Greenhouse gas emissions and their effect on global temperatures

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Introduction

Around 48% of incoming radiation from the sun, largely in the visible spectrum, is absorbed by the surface of the Earth (Fig. 1). The same amount of energy is lost from the surface by evaporation, convection and infrared (thermal) radiation. The latter, around 35% of the total, would be lost to space if it was not for greenhouse gases in the atmosphere, such as water vapour, carbon dioxide (CO_2) and ozone, which absorb the transmitted energy in specific parts of the infrared spectrum, essentially trapping heat. Without these gases, the temperature of the Earth would be in the region of -20°C, similar to the moon (Landrø and Amundsen, 2019a). The greater the concentration of a particular greenhouse gas the greater the amount of heat that is trapped.

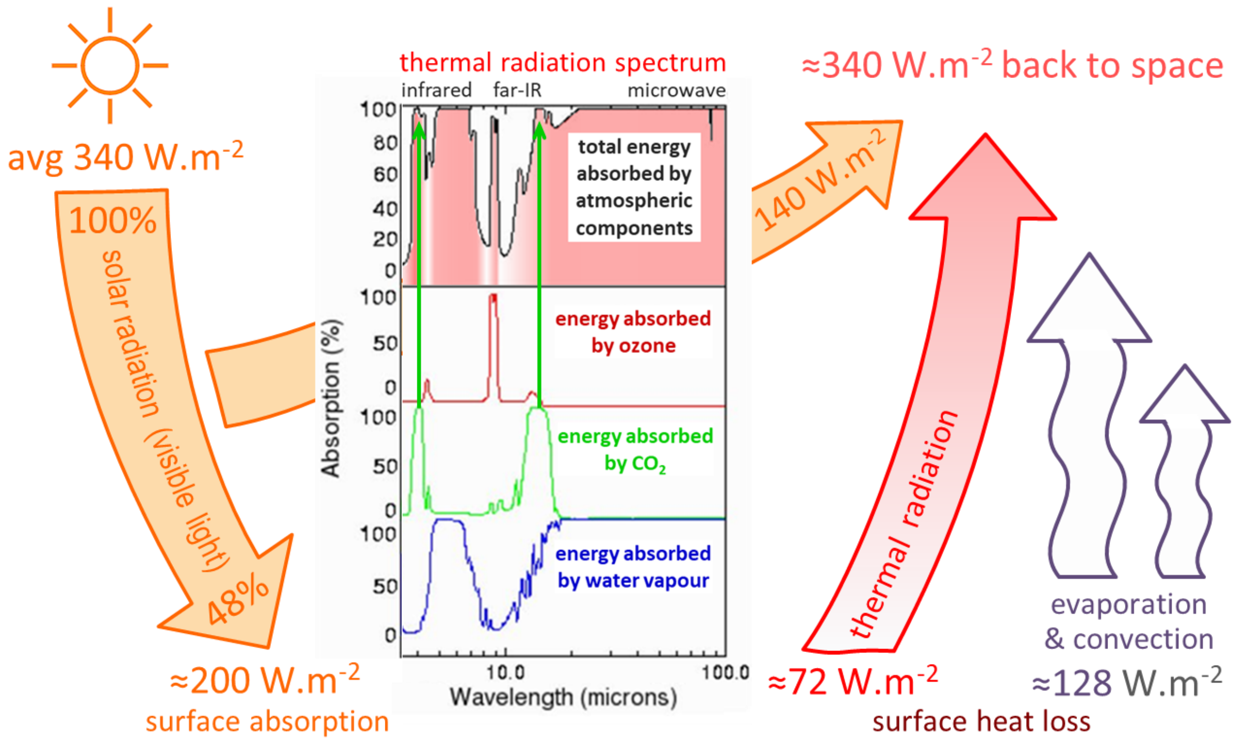

Fig. 1. Conceptual illustration of incoming solar radiation, its partial reflection and its absorption at surface, with subsequent loss as various forms of heat. 17% of the total incoming energy (c.72 W.m^{-2}) is radiated back from the surface as thermal radiation, largely in the infrared spectrum where an increasing proportion is absorbed by greenhouse gases such as carbon dioxide (indicated in green). This means that not all of the incoming solar radiation returns back to space. This is causing temperatures to rise in a process known as radiative forcing. The figure is based on Peixoto and Oort (1992), Lindsey (2009) and Nelson (2011).

