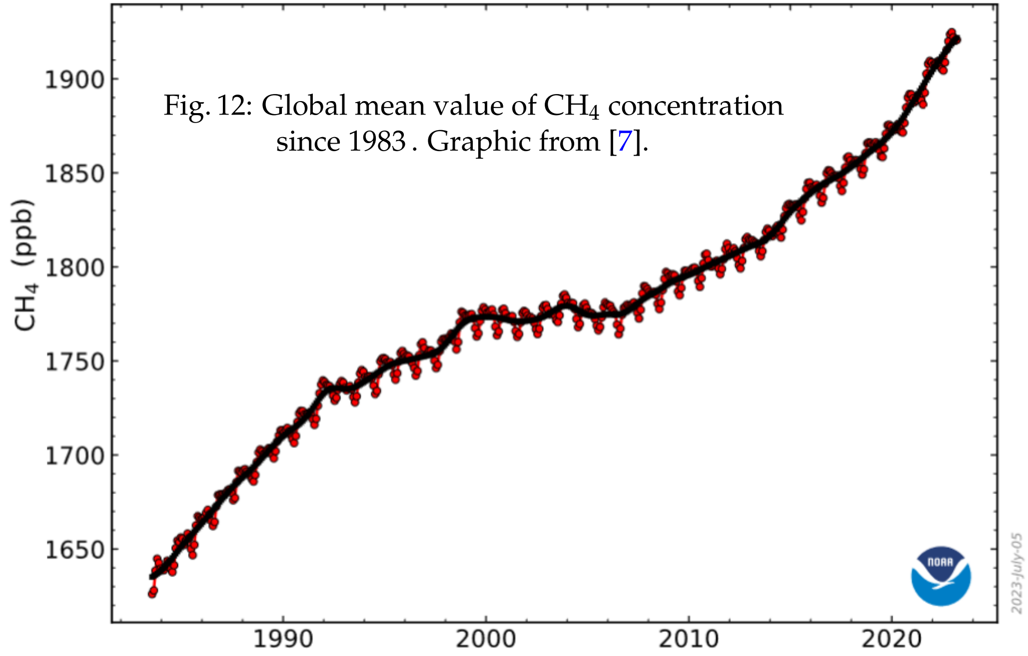

Fig. 12: Global mean value of CH_4 concentration since 1983. Graphic from [7].

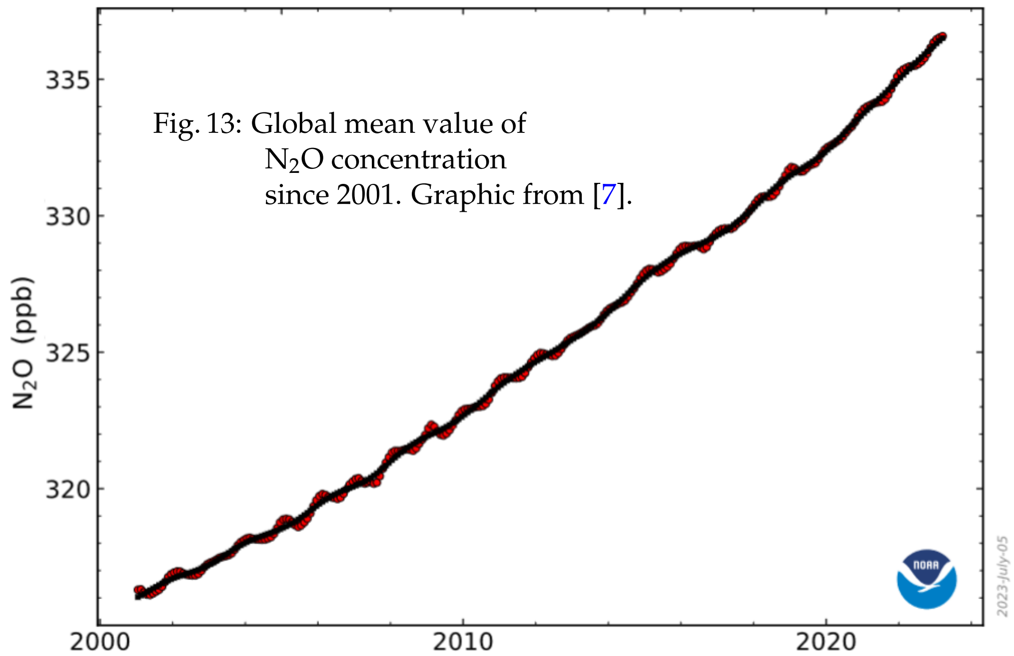

Fig. 13: Global mean value of N_2O concentration since 2001. Graphic from [7].

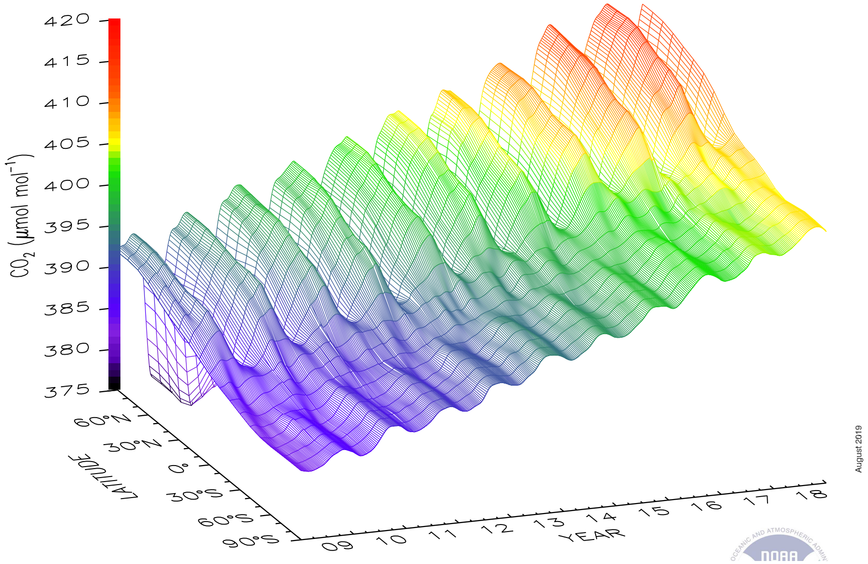

Fig. 14: Regional distribution of CO_2 concentration in the years 2009 through 2018 . Graphic from [7].

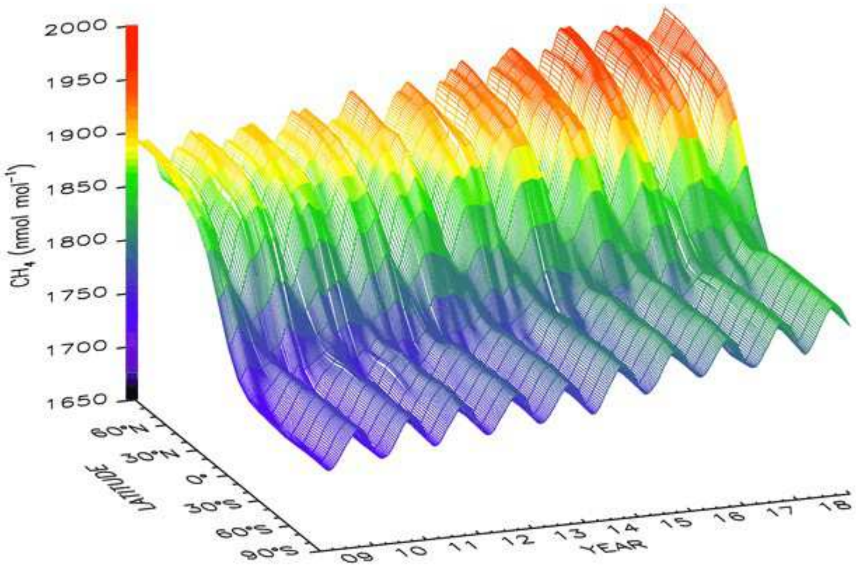

Fig. 15: Regional distribution of CH_4 concentration in the years 2009 through 2018 . Graphic from [7].

The distribution of CO_2 concentration over the Earth's northern and southern hemispheres is interesting. It can be read from fig. 14 . Note that the difference between the hemispheres is not as huge as the graph might suggest at superficial inspection. The vertical scale is not starting at zero, but at 375 ppm . Thus the difference between northern and southern hemisphere is hardly one percent.

Still the difference is significant. Obviously the CO_2 is blown into the air mainly in the northern hemisphere, and then needs 3 to 4 years to diffuse into the southern hemisphere. No doubt this is important evidence when searching for the origin of the rising CO_2 concentration.

CH_4 as well is blown into the air mainly in the northern hemisphere. That can be deduced from fig. 15 . Subsequently it needs years — in this case more than ten years — to diffuse to the southern hemisphere.

Fig. 16: An about 1 m long ice core section from the Greenland GISP2 drill. In this section from 1837 m depth, annual layers are clearly visible.

By means of ice cores, the analysis of greenhouse gas concentrations can be extended up to 800 000 years into the past. For that purpose, hollow-core drills are performed in the ice shields of Greenland and Antarctica down to about 3.5 km depth. A section of an ice core, which has been extracted by this method, is shown in fig. 16 .

In the pores of the ice, the gases are enclosed in that concentration, in which they existed in the atmosphere when the ice originated. In favorable cases, the age of the ice can be concluded from the annual layers, created by dust which deposits each year on the glacier surface. In more difficult cases, alternative methods for age dating exist.

For analysis, the ice cores are sawn into small pieces, melted, and then the type and concentration of the gases, which were enclosed in the ice pores, are determined by means of mass-spectroscopy.

The results are displayed in fig. 17 . From these measurements, and from the measurement results displayed in figures 10 , 12 , and 13 , the authors of the IPCC-report AR5 draw these conclusions [5, chap. 6]:

∗ The concentration of CO_2 in the atmosphere is by today 30 % higher than ever before in the last 800 000 years.
∗ The concentration of CH_4 in the atmosphere is by today 120 % higher than ever before in the last 800 000 years.
∗ The concentration of N_2O in the atmosphere is by today 10 % higher than ever before in the last 800 000 years.
∗ The concentrations of CO_2 , CH_4 , und N_2O in the atmosphere are increasing by today faster than ever before in the last 800 000 years.

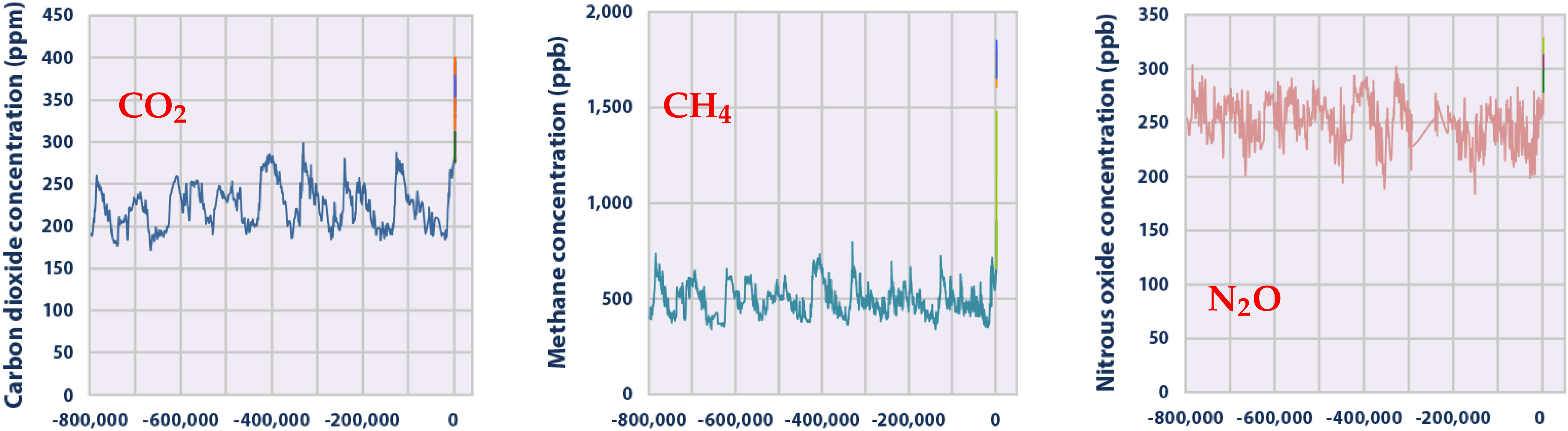

Fig. 17: The concentrations of CO_2 , CH_4 , and N_2O in the years -800 000 through 2015 . The measured curves until 2015 are indicated in the right sides of the three diagrams in different colors. Graphic from [8].

1.5 Water vapor as a greenhouse gas

(Text taken from [8]:)
Water vapor is the most abundant greenhouse gas in the atmosphere. Human activities have only a small direct influence on atmospheric concentrations of water vapor, primarily through irrigation and deforestation. The surface warming caused by human production of other greenhouse gases, however, leads to an increase in atmospheric water vapor because warmer temperatures make it easier for water to evaporate and stay in the air in vapor form. This creates a positive "feedback loop" in which warming leads to more warming.

1.6 Ocean Acidification

CO_2 is dissoluble in water. Air and the water of oceans and lakes are permanently exchanging CO_2. The exchange can be described by this chemical formula:

$$\begin{aligned} CO_2 + 2\,H_2O &\rightleftharpoons CO_2 + OH^- + H_3O^+ \rightleftharpoons \\ &\rightleftharpoons HCO_3{}^- + H_3O^+ \rightleftharpoons H_2CO_3 + H_2O \end{aligned}$$

H_2CO_3 is carbonic acid. The double-arrows are indicating that the chemical reactions are permanently ongoing in both directions. The "dynamical equilibrium" is reached, when the reaction happens as often in one direction as in the opposite direction.

Due to the reaction

$$2\,H_2O \rightleftharpoons OH^- + H_3O^+$$

H_3O^+ ions exist even in pure water. The concentration of H_3O^+ ions in water is a measure for the strengths of aqueous acids and bases. Conventional unit is the pH value. A little bit confusing, the pH value is the smaller, the higher the concentration of H_3O^+ ions is.[9] The pH value of pure water is 7, the pH value of acids is smaller than 7, and the pH value of bases is larger than 7.

Seawater has acidic and basic constituents. The basic outweigh the acidic constituents; hence seawater is a weak base. When scientists report an acidification of seawater, they do not want to say that it becomes an acid. Seawater remains a base, but due to admixture of carbonic acid it becomes a weaker base. It's pH value is getting smaller, but remains larger than 7.

When the CO_2 concentration in air increases, then it is to be expected that the concentration of carbonic acid in the oceans will increase as well. This is indeed the case. In fig. 18 results of measurements are displayed, which have been performed in 1988 – 2007 on the oceanographic station ALOHA in Hawaii. Only the brown dots are are resulting from direct chemical analysis of the seawater. The green dots have been concluded indirectly from measurements of other parameters.