Anthropogenic emissions

At the start of the Industrial Revolution around 1850, the average concentration of CO_2 in the atmosphere was approximately 285 ppm based on measurements of air trapped in ice (Fig. 2). Since 1850, the widespread use of fossil fuels, the removal of forests, intensive agricultural and other human activities have resulted in the release of large amounts of greenhouse gases, not just CO_2, but also methane (CH_4), nitrous oxides (e.g. N_2O) and halo-carbons (e.g. CCl_2F_2 or CFC-12). These have had the effect of trapping more infrared (thermal) energy. As a consequence, the near-surface temperature of the Earth has risen from 13.8°C in 1850 by 1.2°C ± 0.1°C so that the global average temperature is now close to 15°C (Fig. 2). The main temperature rise has occurred during the last 70 years (Steffen et al., 2015), accompanied by a rise in CO_2 levels of 103 ppm (Fig. 2).

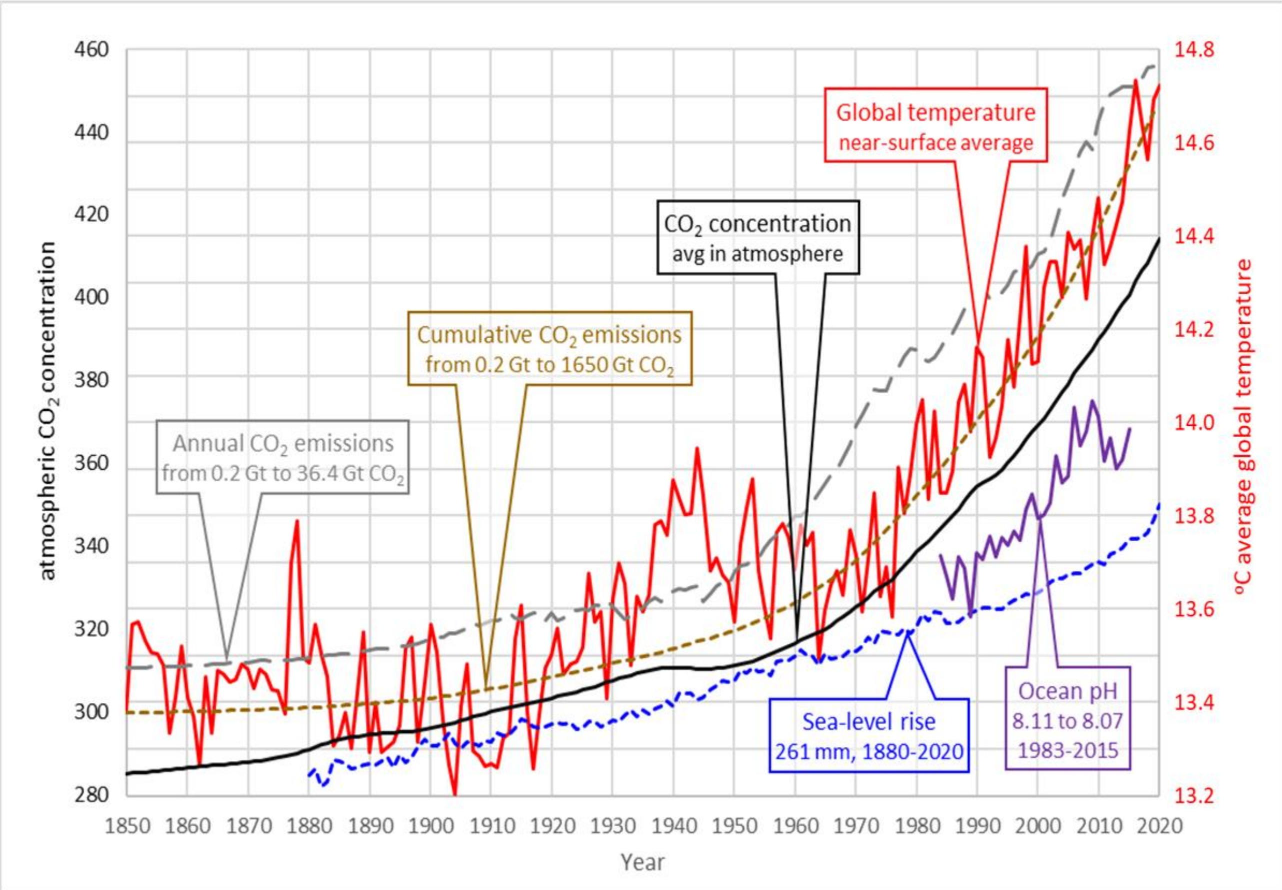

Fig. 2. The 170 year rise in carbon emissions, average atmospheric carbon dioxide concentrations, global temperatures, sea-level height and ocean acidity (from Quirk 2021, with permission). 1850 is the nominal start of the Industrial Revolution when fossil fuels such as coal started to be used in significant amounts. The main sources of the data are NASA Goddard Institute for Space Studies (CO_2 concentration, black curve, left-hand Y axis), Hadley Centre and UEA Climate Research Unit (global temperatures, red curve, right-hand Y axis), Our World in Data after Global Carbon Project (carbon emissions, grey and brown curves) and the US Environmental Protection Agency (sea-level, blue curve, and ocean pH, purple curve).