[9] The exact definition: $\mathrm{pH} = -\log\left(\frac{[H_3O^+]}{\mathrm{mol/Liter}}\right)$, with $[H_3O^+]$ being the concentration of H_3O^+ ions.

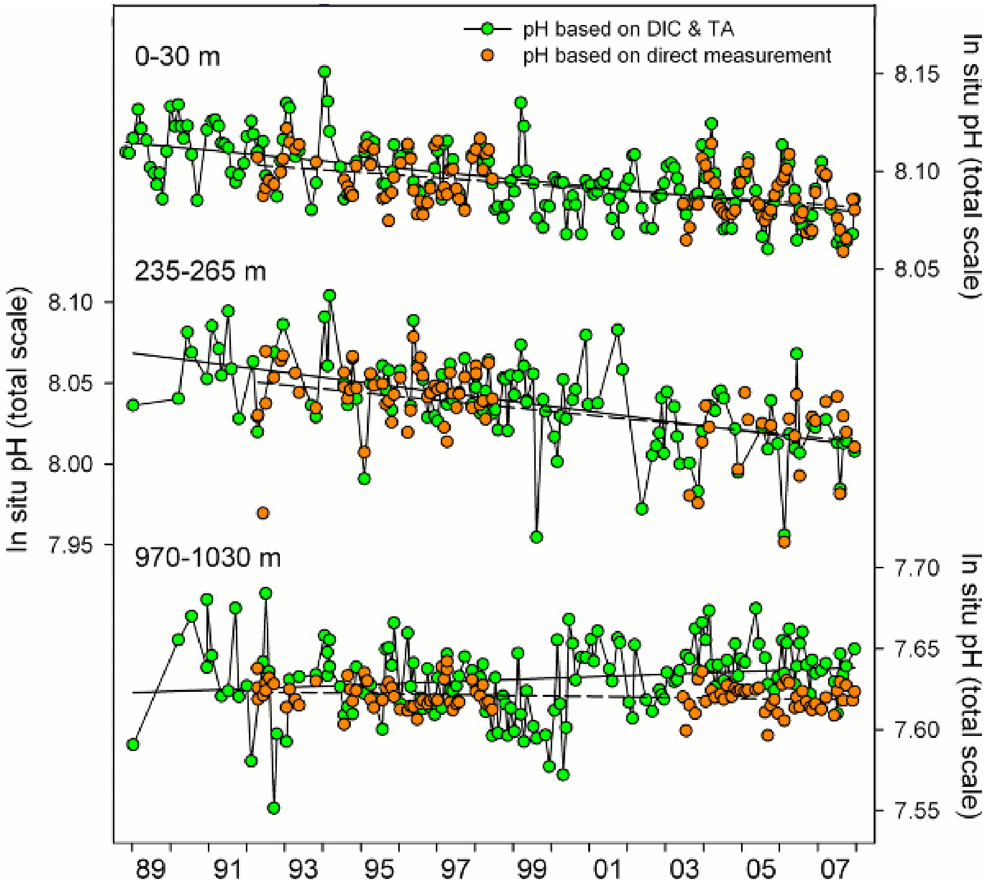

Fig. 18: pH values at various depths below sea surface.
Station ALOHA, 1988 – 2007 . Graphic from [9].

From the statistical evaluation of the measured data, the authors of fig. 18 computed the speed, at which the pH value in low and medium depths of the Pacific is changing, as

$$-0.0019 \pm 0.0002 \text{ per year.}$$

The pH decrease is -0.1 per 50 years. This is not at all a small value; instead it stands for an increase of the concentration of H_3O^+ ions by 26 % in 50 years!

In the deep sea this trend was not observed. Here due to sea currents a more complicated situation prevails.

The consequences of ocean acidification are described (only in German, sorry) in an easily readable article [10, Abschnitt 3.4] of the German Umweltbundesamt. A thorough overview in English is available in a brochure [11] of the UN Convention on Biological Diversity.

In the IPCC report SR15 (2018) the authors remark on ocean acidification: The ocean has absorbed about 30 % of the anthropogenic carbon dioxide, resulting in ocean acidification and changes to carbonate chemistry that are unprecedented for at least the last 65 million years (*high confidence*[10]). Risks have been identified for the survival, calcification, growth, development and abundance of a broad range of marine taxonomic groups, ranging from algae to fish, with substantial evidence of predictable trait-based sensitivities (*high confidence*[10]). There are multiple lines of evidence that ocean warming and acidification corresponding to 1.5°C of global warming would impact a wide range of marine organisms and ecosystems, as well as sectors such as aquaculture and fisheries (*high confidence*[10]). [12, chap. 3]

[10] The authors of the IPCC reports quantify the estimated reliability of their results by these notions: Virtually certain 99–100% probability, Extremely likely 95–100%, Very likely 90–100%, Likely or Confidence level high 66–100%, About as likely as not 33–66%, Unlikely or Confidence level low 0–33%, Very unlikely 0–10%, Extremely unlikely 0–5%, Exceptionally unlikely 0–1%, More likely than not >50–100%

2. Systematic Approach

2.1 Earth's Radiation Balance

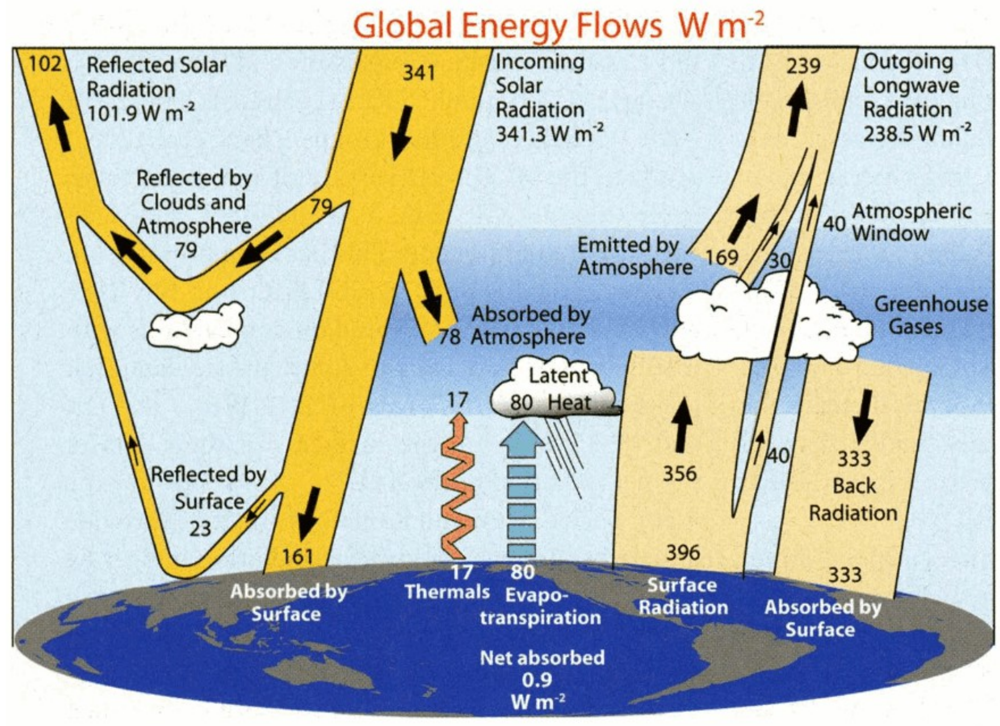

Fig. 19: The radiation balance of Earth. Graphic from [13].

The Earth is moving on a slightly elliptic orbit one time per year around the sun. When the Earth comes most closely to the sun (that happens in the first days of January), the power of solar radiation is approximately 1420 Watt per square meter, while it is only $1325\,\mathrm{W/m^2}$ at largest distance from the sun (the Earth is at that point of her orbit in the first days of July).[11]

The sun does not emit radiation at a perfectly constant rate. There exists a "solar cycle" of about 11 years, during which the power of solar radiation changes by slightly less than $0.1\,\%$. Taking the mean value over the year and over the solar cycle, the Earth receives the

$$\text{solar radiative power} = 1365\,\mathrm{W/m^2}\,.$$

The *mean* solar radiation per square meter of Earth surface is much less, because the sun illuminates only one side of the terrestrial globe simultaneously, and because the Earth gets only a graze of solar radiation near the poles. The computation is surprisingly simple: A sphere's surface is exactly four times as large as it's diameter. Consequently the

$$\begin{aligned}&\text{mean solar radiative power per square meter}\\&\text{of Earth surface} = 1365\,\mathrm{W}/4 = 341.3\,\mathrm{W}\,.\end{aligned}$$

Fig. 19 is suggesting that the atmosphere impacts the Earth's radiation balance significantly. To understand that, lets first consider the scenario of an Earth with no atmosphere: Then the Earth surface would be irradiated with $341.3\,\mathrm{W/m^2}$ on average. $23/(23+161) \approx 13\,\%$ are reflected back into space according to fig. 19. The rest, i. e. $299\,\mathrm{W/m^2}$, is absorbed by Earth; thereby the Earth becomes warmer. The warmer the Earth gets, the more energy she emits as infrared radiation into space. The equilibrium is reached when the the Earth is heated up to $-18\,°\mathrm{C}$. Then she emits $299\,\mathrm{W/m^2}$ as infrared radiation into space, i. e. exactly the same amount of energy as she absorbs from the sun. $-18\,°\mathrm{C}$, that is the temperature in a freezer.

The actual mean surface temperature of $+15\,°\mathrm{C}$ only comes about due to the greenhouse effect of the atmosphere. On the one hand, the atmosphere reflects almost half of the incoming solar radiation; thereby the Earth gets even colder. But on the other hand, the atmosphere reflects a large part of the infrared thermal radiation, which is emitted by the Earth. The second effect predominates; thereby the Earth's mean surface temperature is raised to the already mentioned $+15\,°\mathrm{C}$.

[11] Summer is warmer than winter in the northern hemisphere, even though the Earth comes closer to the sun in winter, because in summer the sun is higher in the sky. See this graph for explanation.

Two further adders to the Earth's energy balance are not mentioned in fig. 19 , because they are negligibly small. The first is the stream of heat from the Earth's hot interior to it's surface: It amounts to only 0.06 W/m^2. The second adder is the heat, which humans set free due to energy production, heating or cooling of buildings, and industrial processes: It's mean value is estimated to be about 0.026 W/m^2.[12]

By the item "Net absorbed 0.9 W/m^2" in fig. 19 the authors of [13] are indicating, that according to their computations by today the Earth is absorbing more radiative energy from the sun than she is radiating herself into space, and consequently is getting warmer.

2.2 The radiation of Sun and of Earth

If the spectrum [13] of the electromagnetic radiation, which a body is emitting into it's environment, is depending *exclusively* on it's temperature, but on nothing else (i. e. not on it's material, not on it's chemical properties, not on it's form, not on it's size, ...), then physicists call that body a "black body".

The sun is in very good approximation a black body, and the Earth is it — though only in somewhat less good approximation — as well. In fig. 20 the spectra of black bodies of different temperatures are displayed.

The sun's surface temperature is approximately 5777 K = 5504 °C . The spectrum of her radiation is indicated in fig. 20 by a yellow line.

300 K = 27 °C ; hence the red line is the spectrum of the radiation, which the Earth is emitting in mid-Europe on a beautiful summer day. The energy, which the sun is emitting per m^2 of *her* surface, is more than one million times larger than the energy, which the Earth is emitting per m^2 of *her* surface (note the logarithmic scale!).

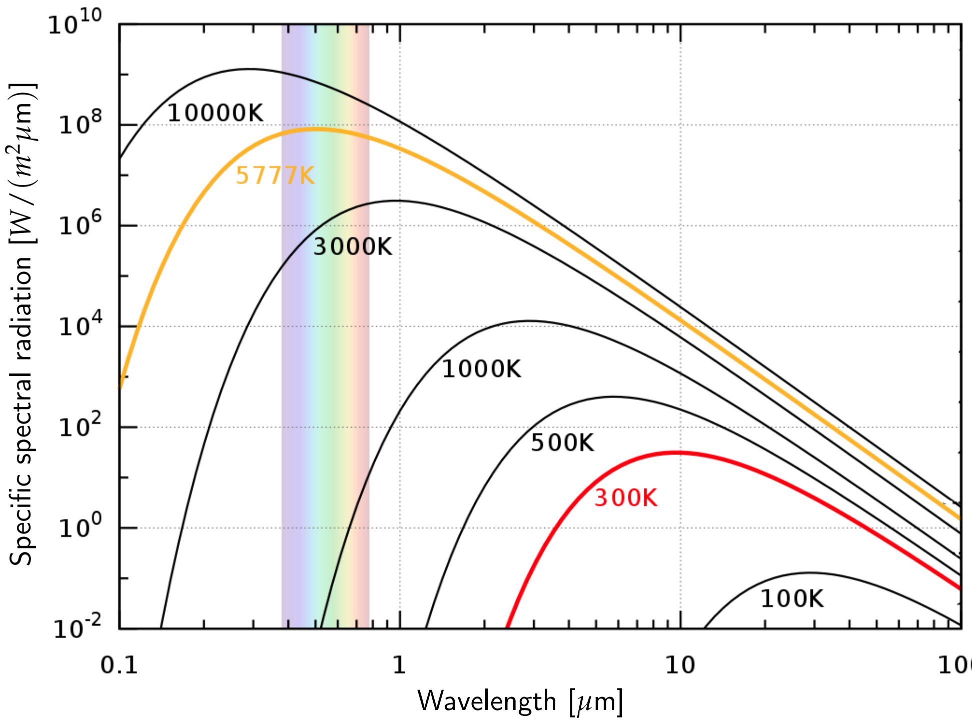

Fig. 20: Black-body spectra. Graphic from [14].

The rainbow colors are indicating, in which colors these wavelengths are sensed by human eyes. The maximum of the radiation emitted by Earth is at 10 μm . Human beings can not see that infrared radiation, but they can sense it on their skins. The maximum of the solar spectrum is just in the center of the range which is sensed by human eyes. Hardly a coincidence! Instead in the many, many millions of years of evolution, our ancestors have obviously developed just such eyes, which have been most helpful in their search for ecological niches.[14]

---

[12] Hence the heat which is set free directly due to burning of wood, coal, gas, and mineral oil, is irrelevant for the warming of the world's climate; but not the greenhouse gases which are thereby set free! Their impact will be evaluated in the sequel. As an aside: The total energy consumption of mankind is only 0.026 W/161 W ≈ 0.04 % of the energy, which the Earth is absorbing from the sun. We therefore can *easily* dispense with CO_2-emitting energy sources and with nuclear energy. We "only" must finally develop efficient methods for intermediate storage of clean energy.

[13] The spectrum is the distribution of the electromagnetic radiation on the various wavelengths.

[14] „Wär' nicht das Auge sonnenhaft, Wie könnten wir das Licht erblicken?" Goethe cites this verse in the introduction to the didactic part of his "Farbenlehre" [15]. Had he understood something important already by then, half a century before Darwin? I think, yes.