Of human emissions, CO_2 has had the greatest effect on temperatures by virtue of its relatively high concentration, measured directly to be 414 ppm in 2020. Nonetheless, other gases such as CH_4 and N_2O have a disproportionate effect and therefore the term carbon dioxide equivalent (CO_2e) is used to reflect this, equating to 464 ppm in 2018 according to global data available at https://www.eea.europa.eu/data-and-maps/data/external/greenhouse-gases, 12% higher than the actual CO_2 concentration.

The amount of CO_2e emitted since 1850 is around 2200 Gt (Masson-Delmotte et al., 2018), representing an average of 182 Gt per 0.1°C rise, or 17 Gt CO_2 per 1 ppm increase in the atmospheric concentration of CO_2.

Greenhouse effect

The theory on the effect of greenhouse gases on global temperatures has been understood for more than 125 years (Crawford, 2017). Arrhenius (1896a; 1896b) calculated the cooling or warming effect of decreasing or increasing amounts of carbonic acid (CO_2 plus water vapour) on the amount of infrared radiation absorbed by the atmosphere and came up with similar numbers to current models (Landrø and Amundsen, 2019a; 2019b). Water vapour is a strong greenhouse gas and is naturally occurring in the atmosphere. Although it is likely that the global rise in temperatures will cause water vapour levels to rise, enhancing the greenhouse effect (Dessler et al., 2013), the strength of this type of feedback effect is still being debated.

One of the motivations for Arrhenius' original research was to see if ice ages could be explained by decreases in CO_2. As we now know, the cooler temperatures in the Pleistocene were a result of lower amounts of incoming solar radiation related to changes in the orbital movement of the Earth (Milankovič cycles) which occur on the 25,000-100,000 year time-scale. From 17,000 to 12,000 years BP (before present) global temperatures rose by around 3.5°C (Fig. 3) whilst atmospheric CO_2 concentrations increased by roughly 75 ppm from 190 ppm to 265 ppm (Shakun et al., 2012). The increase in CO_2 was preceded by a rise in temperature of around 0.3°C due to enhanced solar radiation. This rise was enough to cause Antarctic ice to melt and oceanic circulation to change, accompanied by the release of significant amounts of CO_2. Considering the entire event, the warming at the end of the Pleistocene occurred at an average rate of 0.03°C per 50 years, typical of a Milankovič cycle, compared to the current rise of 0.71°C per 50 years (Fig. 3), the Earth's response to a rapid increase in greenhouse gases (Fig. 2).

Different rates of global warming

Another way of comparing Milankovič-driven and emissions-driven warming is to consider the change in CO_2 concentrations per 0.1°C temperature rise. During the late Pleistocene the rate was 2.1 ppm CO_2 per 0.1°C increase (Shakun et al., 2012) whereas since 1950 it has been 10.3 ppm per 0.1°C (Fig. 2). In other words, the anthropogenic impact on climate change is unequivocal (Fig. 3) and, as far as we know, the rate and scale of change is unprecedented in geological history. In comparison, the effect of major volcanic eruptions on climate are minor both in terms of impact and duration (e.g. Gerlach, 2011). In fact aerosols such as sulphur dioxide tend to cause a temporary cooling rather than warming by reflecting more solar radiation (Cole-Dai, 2010).