2.3 The Greenhouse Effect

In the upper part of fig. 21 the radiation spectra of Sun and Earth are displayed again, but this time on a linear vertical scale; therefore their shapes now differ slightly from fig. 20 . Furthermore the spectrum of the radiation emitted by Earth is indicated for $288\,K = +15\,°C$, the mean temperature of Earth surface. And the spectrum of the sun has been squeezed vertically such, that it seems just as large as the spectrum of Earth.

The yellow and red areas below the spectral curves are representing the energy, which actually arrives at Earth surface, respectively which actually is radiated from Earth into space. The difference between yellow curve and yellow area resp. red curve and red area is that part of the energy, which is absorbed or reflected by the atmosphere. The ingredients of the atmosphere, which in each case are effective, can be read from the bottom part of fig. 21 .

In the hard UV = ultraviolet with wavelengths less than $0.3\,\mu m$, almost no radiation from the sun arrives at Earth surface. This is caused on the one hand by the efficient absorption due to O_3 = ozone in this spectral range,[15] and on the other hand by Rayleigh-scattering,[16] which is much more effective for short-wavelength radiation than for long-wavelength radiation.[17]

In the infrared range of solar radiation, absorption due to water molecules is effective.[18] Clouds reflect and absorb radiation from the sun and from the Earth *much* more effectively than the individual molecules of water vapor. Everybody knows that a dense cloud layer can almost completely prohibit the cooling at night, while in starry nights the temperature is *much* lower than by day. And a dense cloud layer can easily reflect and absorb more than 90 % of the incoming solar radiation. In fig. 21 always a clear sky with no clouds is assumed. By H_2O = Water Vapor invisible separate water molecules in cloudless air are meant.

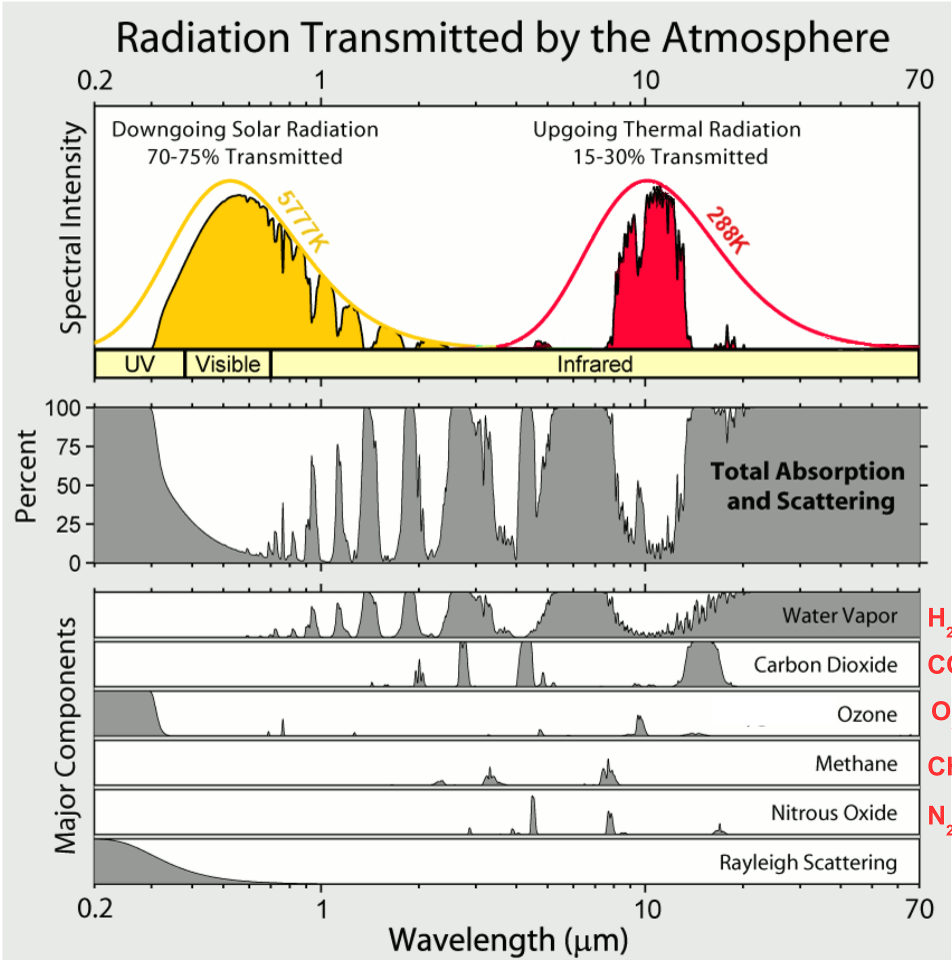

Fig. 21: The effect of the greenhouse gases. Graphic from [16].

H_2O does not only affect the incoming solar radiation, but also very strongly the infrared radiation emitted by Earth. H_2O leaves only a nar-

15 When some years ago a large ozone hole formed in the upper atmosphere above Antarctica, the people in the south of South America (Tierra del Fuego) needed to protect themselves very carefully against sunburn, even if they wanted to leave their houses only for short time.

16 Rayleigh-scattering is a process, in which photons — the particles of electromagnetic radiation — are scattered (reflected) by molecules in the atmosphere like billiard balls.

17 At early morning and at evening the sun seems red, because the radiation has to traverse a much longer path through the atmosphere than at noon, before it arrives at Earth surface. On that long way, much more blue than red radiation gets lost due to Rayleigh-scattering.

18 For physicists: The regular sequence of absorption bands is characteristic for the excitation of vibrations of the water molecules.

row “spectral window” inbetween about 8 and 15 μm , through which infrared radiation can escape from Earth into space. On it's long-wavelength flank, the window is furthermore narrowed down due to absorption by CO_2 .

The content of water vapor in the atmosphere does strongly vary. The colder the air, the faster water vapor condenses to droplets and falls as rain down to earth. As the atmosphere's temperature is fast decreasing at increasing height, it's content of water vapor decreases as well at increasing height. Therefore the dominating influence of water vapor, which is suggested by fig. 21 , is limited to the lower three- to five-thousand meters. At larger altitudes, the impact of the other greenhouse gases CO_2 = carbon dioxide, CH_4 = methane, and N_2O = nitrous oxide (sometimes called laughing gas) is much more important than one might guess from fig. 21 .

2.4 Aerosols

The name “aerosols” is used for a wide variety of small particles suspended in air. The particle size may be as small as few nanometers or as large as several micrometers.[19] Amongst others, aerosols are small crystals of marine salt, dust of various minerals, sulfates and ashes from volcanic eruptions, pollen and spores, soot and other carbon particles, abrasion from streets and car tires, and countless further types of tiny particles.

While the atmosphere's content of greenhouse gases results in warming of the Earth, it's content of aerosols has in general (but not always!) a cooling effect: The probability, that solar radiation will be scattered by an aerosol-particle, is much higher than the probability that the infrared radiation emitted by Earth will be scattered by the same particle.[20]

For example, at times fine sand from the Sahara is transported by the wind over the Alps to Bavaria. Then the sky above Bavaria seems yellowish gloomy, and the solar radiation intensity is perceptibly attenuated (cooling effect of the aerosol!). But in most cases the sand remains only few days in the air; then it sinks down to ground, or is washed out by rain. If the sand ends up on snow (e. g. on a glacier in the Alps, or in winter on flat country), then the contaminated snow will reflect less solar radiation than clean snow. Consequently the Earth now absorbs more energy from the sun than before, i. e. the (former) aerosol now all with a sudden has the opposite effect than in the atmosphere! Many other aerosols, e. g. volcanic ashes, as well have a cooling effect in the atmosphere, but a warming effect once they have landed on ground.

Small coal particles (called “black carbon” in the slang of climatologists) have already in the atmosphere a warming effect, i. e. they are — in contrast to most other aerosols — not counteracting the greenhouse gases H_2O , CO_2 , CH_4 , N_2O , but fortify their effect.

As aerosols are so very heterogeneous, their correct quantitative assessment is one of the main weak points of climate models. And they must certainly not be ignored, because the climatic effectiveness of aerosols is not much smaller than that of greenhouse gases.

---

[19] 1 micrometer $= 1\,\mu\text{m} = 10^{-6}\,\text{m} = 0.000\,001\,\text{m}$; 1 nanometer $= 1\,\text{nm} = 10^{-9}\,\text{m} = 0.000\,000\,001\,\text{m}$

[20] This is because most aerosol particles are smaller than the wavelength of the infrared radiation emitted by Earth. Thats the same effect as that of pebbles on the street: If you drive over them with roller skates (small wheels), they might easily catapult you onto your nose. If you drive over them with the bicycle (large wheels), you hardly notice them. Likewise electromagnetic radiation will be scattered by an aerosol particle with higher probability if the wavelength of the radiation is of same order of magnitude or shorter than the particle size, while radiation of much longer wavelength will simply ignore the same particle. By the way, for exactly the same reason short-wavelength radiation is stronger than long-wavelength radiation affected by Rayleigh scattering due to molecules, see bottom line of fig. 21 .

2.5 Radiative Forcing

If Earth absorbs more radiative energy from the sun than she emits herself as infrared radiation into space, then she gets warmer. Conversely, the Earth cools down if she emits more radiative energy into space than she absorbs from the sun. If absorption and emission of radiative energy exactly balance, then the Earth's temperature stays constant, see section 2.1 .

What will happen if the N_2O concentration in the atmosphere increases from currently 333 ppb (see fig. 13) to 336 ppb ? Qualitatively, the issue is simple: More greenhouse gases in the atmosphere impede the infrared radiation from Earth into space. Consequently the Earth then radiates so and so many W/m^2 less into space, than she absorbs from the sun. Hence she gets warmer and therefore emits more infrared radiation (see fig. 20), until eventually a new equilibrium has developed at higher Earth temperature.

But can we answer the question quantitatively? By how many W/m^2 exactly will a 3 ppb increase of N_2O concentration shift the Earth's radiation balance? Such questions are extremely difficult to answer due to the mutual interdependence of the various climate parameters. Any change of one parameter results immediately into changes of hundreds of other parameters. In that situation, we can proceed like this: We make the (unrealistic) assumption, that we could change one parameter, without changing any other parameter.[21]

Then we measure (only in thoughts) at the atmosphere's upper border[22]: What was the net flux of radiative energy[23] in Earth direction before the change of that parameter, and what is the net energy flux after the parameter changed? The change of that net value then is in our example the impact onto the radiation balance, i. e. the *radiative forcing*, of 3 ppb N_2O .

The climatologists think, that these values of the radiative forcing of greenhouse gases are at least approximately correct [5, chap. 8, table 8.2]:

	concentration 2011	1750	radiative forcing
CO_2	391 ppm	278 ppm	$1.82\,W/m^2$ per $(391-278)$ ppm
			$= 1.6\cdot 10^{-5} W/m^2$ per 1 ppb
CH_4	1803 ppb	722 ppb	$0.48\,W/m^2$ per $(1803-722)$ ppb
			$= 4.4\cdot 10^{-4} W/m^2$ per 1 ppb
N_2O	324 ppb	270 ppb	$0.17\,W/m^2$ per $(324-270)$ ppb
			$= 3.2\cdot 10^{-3} W/m^2$ per 1 ppb
others	1412 ppb	≈ 0	$0.36\,W/m^2$ per 1412 ppb
total			$2.83\,W/m^2$

In the category "others" about 2 dozens of greenhouse gases are subsumed, which came into the world only due to the industrial activities of mankind.

Thus in the table the estimated radiative forcings due to the changes of concentrations of the respective greenhouse gases inbetween 1750 and 2011 are compiled. Note that CO_2 is (besides H_2O) the most important greenhouse gas only because there exists so much of it in the atmosphere. The radiative forcing of a single CH_4 molecule is more than 27 times as large as that one of a single CO_2 molecule. And the radiative forcing of a single N_2O molecule is even 200 times as large as that one of a single CO_2 molecule.

The precise numeric values, which are quoted as radiative forcings of particular gases, must be considered with some reservations, because it is really far-off from reality to assume that one climate-relevant parameter could be changed without changing countless related parameters. Anyway the "radiative forcing" concept is useful, because it provides suitable approximate values for simple estimates.[24]

[21] In variants of this concept it is assumed, that due to the change of one parameter a small number of certain further parameters will change, while all other parameters stay constant, see [5, chap. 8, sec. 8.1.1].

[22] This is a simplification, see [5, chap. 8, sec. 8.1.1] for the exact definition.

[23] i. e. the difference between the radiative energy which the Earth absorbs from the sun, and the radiative energy which the Earth is emitting into space

[24] e. g. for the question regarding the impact of a 3 ppb increase of the N_2O concentration in the atmosphere. From the above table we can conclude: Due to that change, the Earth will radiate about $9\cdot 10^{-3} W/m^2$ less energy into space than before.

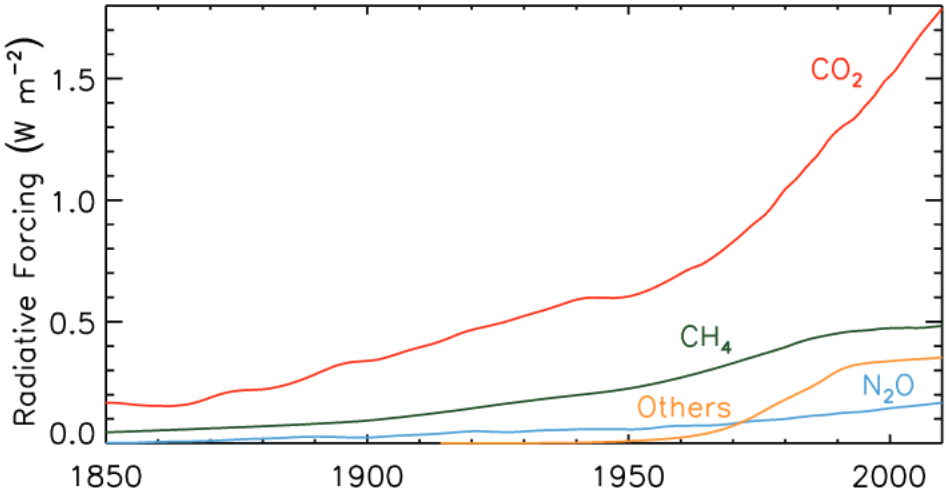

Fig. 22: Radiative forcing of greenhouse gases. Graphic from [5, chap. 8].

The increasing importance of CO_2 can be seen in fig. 22 . The radiative forcing of greenhouse gases is more and more dominated by CO_2 .

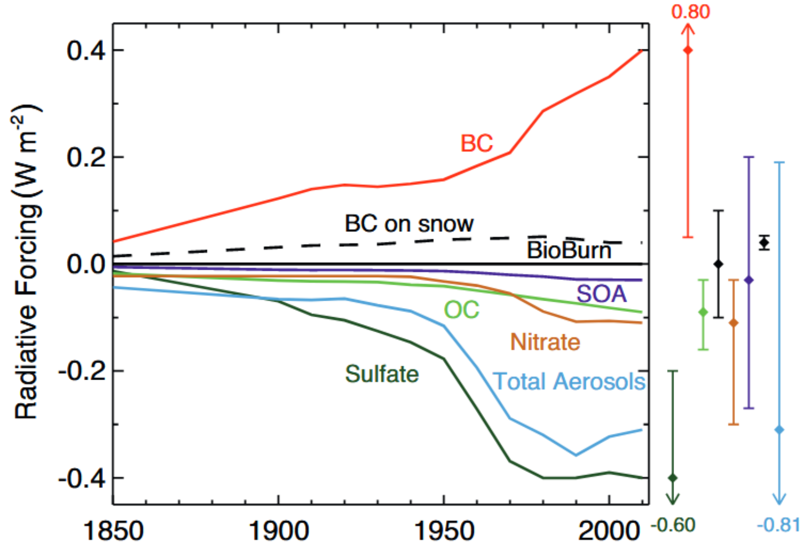

Fig. 23: Radiative forcing of aerosols. Graphic from [5, chap. 8].

The radiative forcing concept is also applied to the aerosols, see fig. 23 . The vertical lines on the right indicate the uncertainties of the respective 2011 values. Some of the uncertainties are so huge that these lines do not fit onto the graph; the numerical values on the arrows indicate the ends of these lines outside the drawn area. Aerosols are so difficult to quantify because they are very irregular in time and space, very inhomogeneous (nitrate and nitrate are not identical), and very complicated in their interaction with clouds: on the one hand, they can be condensation nuclei for clouds, then the negative radiative forcing is amplified because clouds reflect solar radiation very efficiently. On the other hand, they can cause existing clouds to rain earlier; this suddenly results in a positive radiative forcing.

The radiative forcing of BC = black carbon = soot is positive, thus it is warming. The radiative forcing of BioBurn — these are in particular large-scale slash-and-burn as they are usual in Indonesia and Brazil — is estimated as zero, because warming and cooling effects approximately cancel. SOA = Secondary Organic Aerosols are particles, which are created only in the atmosphere due to chemical reactions of other gases. OC = Organic Carbon; these are aerosols, which are not (like Black Carbon) composed of pure carbon; instead they are organic carbon compounds. Sulfates result mainly from volcanic eruptions.

The vertical axis in fig. 23 is spread about twice as large as in fig. 22 . Thus the impact of aerosols onto the radiation balance is smaller than the impact of greenhouse gases, but not much smaller. The authors of [5, chapter 8] estimate that in 2011 about one third of the positive radiative forcing of greenhouse gases has been compensated by the negative radiative forcing of aerosols; at the same time they emphasize the large uncertainty of scientists regarding the correct quantitative assessment of aerosols.

Forest clearance for agricultural (or other) use has the effect that more incident solar radiation is reflected. The radiative forcing of land use is estimated as $-0.15 \pm 0.10\,W/m^2$ [5, chap. 8].

3. Cause(s) of Climate Change

In section 1 measurement results, in particular the global temperature rise and the rise of greenhouse gas concentrations in the atmosphere, have been stated without comments. This section is concerned with demonstrating, first, that temperature increases are caused by increasing concentrations of greenhouse gases, and second, that increasing concentrations of greenhouse gases are caused by human industrial and agricultural activities.

It is well known, that climate changes have repeatedly happened on Earth in the past. Ice ages were followed by warm periods, and some thousand years later temperature decreased again ... Such natural climate changes are called “internal variability” in the slang of the scientists.

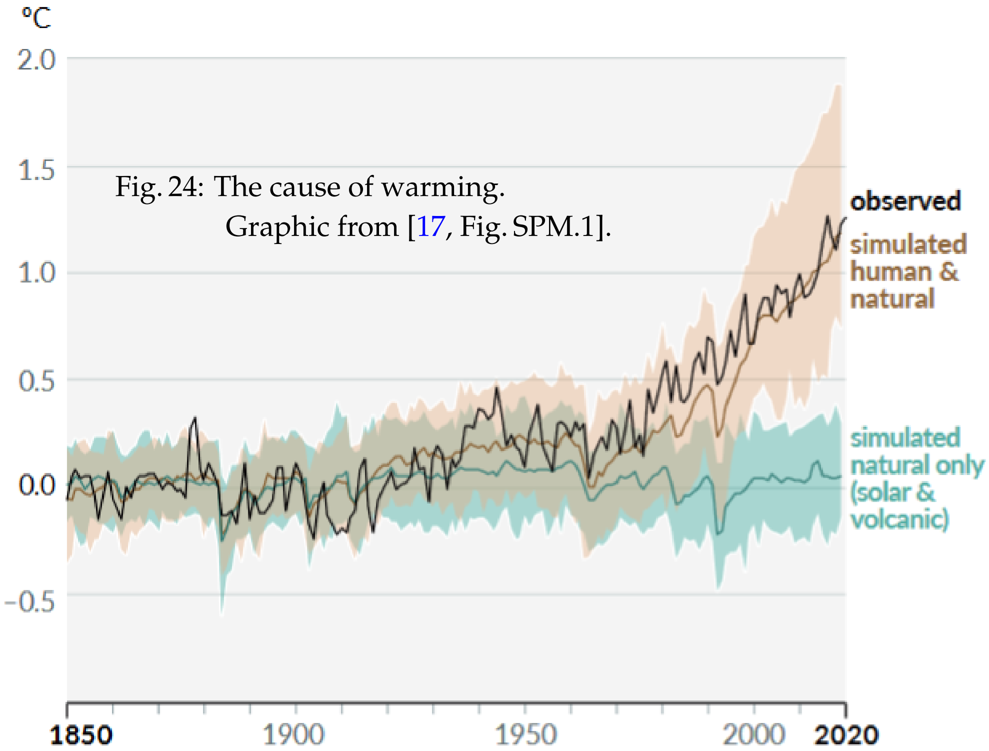

Fig. 24: The cause of warming.
Graphic from [17, Fig. SPM.1].

Could possibly the present climate warming be nothing but an effect of “internal variability”? To answer this question, climatologists have developed computer models that have become increasingly detailed and reliable over the years. These models can be used to calculate the effect and significance of the various possible factors influencing climate development.

An example is shown in Fig. 24 . This graphic displays the result of several combined model simulations. The models (brown line) reproduce the observed temperature development (black line) quite well. But only if all influencing factors, including man-made ones, are taken into account. If the calculations are done without the greenhouse gases and aerosols emitted by humans, then the green line results, where there is no long-term temperature increase at all. The IPCC scientists conclude [18, A.1.2, A.1.3]:

* The *likely*[10] range of total human-caused global surface temperature increase from 1850—1900 to 2010—2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. Over this period, it is *likely*[10] that well-mixed greenhouse gases (GHGs) contributed a warming of 1.0°C to 2.0°C[25] and other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural (solar and volcanic) drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C.
* Observed increases in well-mixed GHG concentrations since around 1750 are unequivocally caused by GHG emissions from human activities over this period.

Results of further climate models are shown in more detail in fig. 25 on the following page:

[25] Contributions from emissions to the 2010—2019 warming relative to 1850—1900 assessed from radiative forcing studies are: CO2 0.8 [0.5 to 1.2]°C; methane 0.5 [0.3 to 0.8]°C; nitrous oxide 0.1 [0.0 to 0.2]°C and fluorinated gases 0.1 [0.0 to 0.2]°C.

In diagram a), the measured mean temperature of Earth surface is indicated by a black line. The temperature is displayed in much finer time-steps than in fig. 1 , because the climate simulations can of course not reasonably be done with average values in year-by-year steps.

In the five diagrams b) through f), the temperature changes are displayed, which in the various simulations resulted from particular influencing factors.

El Niño is the well-known varying sea current in the equatorial Pacific, which is of similar importance for the American climate as the gulf stream for the European climate. Southern Oscillation is the large-scale circulation in the atmosphere, which is closely correlated with El Niño.

In diagram c) the simulations of volcanic eruptions are displayed. The latest and strongest peak came about due to the 1991 Pinatubo eruption. If you take a closer look, you can see that the temperature contribution is above zero a few years after the eruptions, because then the ashes have sunk to the ground, and the polluted soils (particularly polluted surfaces of snow and ice) absorb more solar radiation than clean soils.

In diagram d) the impact of the approximately 11-year solar cycle can be discerned.

The warming displayed in diagram e) is the only one on which humans can exert influence.

The sum of the contributions shown in b) through f) is painted in a) over the black measured temperature curve. There are discrepancies between measurement and simulations around the years 1909 and 1944 ; overall, however, the simulated curves are quite well reproducing the measured one.

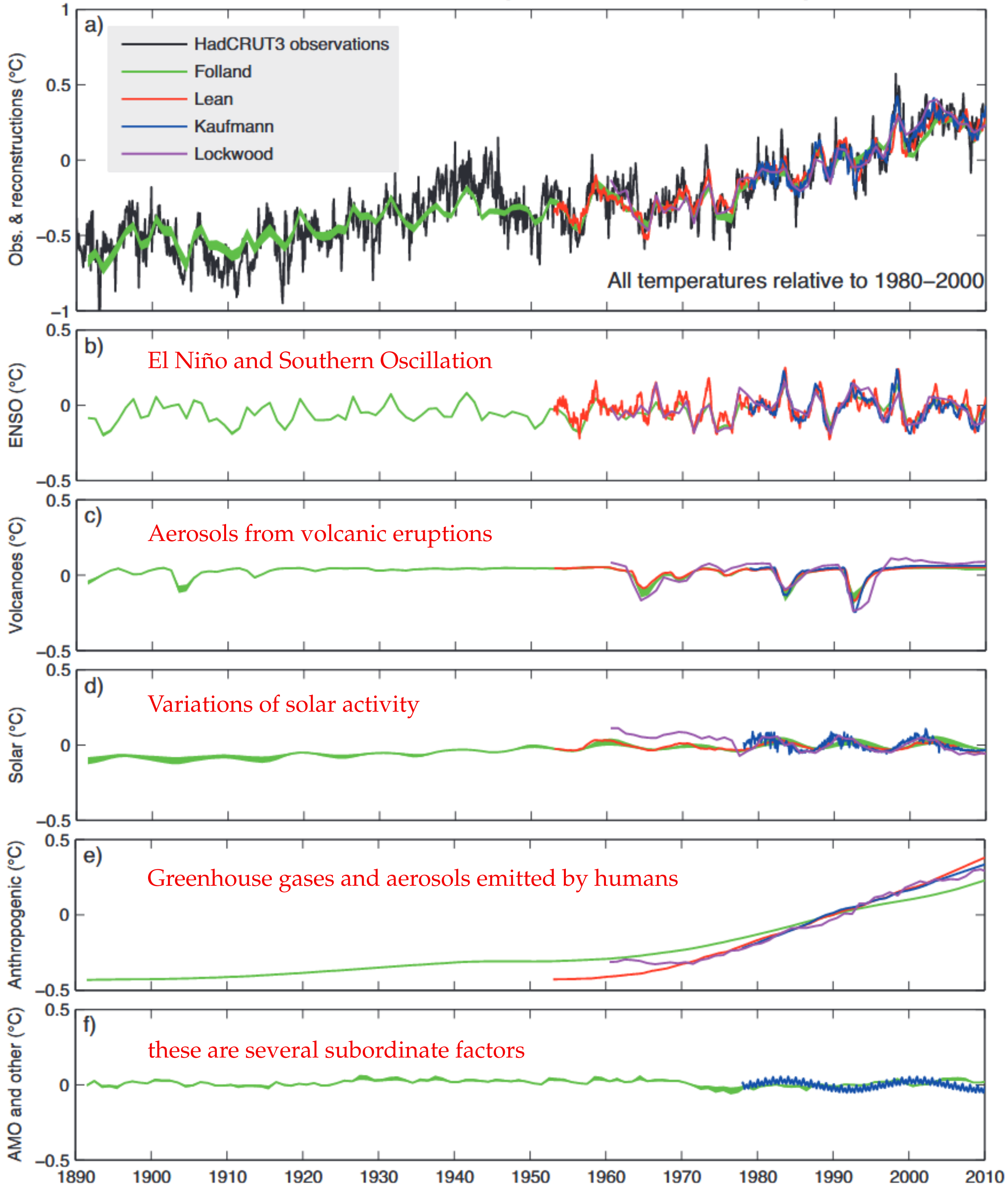

Fig. 25 : Impacts of various factors onto Earth surface temperature, as computed by four different climate models. Graphic from [5, chap. 10].

The essential point is that the long-term warming of Earth is caused in these simulations *exclusively* by the man-made increase of greenhouse gases and aerosols in the atmosphere. The contributions of all other factors only fidget around zero.

Fig. 26 summarizes these results: The Earth's surface temperature has increased by 1.07 °C by 2020 compared to the temperature in 1850 – 1900 (gray bar). This is exactly equal to the sum of man-made warming from greenhouse gases (+1.5 °C, red bar) and man-made cooling from aerosols (-0.4 °C, blue bar). The contributions from solar activity, volcanic eruptions, and internal variability (= natural climate variations) are zero.
This implies the unambiguous conclusion:

> The increasing concentration of man-made greenhouse gases and aerosols in the atmosphere explains *qualitatively and quantitatively* the global temperature rise, which we are observing since some decades. No other factors are known, which could explain — either alone or in combination — this rise in temperature.

By the way: The insight that changes in the concentration of greenhouse gases in the atmosphere have enormous effects on the temperature of the earth's surface is by no means new. As early as 1896, the well-known chemist Svante Arrhenius published an article [19] in which he described quite in detail how an increase in the concentration of CO_2[26] in the air would affect the warming of the Earth's surface.

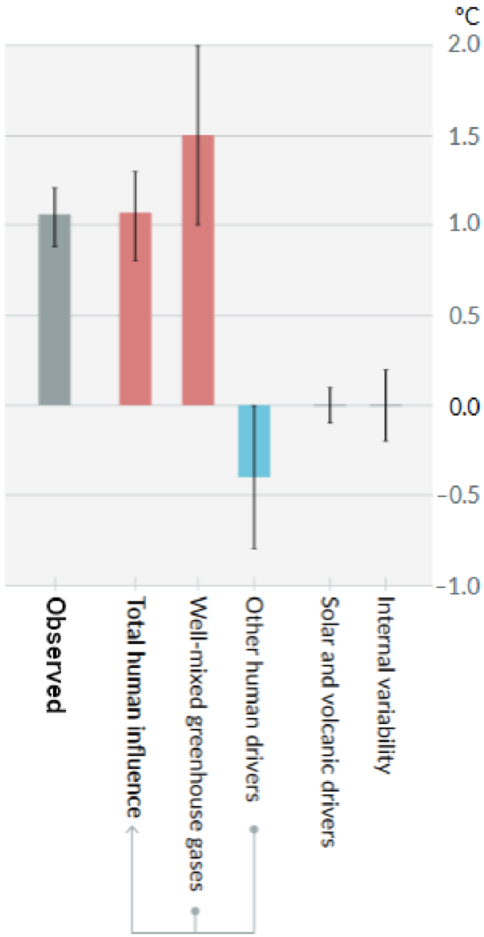

Fig. 26: The cause of warming.
Graphic from [17, Fig. SPM.2].

[26] Arrhenius used for carbon dioxid the by then common name "carbonic acid".

4. Emission and Absorption of Greenhouse Gases

Greenhouse gases in the atmosphere are indispensable to life — that applies literally, without greenhouse gases it would be too cold on Earth for any life. On the other hand, there must not be too much of them, because otherwise we get on Earth a threatening temperature rise, such as we are experiencing right now. If we want to understand why the natural balance of greenhouse gases, which Earth has seen since hundreds of thousands of years, now all of a sudden gets out of hand, then we must check the issue very precisely, and analyze the relevant processes in detail.

4.1 The Carbon Cycle

The burning of e. g. octane (C_8H_{18}) to carbon dioxide and water is described by the chemical equation

$$2\,C_8H_{18} + 25\,O_2 \longrightarrow 16\,CO_2 + 18\,H_2O + \underbrace{\text{energy}}_{\text{heat}}\,.$$

In burning processes like that, energy in the form of heat is set free.

Inversely, additional energy must be fed into the chemical reaction, to reduce CO_2 . That is exactly what green plants are doing in photosynthesis:[27]

$$6\,CO_2 + 6\,H_2O + \underbrace{\text{energy}}_{\text{sunlight}} \longrightarrow \underbrace{C_6H_{12}O_6}_{\text{glucose}} + 6\,O_2$$

Carbon dioxide and water are indispensable food for plants; likewise oxygen and the carbon compounds synthesized by plants are indispensable food for humans and animals. Because the photosynthesis activity of plants is concentrated to the summer season, while emission of CO_2 happens steadily throughout the whole year due to the metabolism of humans, animals, and microorganisms, and due to the industrial activities of humans, there are the characteristic summer/winter oscillations of CO_2 concentration in the atmosphere, that can be seen in figs. 10 and 14 .

The main paths of the carbon cycle are sketched in fig. 27 on the next page. The unit used is

$$\begin{aligned}&\text{Pg} = \text{Peta-gram} = 10^{15}\,\text{gram} = 10^{9}\,\text{tons} =\\&= \text{billion tons} = \text{Giga-tons} = \text{Gt}\,.\end{aligned}$$

It is customary in the description of such cycle processes not to indicate the weight of CO_2 = carbon dioxide, but the weight of the C = carbon contained in it, i. e. only $12/(12+16+16)$ of the CO_2 weight, and mark that fact by a C at Pg resp. Gt :

$$\begin{aligned}&1\,\text{PgC}\,CO_2 = 1\,\text{GtC}\,CO_2 = (12+16+16)/12\,\text{Pg}\,CO_2 \approx\\&\approx 3.67\,\text{Pg}\,CO_2 = 3.67\,\text{Gt}\,CO_2\\&1\,\text{Pg}\,CO_2 = 1\,\text{Gt}\,CO_2 = 12/(12+16+16)\,\text{PgC}\,CO_2 \approx\\&\approx 0.27\,\text{PgC}\,CO_2 = 0.27\,\text{GtC}\,CO_2\end{aligned}$$

By the way: 1 ppm CO_2 in the atmosphere weighs 2.1 PgC .

All “natural” contributions are indicated in fig. 27 in black, while red color is used for those contributions which are caused by the industrial or agricultural activities of humans. All numeric values are mean values per year in the period 2000 – 2009 .

[27] This is a strongly simplified account of photosynthesis. Actually the process proceeds over many intermediate steps, and besides glucose many other carbon-containing compounds are synthesized.

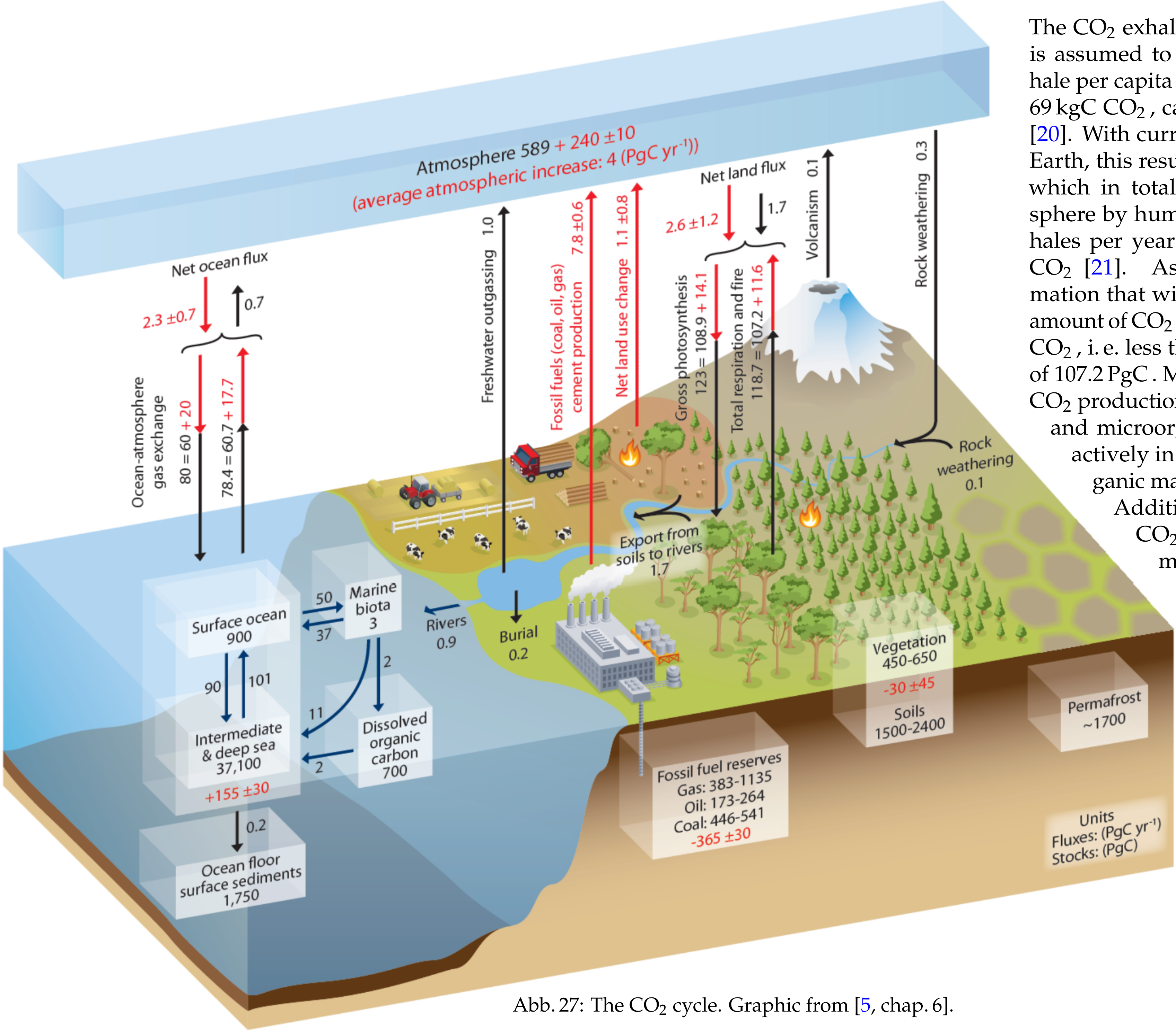

Abb. 27: The CO_2 cycle. Graphic from [5, chap. 6].

The CO_2 exhaled by animals and humans is assumed to be 107.2 PgC. Humans exhale per capita and per year approximately 69 kgC CO_2, cattle 217 kgC, pigs 19.4 kgC [20]. With currently 7.7 billion humans on Earth, this results into about 0.5 PgC CO_2, which in total is exhaled into the atmosphere by humans. The total livestock exhales per year about 3 – 4 times as much CO_2 [21]. Assuming in rough approximation that wild animals exhale the same amount of CO_2, this sums up to about 3 PgC CO_2, i. e. less than 3 % of the total amount of 107.2 PgC. More than 97 % of the natural CO_2 production is attributable to microbes and microorganisms, which participate actively in the decay and rotting of organic matter.

Additional contributions to the CO_2 accumulation in the atmosphere come from the not exactly balanced CO_2 exchange with the oceans, and emissions from freshwater lakes and from volcanoes.

The by far most important natural CO_2-sink is photosynthesis, which filters per year 108.9 PgC CO_2 out of the air. Furthermore some CO_2 gets bounded in the weathering of rocks.

In total, due to natural processes the amount of

CO_2 in the atmosphere decreases according to this estimate per year by 0.2 PgC.

Amongst the man-made contributions to the atmosphere's CO_2 balance, which are indicated in fig. 27 in red, the main adders are the burning of fossil fuels, and cement production. The increase of these adders from 1750 through 2014 is displayed in fig. 28. Only since mid of the 19th century there is a noteworthy coal consumption, which since begin of the 21st century is increasing faster than ever before. After 40 years it has recently again overtaken the oil consumption. Due to the flaring of gas, which is appearing as an unwanted by-product at many oil wells, the oil producing countries are constantly showing up at top of the statistics of per-capita CO_2 emissions.

CO_2 is emitted in cement production, because calcium oxide = lime = CaO, which in the chemical reaction

$$CaCO_3 \xrightarrow{\text{heat}} CaO + CO_2$$

is fabricated from $CaCO_3$ = calcium carbonate = limestone or chalk, is a central ingredient of cement powder.

About 9.5 PgC carbon dioxide have in total been emitted in 2014 due to burning of fossil fuels and cement production according to fig. 28. The diagram is consistent with the 7.8 PgC CO_2 displayed in fig. 27 as mean value of the years 2000 – 2009.

A further man-made contribution to the enrichment of the atmosphere with CO_2 is called "net land use change" in fig. 27. Here the word "net" must be taken seriously. When a jungle is cleared and converted into a soy plantation, far less photosynthesis takes place on this area than before. On the other hand, less CO_2 is later produced from the soy plants than by rotting processes from the trees of the jungle. Overall, however, the positive effect of forests on the Earth's CO_2 balance outweighs by far. Afforestation is — after avoiding CO_2 production — the most effective measure to limit the increase of CO_2 concentration in the atmosphere.

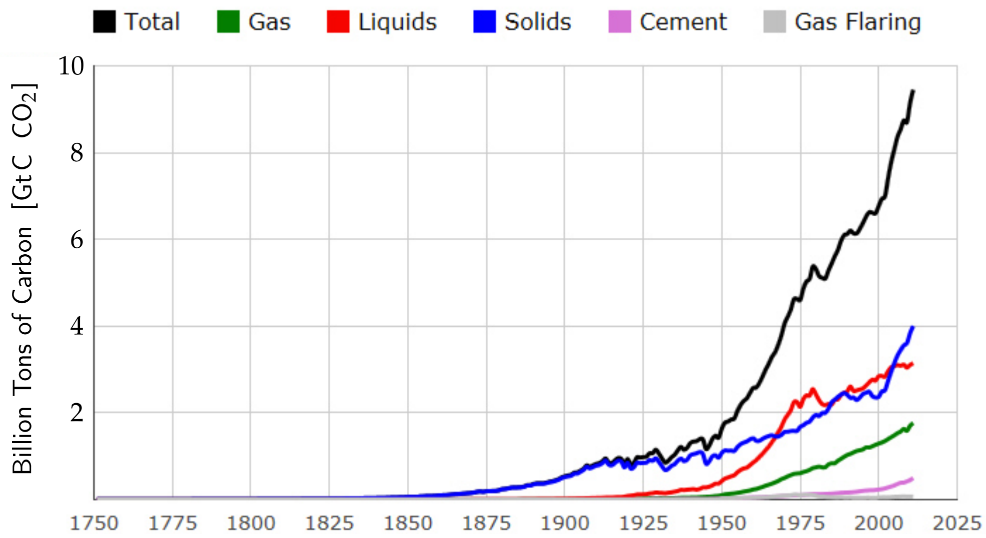

Fig. 28: Global CO_2 emissions due to burning of fossil fuels and cement production. Graphic from [22].

Conversely, the large-scale slash-and-burn in the Amazon jungle, which is currently (2019 – 2021) taking place in Brazil, is aggravating the situation.

The increased CO_2 concentration in the air has a fertilizing effect on the green plants. They increase their photosynthesis performance, and grow faster. This effect is shown in fig. 27 with 2.6 PgC CO_2 per year.[28]

Overall, the atmosphere has been enriched in the years 2000 – 2009 with additional 6.3 PgC CO_2 per year. The atmosphere forwarded 2.3 PgC of that to the oceans, resulting into ocean acidification, see section 1.6. The reminder, i. e. 4 PgC CO_2 per year, remained in the air and intensified the greenhouse effect. These 4 PgC CO_2 per year increased the CO_2-concentration in the atmosphere in the period 2000 – 2009 by 4 ppm/2.1 = 1.9 ppm per year. This is consistent with the measured results displayed in fig. 10.

[28] Why this effect is indicated as $14.1 - 11.6$ I did not understand.

	approximate CO_2 production per year in the period 2000 – 2009
exhaled by humans	0.5 GtC CO_2
exhaled by wild animals and microbes	104.9 GtC CO_2
outgased from waters	1.7 GtC CO_2
outgased from volcanoes	0.1 GtC CO_2
exhaled by livestock	1.8 GtC CO_2
fossil fuels	7.5 GtC CO_2
cement production	0.3 GtC CO_2
net land use change	1.1 GtC CO_2
sum	117.9 GtC CO_2

The sources, which enrich the atmosphere with CO_2 , are compiled in the table. In total, 117.9 GtC CO_2 were produced on average per year in the period 2000 – 2009 . But "only " 6.3 GtC CO_2 remained permanently in the air or in the oceans. $(117.9 - 6.3)$ GtC $= 111.6$ GtC CO_2 could be naturally removed. Stated conversely: The CO_2 production exceeded the climate-compatible value by 6.3 GtC CO_2 per year.[29]

> To stop the temperature increase on Earth, we must reduce the yearly CO_2 production relative to the average 2000 – 2009 value by approximately 6.3 GtC $=$ 23.1 Gt CO_2 .[29]

The contributions to the CO_2 balance to which we have access are marked red in the table. Let us first consider the item "net land use change". Instead of clearing forests, we could afforest the Earth and thus increase the CO_2 budget permitted for industrial activities. If we want to blow just as much CO_2 into the air every year as on average in the years 2000 – 2009 , how much afforestation is required worldwide so that the CO_2 concentration in the atmosphere will still not rise?

In rough approximation, 80 million hectare = 800 000 km^2 forest filter about 1 Gt $CO_2 = 1\,\text{GtC} \cdot 12/(12 + 2 \cdot 16)\, CO_2 = 0,27\,\text{GtC}\, CO_2$ per year due to photosynthesis out of the air [12, sec. 3.6 box 7]. Hence we can increase the admissable yearly CO_2 budget by 6.3 GtC CO_2 due to afforestation of $6.3 \cdot 800\,000\,km^2/0.27 \approx 19$ million km^2 of Earth surface. 19 million km^2 is slightly more than the area of South America (18 million km^2) or scarcely twice the area of Europe (10 million km^2).

These are completely unrealistic orders of magnitude. A more realistic goal would be at least to compensate deforestations, which may be unavoidable in some places, by afforestations in others. If we should accomplish that, then we need to reduce the three other red colored items in the table "only" by $(6.3 - 1.1)$ GtC $= 5.2$ GtC $= 19.1$ Gt CO_2 .[29]

A differentiated discussion of possible scenarios, by which the necessary CO_2 reduction could be achieved, can be found in the IPCC's SR15 report [12, chap. 2].

Unfortunately, the world is still *a long way* from achieving the necessary reduction in CO_2 emissions. In spring 2025, the International Energy Agency published a report [23], from which the graphics on the following page are taken:

[29] The precise numeric value 6.3 GtC $=$ 23.1 Gt CO_2 must be interpreted with much caution. First, this value does include the increased photosynthesis performance of plants due to the raised CO_2 concentration in the atmosphere, i. e. there exists a complex non-linear feedback-effect. And second, it is a rough simplification to consider changes of CO_2 isolated from other parameters, which as well have significant climate impacts. To me it seems useful, however, to state a numeric value which at least is a reasonable approximation, so that we know where we need to get to.

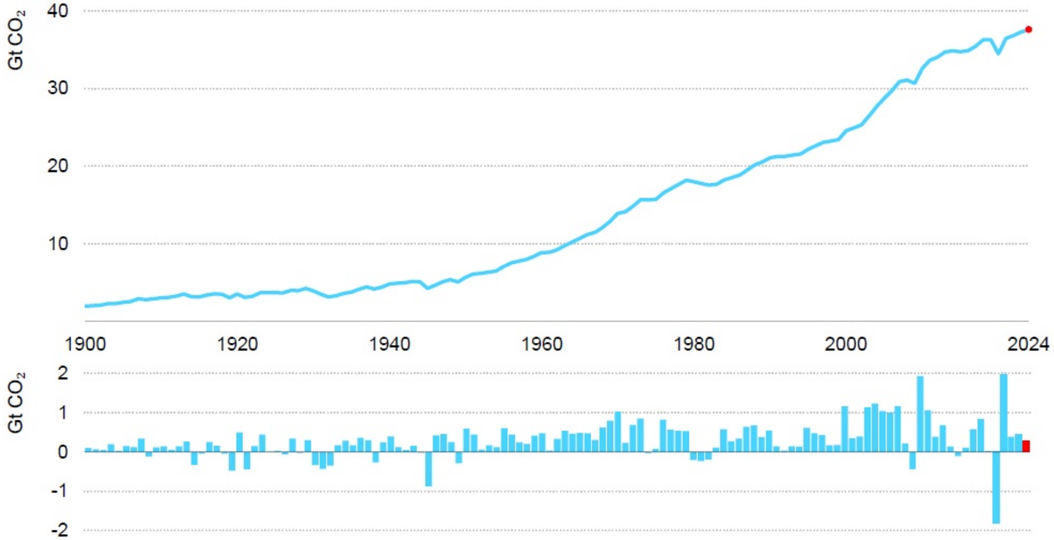

Fig. 29: Global annual CO_2 emissions from burning of fossil fuels. Graphic from [23].

The top graph in Fig. 29 shows the weight of CO_2 (not just the C it contains!) emitted annually from energy production up to and including 2024, while the bottom graph shows the change compared to the previous year. Only 2020 saw a significant decline in emissions due to the corona epidemic, and 2009 a smaller decline due to the global financial crisis. Apart from that, emissions continue to rise every year.

Fig. 30 shows the CO_2 emissions per country and per capita. In terms of per capita emissions, China has now reached second place behind the USA.

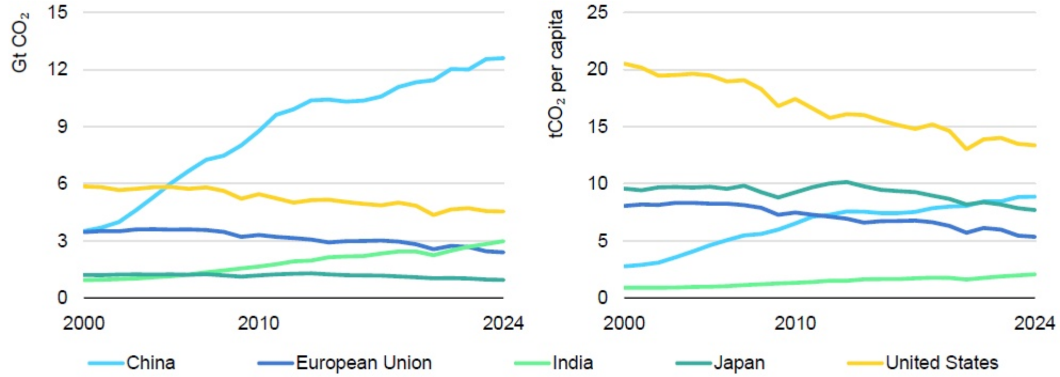

Fig. 30: Global annual CO_2 emissions per country (left) and per capita (right) from burning of fossil fuels. Graphic from [23].

Couldn't we, instead of abstaining from the combustion of fossil fuels, capture the produced CO_2 and render it harmless by some appropriate type of storage, but not blow it simply into the air? If we would burn biomass, and capture and store the CO_2 thereby produced, then the CO_2 balance would even be negative because the biomass had previously extracted CO_2 from the atmosphere by photosynthesis. This idea runs under the name CCS = Carbon Capture and Storage. A good introduction to this topic can be found in Wikipedia [24]. According to my unprofessional impression (*confidence level: more likely than not*[10]) there are even more problems with CCS than with the switch to climate-neutral energy sources. Therefore I guess that CCS will not be the solution to the CO_2 problem, and will probably not even significantly contribute to the problem's solution.

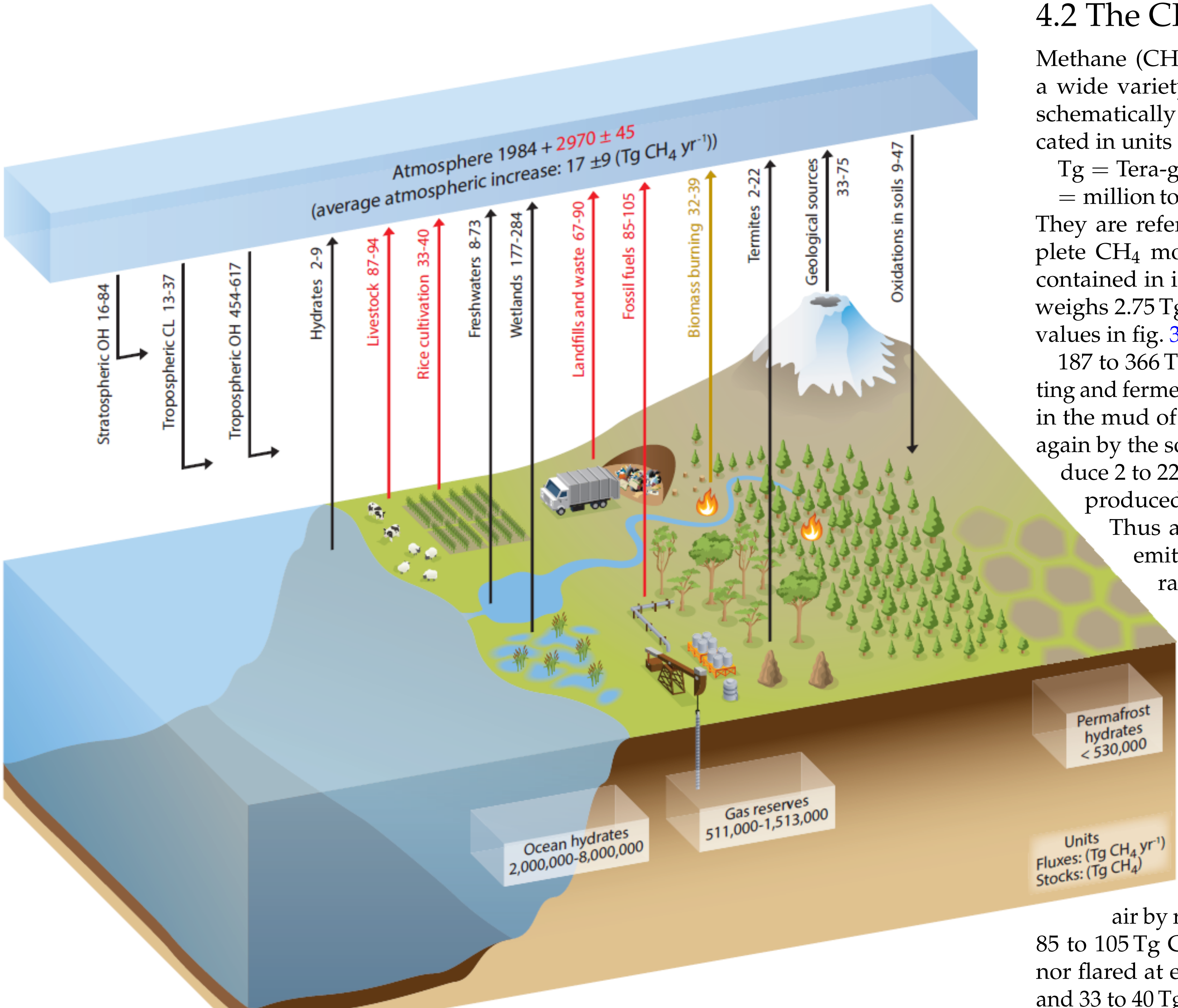

Fig. 31: The CH_4 balance. Graphic from [5, chap. 6].

4.2 The CH_4 Balance

Methane (CH_4) gets into the atmosphere on a wide variety of ways, which are sketched schematically in fig. 31 . The values are indicated in units of

$$\text{Tg} = \text{Tera-gram} = 10^{12}\,\text{gram} = 10^{6}\,\text{tons} = \\ = \text{million tons} = \text{Mega-tons} = \text{Mt}\,.$$

They are referring to the weight of the complete CH_4 molecule, not only to the carbon contained in it. 1 ppb CH_4 in the atmosphere weighs 2.75 Tg . The large uncertainties of the values in fig. 31 is striking.

187 to 366 Tg CH_4 are produced during rotting and fermentation processes in swamps and in the mud of waters; 9 to 47 Tg are absorbed again by the soil after some time. Termites produce 2 to 22 Tg CH_4 , another 33 to 75 Tg are produced during geological processes. Thus a total of 175 to 454 Tg CH_4 are emitted into the atmosphere by natural processes.

32 to 39 Tg CH_4 are resulting from biomass burning. They are sketched in yellow, because the climatologists did not want to decide whether this is a natural or a man-made process.

Clearly man-made are 152 to 195 Tg CH_4 from the rotting in garbage dumps, 87 to 94 Tg CH_4 burped into the air by ruminant livestock (cattle, sheep), 85 to 105 Tg CH_4 which are neither collected nor flared at extraction of oil and natural gas, and 33 to 40 Tg CH_4 outgassing from rice fields.

Thus a total of 357 to 434 Tg CH_4 is coming from processes which were — in significant volume — only introduced by humans in modern times. In the atmosphere, OH^- ions and chlorides react with methane, and convert it into less climate-damaging substances. Thereby 483 to 738 Tg CH_4 disappear from the atmosphere every year. These processes would be completely sufficient to compensate all natural CH_4 sources and also the CH_4 from burnt biomass; therefore there was no increase of CH_4 concentration in the atmosphere before 1750.

According to the estimate of fig. 31 , the amount of CH_4 in the atmosphere increased in the period 2000 – 2009 per year on average by 17 ± 9 Tg ; that corresponds to a concentration increase of $17\,\text{ppb}/2.75 \pm 9\,\text{ppb}/2.75 = 6.18 \pm 3.3\,\text{ppb}$. Actually the measured concentration increase in this period was smaller, i. e. only about 2 ppb per year, see fig. 12 . In those years, however, the increase of CH_4 concentration was exceptionally small.[30] In recent years the CH_4 concentration is increasing by about 9 ppb per year (see fig. 12), corresponding to a yearly $9\,\text{Tg} \cdot 2.75 \approx 25\,\text{Tg}$ increase of CH_4 in the atmosphere.

Consequently we must reduce the yearly emission of CH_4 by 25 Tg , to avoid the climate damage.

Comparing this reduction target with the average man-made yearly emissions in the period 2000 – 2009 , namely

rotting in landfills	152 to 195 Tg CH_4
ruminant livestock (cattle, sheep)	87 to 94 Tg CH_4
collateral damage at oil production	85 to 105 Tg CH_4
rice cultivation	33 to 40 Tg CH_4 ,

then it is obvious that a reduction by about 25 Tg CH_4 should definitely be achievable without restricting rice cultivation or livestock breeding.[31]

Remark: This result is a surprise for me. I have believed for years that methane burping cattle cause a serious environmental problem. In fact, however, the precise quantitative analysis shows that nature can easily cope with that, if we achieve the necessary reduction in methane emissions from waste disposal and fossil fuel production.

4.3 The N_2O Balance

N_2O results from a variety of more or less intricate chemical reactions involving nitrogen. In fig. 32 on the next page, a superficially schematized account of the sources is given, from which — over whatever transformations of nitrogen-containing molecules — eventually N_2O reaches the atmosphere. For a more detailed description of these processes, see [5, chap. 6 sec. 6.1.3.1].

[30] There is no consensus amongst scientists regarding the explanation for that fact.

[31] The huge global livestock is causing a lot of further problems than only methane belches. Therefore some livestock reduction may very well be necessary, but not because of the CH_4 problem.

The N_2O weight is indicated in fig. 32 in units of

$$\text{Tg} = \text{Tera-gram} = 10^{12}\,\text{gram} = 10^{6}\,\text{tons} =$$
$$= \text{million tons} = \text{Mega-tons} = \text{Mt}\,.$$

The N at TgN is indicating that these values are referring to the two nitrogen atoms in the N_2O molecule only; the oxygen atom is not included in the calculation. 1 ppb N_2O in the atmosphere weighs 4.79 TgN .

5.4 to 45.6 TgN N_2O per year are emitted from natural sources, which are indicated in black in fig. 32 . And in total 4.3 to 27.2 TgN N_2O per year are removed due to chemical reactions in the stratosphere.

Additional 2.7 to 12.1 TgN N_2O are — more or less indirectly — emitted by humans (see red numbers in fig. 32). The by far most important source is agriculture with 1.7 to 4.8 TgN N_2O , due to the nitrogen-fertilization of growing-areas.

Note the large uncertainties of the numeric values. Actually the N_2O concentration in the atmosphere increased by (3.6 ± 0.15) TgN per year in the period 2000 – 2009 . That amounts to a concentration increase by $(3.6 \pm 0.15)\,\text{ppb}/4.79 = (0.75 \pm 0{,}03)\,\text{ppb}$, in line with fig. 13 .

> To stop the temperature increase on Earth, we must reduce the (direct and indirect) N_2O emissions by about 3.6 TgN per year versus the 2000 – 2009 average value.

How can we achieve that objective? Due to the intricate processes of nitrogen chemistry, this is a difficult question. Certainly it is no acceptable option to abandon nitrogen fertilization in agriculture. A differentiated discussion of potential scenarios, by which the emission of greenhouse gases could be reduced to a climate-neutral quantity, can be found in the report SR15 [12, chap. 2] of the IPCC.

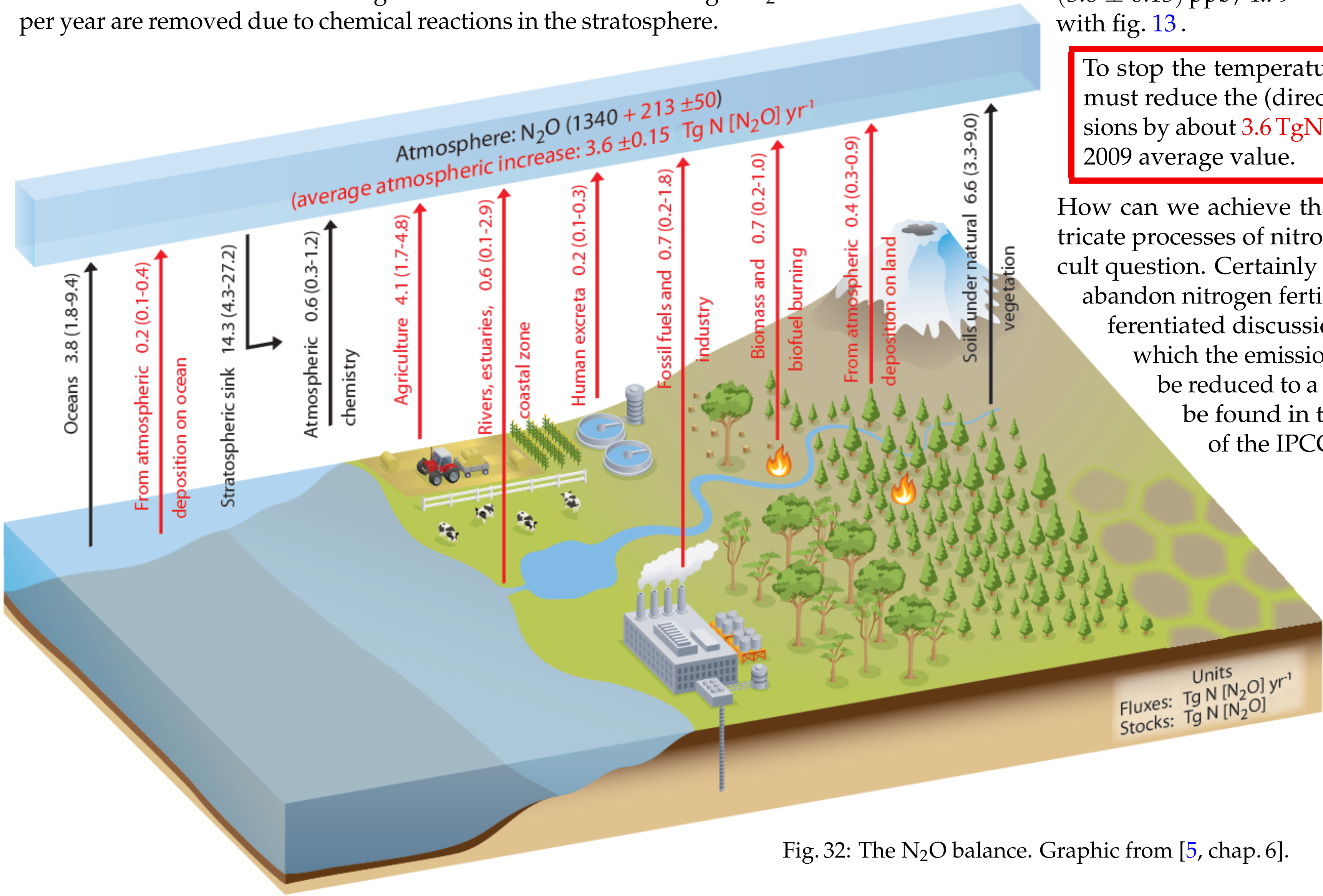

Fig. 32: The N_2O balance. Graphic from [5, chap. 6].

5. (How) Can the Climate Change be stopped?

5.1 The global Temperature Rise

195 countries (including Germany) committed at the United Nations Climate Change Conference, which took place in Paris in December 2015, to confine global warming to a maximum of 2 °C, but if possible to a maximum of 1.5 °C, compared to the pre-industrial level[32]. [25]

In order to suppress natural temperature fluctuations (e. g. due to the solar cycle, or due to large volcanic eruptions) in the determination of the actual Earth surface temperature, the mean global temperature at a given point in time is calculated as the mean value of a 30 year long period centered[33] around this date. [12, sec. 1.2.1]

The average global temperature thus computed was in 2017 by 1.0 °C (likely between 0.8 °C and 1.2 °C) higher than in the pre-industrial era, and rose in 2017 at a speed of 0.2 °C (likely between 0.1 °C and 0.3 °C) per decade (*high confidence*[10]) [12, sec. 1.2.1.3 and executive summary].

The IPCC scientists are convinced, that in the 30-year average all natural climate fluctuations are *completely* suppressed, such that the cited temperature increase is *exclusively* caused by man-made emissions of greenhouse gases[34] and aerosols. [12, sec. 1.2.1.3 and executive summary]

5.2 Warming by 2 °C or by 1.5 °C ?

The participants of the Paris Climate Conference 2015 were uncertain whether global warming must be limited to 1.5 °C, or whether a 2 °C limit is sufficient. This can be recognized by the somewhat vague wording "maximum 2 °C, but if possible maximum 1.5 °C", on which they finally agreed. In order to have a more solid basis for future decisions, the conference asked the IPCC to examine and compare the implications of both limits more closely.

Almost three years later, the IPCC scientists published the result[12] of this investigation. Here are some statements from their report[12, chap. 3, executive summary]:

* Climate models project robust differences in regional climate between present-day and global warming up to 1.5 °C, and between 1.5 °C and 2 °C (*high confidence*[10]), depending on the variable and region in question (*high confidence*[10]). Large, robust and widespread differences are expected for temperature extremes (*high confidence*[10]). Regarding hot extremes, the strongest warming is expected to occur at mid-latitudes in the warm season (with increases of up to 3 °C for 1.5 °C of global warming, i.e., a factor of two) and at high latitudes in the cold season (with increases of up to 4.5 °C at 1.5 °C of global warming, i.e., a factor of three) (*high confidence*[10]).[35]

* Global mean sea level rise is projected to be around 0.1 m (0.04 − 0.16 m) less by the end of the 21st century in a 1.5 °C warmer world compared to a 2 °C warmer world (*medium confidence*[10]). Pro-

[32] Because there were no regular or even globally representative temperature measurements in the pre-industrial era, the mean temperature value in the 51 years 1850 – 1900 is by definition [12, sec. 1.2.1] regarded as the "pre-industrial level".

[33] If the global temperature shall be computed for a recent date (e. g. for the year 2018), then the method of average determination must of course be modified appropriately.

[34] These are the emission, which are indicated in the diagrams 27 , 31 , and 32 in red color. The CO_2 exhaled by humans does *not* belong to the man-made emissions.

[35] The second part of this paragraph obviously is not a comparison of 1.5 °C versus 2 °C global warming; instead it is pointing out, that the seemingly harmless quantity 1.5 °C might be strongly deceiving, because regional temperature changes will be a multiple of that.

jected global mean sea level rise for 1.5 °C of global warming has an indicative range of 0.26 – 0.77 m, relative to 1986 – 2005 , (*medium confidence*[10]). There is *high confidence*[10] that sea level rise will continue beyond 2100 . Instabilities exist for both the Greenland and Antarctic ice sheets, which could result in multi-meter rises in sea level on time scales of century to millennia. There is *medium confidence*[10] that these instabilities could be triggered at around 1.5 °C to 2 °C of global warming.[36]

* Risks of local species losses and, consequently, risks of extinction are much less in a 1.5 °C versus a 2 °C warmer world (*high confidence*[10]). The number of species projected to lose over half of their climatically determined geographic range at 2 °C global warming (18 % of insects, 16 % of plants, 8 % of vertebrates) is projected to be reduced to 6 % of insects, 8 % of plants and 4 % of vertebrates at 1.5 °C warming (*medium confidence*[10]). Risks associated with other biodiversity-related factors, such as forest fires, extreme weather events, and the spread of invasive species, pests and diseases, would also be lower at 1.5 °C than at 2 °C of warming (*high confidence*[10]).

* Constraining global warming to 1.5 °C , rather than to 2 °C and higher, is projected to have many benefits for terrestrial and wetland ecosystems and for the preservation of their services to humans (*high confidence*[10]). Risks for natural and managed ecosystems are higher on drylands compared to humid lands. The global terrestrial land area projected to be affected by ecosystem transformations (13 % , interquartile range 8–20 %) at 2 °C is approximately halved at 1.5 °C global warming to 4 % (interquartile range 2–7 %) (*medium confidence*[10]). Above 1.5 °C , an expansion of desert terrain and vegetation would occur in the Mediterranean biome (*medium confidence*[10]), causing changes unparalleled in the last 10 000 years (*medium confidence*[10]).

* Many impacts are projected to be larger at higher latitudes, owing to mean and cold-season warming rates above the global average (*medium confidence*[10]). Constraining warming to 1.5 °C would prevent the thawing of an estimated permafrost area of 1.5 to 2.5 million km^2 over centuries compared to thawing under 2 °C (*medium confidence*[10]).

* Ocean ecosystems are already experiencing large-scale changes, and critical thresholds are expected to be reached at 1.5 °C and higher levels of global warming (*high confidence*[10]). In the transition to 1.5 °C of warming, changes to water temperatures are expected to drive some species (e.g., plankton, fish) to relocate to higher latitudes and cause novel ecosystems to assemble (*high confidence*[10]). Other ecosystems (e.g., kelp forests, coral reefs) are relatively less able to move, however, and are projected to experience high rates of mortality and loss (*very high confidence*[10]). For example, multiple lines of evidence indicate that the majority (70–90 %) of warm water (tropical) coral reefs that exist today will disappear even if global warming is constrained to 1.5 °C (*very high confidence*[10]).

* Current ecosystem services from the ocean are expected to be reduced at 1.5 °C of global warming, with losses being even greater at 2 °C of global warming (*high confidence*[10]). The risks of declining ocean productivity, shifts of species to higher latitudes, damage to ecosystems (e.g., coral reefs, and mangroves, seagrass and other wetland ecosystems), loss of fisheries productivity (at low latitudes), and changes to ocean chemistry (e.g., acidification, hypoxia and dead zones) are projected to be substantially lower when global warming is limited to 1.5 °C (*high confidence*[10]).

* Limiting global warming to 1.5 °C , compared with 2 °C , is projected to result in smaller net reductions in yields of maize, rice, wheat, and potentially other cereal crops, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America; and in the CO_2-

[36] Here one of the dreaded tipping points is addressed. If the ice shields of Greenland or Antarctica were to melt completely, then there would be a catastrophic sea-level rise of many meters within centuries or millennia. In addition, the ice-free soil would then absorb considerably more solar radiation than the surface of the ice before, i. e. the Earth again would get warmer.

dependent nutritional quality of rice and wheat (*high confidence*[10]). A loss of 7–10 % of rangeland livestock globally is projected for approximately 2 °C of warming, with considerable economic consequences for many communities and regions (*medium confidence*[10]).

* Limiting global warming to 1.5 °C would limit risks of increases in heavy precipitation events on a global scale and in several regions compared to conditions at 2 °C global warming (*medium confidence*[10]).

* Limiting global warming to 1.5 °C is expected to substantially reduce the probability of extreme drought, precipitation deficits, and risks associated with water availability (i.e., water stress) in some regions (*medium confidence*[10]).

I can not believe that any reader who carefully considered these projections, compiled by serious scientists, will doubt that we must really make greatest efforts to limit the Earth temperature increase to maximum 1.5 °C , and to avert a warming by 2 °C (or even more).

5.3 The remaining CO_2 budget

Although the temperature rise on Earth is determined by a wide range of greenhouse gases and aerosols, by far the most important is carbon dioxide. Changes in the concentration of CO_2 in the atmosphere are reflected almost linearly in the change in the Earth's surface temperature. According to Fig. 22 this was to be expected, and in Fig. 33 it is clearly evident. Note the different spread out time scales in Fig. 33 . The colored lines on the far right show the results of model calculations with different CO_2 concentrations. (Don't be fooled by the fact that in the past there have been CO_2 concentrations and temperatures on Earth as high as those threatening humanity in the coming centuries. That was millions of years ago. Humans live on Earth only since 200 000 years).

If we should manage to stop the CO_2 rise, then there will still remain the increased CO_2 concentration in the atmosphere that we have built up since the beginning of industrialization. Will the CO_2 concentration naturally return to it's pre-industrial value?

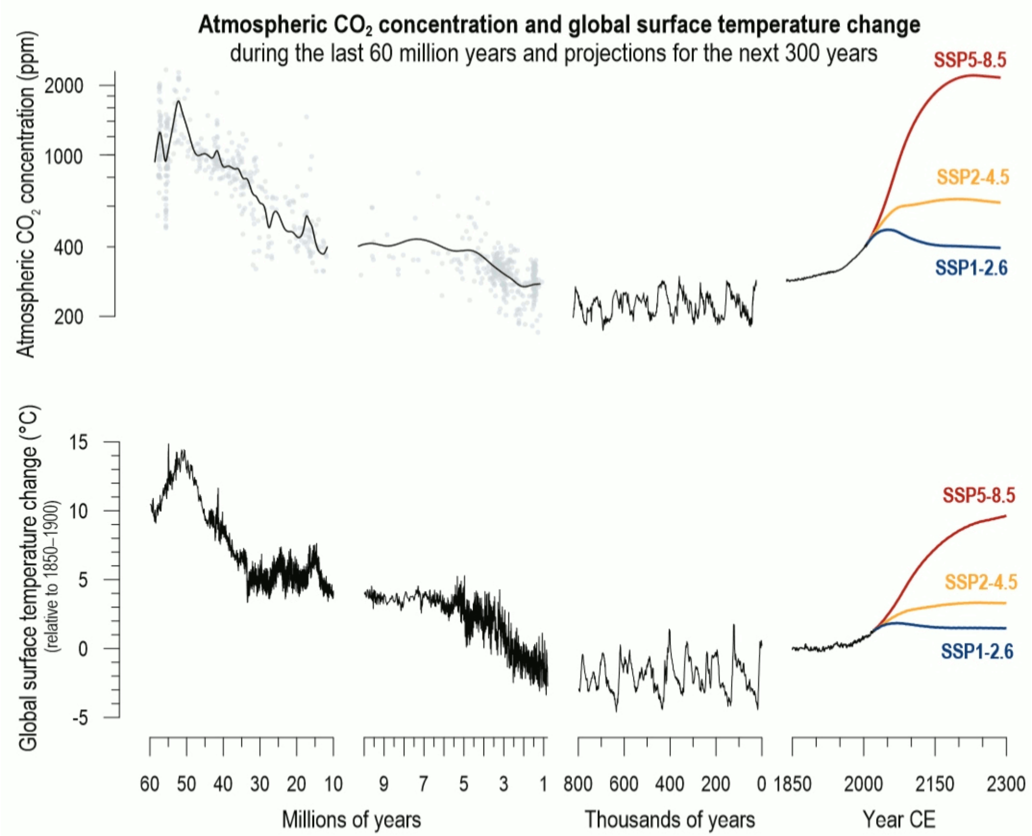

Fig. 33: The correlation between CO_2 in the atmosphere and the Earth's surface temperature. Graphic from [17, fig. TS.1].

It will, but only slowly. With regard to that question, the IPCC Assessment Report 5 states: The removal of human-emitted CO_2 from the atmosphere by natural processes will take a few hundred thousand years (*high confidence*[10]). [. . .] This very long time required by sinks to remove anthropogenic CO_2 makes climate change caused by elevated CO_2 irreversible on human time scale. [5, chap. 6]

In [5, chap. 6 sec. 5] possible methods are described how the excessive CO_2 content of the atmosphere could be reduced more quickly by technical means. IPCC scientists are rather sceptical about these ideas, however:

Unconventional ways to remove CO_2 from the atmosphere on a large scale are termed Carbon Dioxide Removal (CDR) methods. CDR could in theory be used to reduce CO_2 atmospheric concentrations but these methods have biogeochemical and technological limitations to their potential. Uncertainties make it difficult to quantify how much CO_2 emissions could be offset by CDR on a human time scale, although it is *likely*[10] that CDR would have to be deployed at large-scale for at least one century to be able to significantly reduce atmospheric CO_2 . In addition, it is *virtually certain*[10] that the removal of CO_2 by CDR will be partially offset by outgassing of CO2 from the ocean and land ecosystems.

The level of confidence on the side effects of CDR methods on carbon and other biogeochemical cycles is *low*[10]. [5, chap. 6]

The irreversibility of the once reached CO_2 level in the atmosphere is the reason why we cannot postpone the problem. Once the CO_2 which increases the global temperature by more than 1.5 °C is in the atmosphere, we can't get rid of it "on human time scale", unless we want to speculate on the vague possibility of substantially improved CDR procedures.

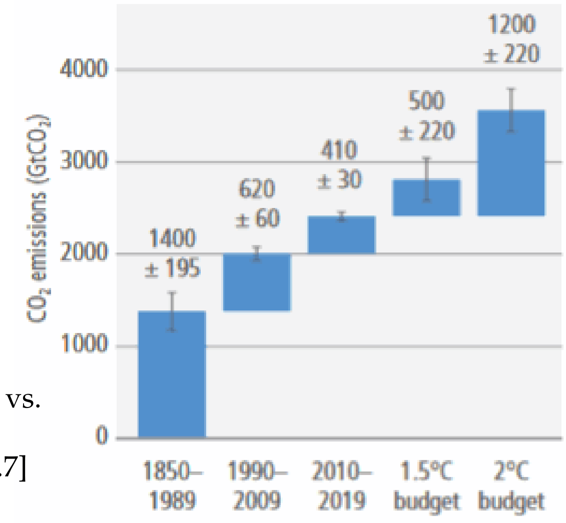

Fig. 34: Historic CO_2 emissions vs. future carbon budgets , Graphic from [26, fig. 2.7]

Thus there is only a limited CO_2 budget remaining, which we may still blow into the air in the coming years, before the 1.5 °C limit (or even the 2 °C limit) will be exceeded. In fig. 34 this remaining budget is displayed. Note the large uncertainty of ±200 Gigatons CO_2 . Thus to meet the 1.5 °C limit we may emit in total, starting from Jan-01-2020, approximately the same amount of CO_2 as we have emitted in the complete 2010 – 2019 period.

5.4 Will we meet the 1.5 °C limit ?

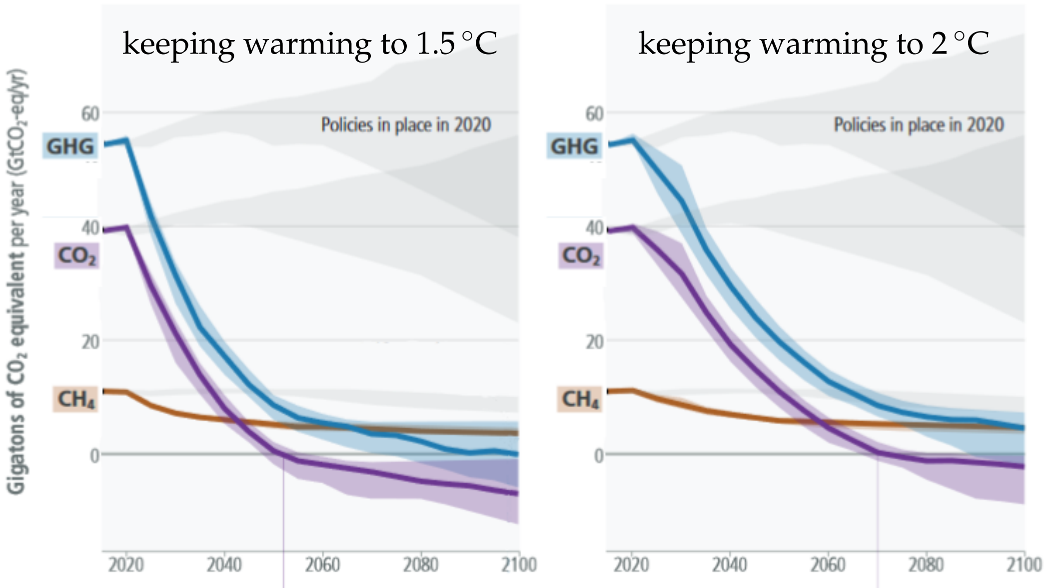

Fig. 35: Greenhouse gas reduction scenarios , from graphic [18, fig. 3.6]

Model scenarios for reductions in emissions of CO_2, CH_4, and total greenhouse gases (GHG = GreenHouseGases) that could limit temperature increases to 1.5 °C and 2 °C, respectively, are shown in fig. 35 with the reductions that governments have announced or already started to implement (the gray shaded areas “policies in place 2020”). For comparision, fig. 29 is again displayed on this page top right. At the rate we are going so far, we obviously will not even manage to limit warming to 2 °C.

It is interesting that both model scenarios assume negative CO_2-emissions in the future. This means that more CO_2 is removed from the atmosphere by man-made measures such as e. g. the reforestation of steppes or the renaturation of peatlands than is blown into it by human activities such as e. g. the burning of fossil fuels.

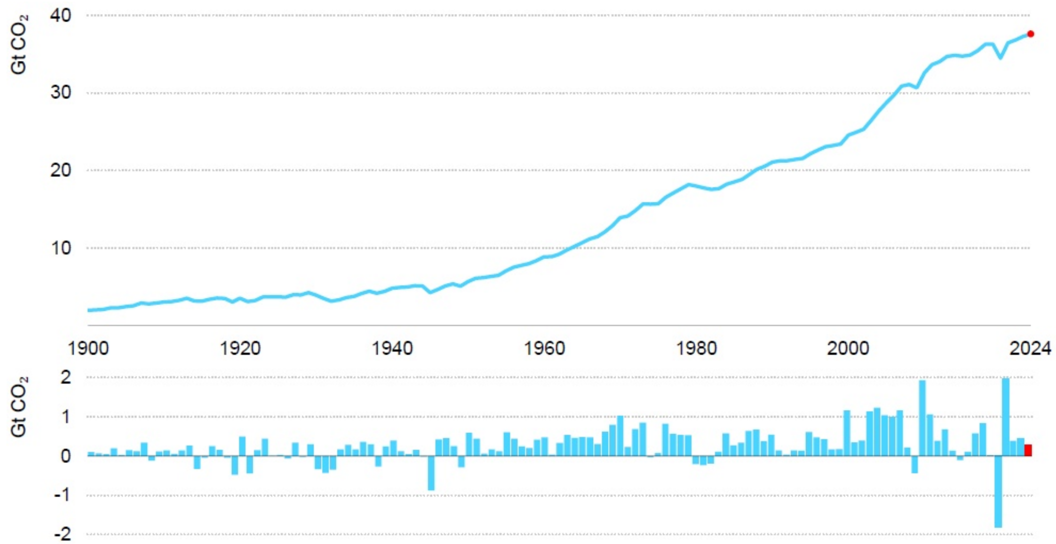

Fig. 29: Global annual CO_2 emissions from burning of fossil fuels. Graphic from [23].

5.5 Should we give up?

The comparison of Fig. 35 and Fig. 29 is really very depressing. Nevertheless, we should not give up, because global warming of 3°C, for example, would be terrible, but still less bad than warming of 5°C, for example. And a warming of 5°C would still be less bad than a warming of 7°C. At some point, humanity will certainly come to it’s senses and stop heating up the earth. The sooner we will switch to reasonable behavior, the less unbearable life will be for future generations on this planet.

The IPCC has most recently described in its report [26] a wealth of possible measures, and discussed their respective effectiveness, that can be used to limit the rise in the earth’s temperature. It is up to us to *finally* implement these proposals.

References

[1] National Oceanic & Atmospheric Administration, USA: *Global Time Series* https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/global/time-series

[2] World Glacier Monitoring Service: *Global Glacier State* https://wgms.ch/global-glacier-state/

[3] E. J. O. Schrama, B. Wouters, R. Rietbroek : *A mascon approach to assess ice sheet and glacier massbalances and their uncertainties from GRACE data* , J. Geophys. Res. Solid Earth **119**, 6048 – 6066 (2014), https://doi.org/10.1002/2013JB010923

[4] Graphic from the GFZ (Geoforschungszentrum) Potsdam, Germany https://www.gfz-potsdam.de/en/section/earth-system-modelling/topics/solid-earth-dynamics/glazial-isostatic-adjustment-gia/

[5] Intergovernmental Panel on Climate Change, Working Group I : *Climate Change 2013: The Physical Science Basis* , Assessment Report 5 , (2013), https://www.ipcc.ch/report/ar5/wg1/

[6] Diagrams and graphics from the Climate Change Initiative of the European Space Agency http://cci.esa.int/

[7] Diagrams and Graphics of the Global Monitoring Division , National Oceanic & Atmospheric Administration, USA https://www.esrl.noaa.gov/gmd/

[8] United States Environmental Protection Agency (EPA): *Atmospheric Concentrations of Greenhouse Gases* , https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases
This is a compilation of data from different research groups. The sources are listed at the very bottom of this website.

[9] J. E. Dore, R. Lukas, D. W. Sadler, M. J. Church, D. M. Karl : *Physical and biogeochemical modulation of ocean acidification in the central North Pacific* , PNAS **106**, 12235 – 12240 (2009), https://doi.org/10.1073/pnas.0906044106

[10] Umweltbundesamt : *Klimawandel und Marine Ökosysteme* (2009), https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3805.pdf

[11] UN Convention on Biological Diversity (ed.) : *An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity* (2014), https://www.cbd.int/doc/publications/cbd-ts-75-en.pdf

[12] Intergovernmental Panel on Climate Change : *Global Warming of 1.5 °C* , Special Report , (2018), https://www.ipcc.ch/sr15/

[13] K. E. Trenberth, J. T. Fasullo, J. Kiel : *Earth's global energy budget* , Bull. Am. Met. Soc. **90**, 311 – 323 (2009), https://doi.org/10.1175/2008BAMS2634.1

[14] Anonymous author : *Black-Body Spectrum* , https://commons.wikimedia.org/wiki/File:BlackbodySpectrum_loglog_de.svg

[15] Johann Wolfgang Goethe : *Zur Farbenlehre* (Cotta, Tübingen, 1810) http://www.deutschestextarchiv.de/book/show/goethe_farbenlehre01_1810

[16] R. A. Rohde : *Spectra of greenhouse gases* , https://commons.wikimedia.org/wiki/File:Atmospheric_Transmission.png
The graphic has been significantly modified for this article.

[17] Intergovernmental Panel on Climate Change, Working Group I : *Climate Change 2021: The Physical Science Basis* , Assessment Report 6 , (2021), https://www.ipcc.ch/report/ar6/wg1/

[18] Intergovernmental Panel on Climate Change : *Climate Change 2023: Synthesis Report* , Assessment Report 6 , (2023), https://www.ipcc.ch/report/ar6/syr/

[19] S. Arrhenius : *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground* , Phil. Mag. Series 5 , **41**, 237 – 276 (1896), https://zs.thulb.uni-jena.de/rsc/viewer/jportal_derivate_00165237/PMS_1896_Bd41_245.tif

[20] Q. Cai, X. Yan, Y. Li, et al. : *Global patterns of human and livestock respiration* , Sci. Rep. **8**, 9278 (2018), https://doi.org/10.1038/s41598-018-27631-7

[21] Y. T. Prairie, C. M. Duarte : *Direct and indirect metabolic CO_2 release by humanity* , Biogeosci. **4**, 215 – 217 (2007), https://doi.org/10.5194/bg-4-215-2007

[22] T. Boden, G. Marland, R. J. Andres : *Global, Regional, and National Fossil-Fuel CO2 Emissions (1751 - 2014)* , CDIAC, Oak Ridge National Laboratory, USA https://doi.org/10.3334/CDIAC/00001_V2017

[23] International Energy Agency : *Global Energy Review 2025*, https://www.iea.org/reports/global-energy-review-2025

[24] *Carbon capture and storage* , Wikipedia , https://en.wikipedia.org/wiki/Carbon_capture_and_storage

[25] UN Climate Change Conference 21: *Action taken by the Conference* , https://unfccc.int/documents/9097

[26] Intergovernmental Panel on Climate Change, Working Group III : *Climate Change 2022: Mitigation of Climate Change* , Assessment Report 6 , (2022), https://www.ipcc.ch/report/ar6/wg3/