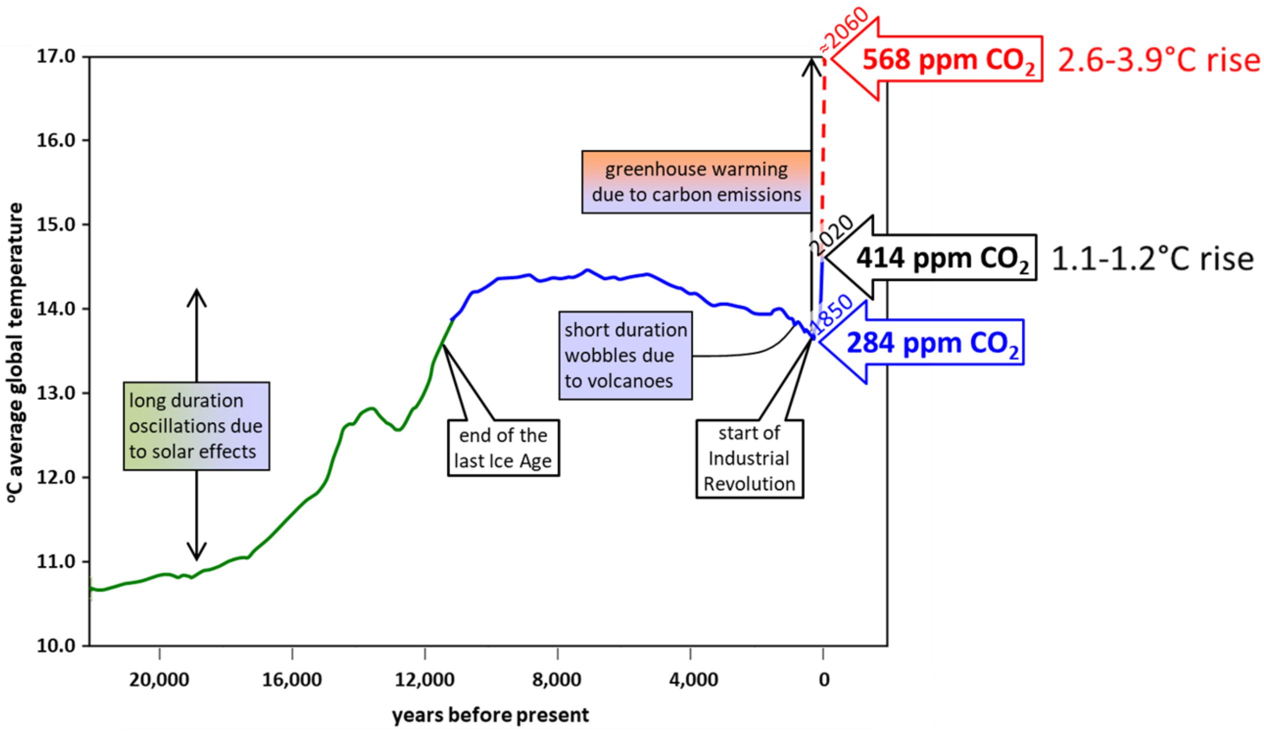

Fig. 3. Figure illustrating the rise in temperature since the late Pleistocene. The sources of the data are as follows: solid green line - Shakun et al. (2012), solid blue line - Marcott et al. (2013), dashed red line model – projection based on synthesis of IPCC models (e.g. IPCC, 2014).

Predictable temperature rise

Using established physical laws (e.g. Landrø and Amundsen, 2019b), a simple 1D model of the effect of CO_2 on near surface temperatures can be built using the formula $\Delta T = T_B.\alpha.ln((C/C_0).e)/(S(1-a))$ where:

ΔT = change in temperature in °K or °C;

T_B = baseline temperature in °K (i.e. 13.8 °C + 273.2);

α = Arrhenius' constant in $W.m^{-2}$, which incorporates the Boltzmann constant;

$ln((C/C_0).e)$ = natural logarithm of the new atmospheric concentration of CO_2 (*C*) proportional to the original (*C_0*) multiplied by an equivalence factor (*e*), accounting for the effect of an increase in other greenhouse gases such as water vapour and methane;

$\alpha.ln((C/C0).e)$ is also known as the radiative forcing factor;

S = solar irradiance constant in $W.m^{-2}$, measured from space;

a = the average albedo (reflectance) of the Earth, as a fraction of 1.

Using inputs shown in Table 1, largely from NASA (e.g. Lindsey, 2009), we can match the historical 1.2°C rise in temperature with this equation, albeit with a range between 0.5°C to 1.5°C. The wide range comes from sensitivities in the values of *e*, the equivalence factor, and *a*, the average albedo. In contrast, uncertainties in the values used for *T_B* (baseline temperature), *α* (Arrhenius' constant) and *S* (solar irradiance constant) only have a relatively minor effect on the results. Although sophisticated 4D climate models are nowadays used to predict future warming (IPCC, 2014), it is revealing that a simple model can still be used to reproduce the historical information on CO_2 concentrations and global temperatures.

best estimate	parameter related to greenhouse warming effect	range
1.10	**$\Delta T = T_B.\alpha.ln(C/C_0)_e/(S(1 - a))$** **°C theoretical temperature change due to rise in $[CO_2]$**	**0.6-1.5**
287.0	T_B - °K Earth's avg baseline temperature (13.8°C)	287-289
5.35	α - constant, $W.m^{-2}$, incl. Stefan Boltzmann's constant, σ	? 5.3-5.4 ?
414.2	C - ppm atmospheric $[CO_2]$ 2020 (NOAA/NASA)	414.7
285.2	C_0 - ppm atmospheric $[CO_2]$, 1850 (Industrial Revolution)	295-275
129.0	ppm change in $[CO_2]$, ($C-C_0$), 1850-2020 (<50% on ΔT)	≥114
1.30	$[CO_2]$ equiv multiplier to represent all anthrop emissions	1.12-1.59
252.3	ppm change in $[CO_2]$ equiv used in $(C/C_0)_e$, 1850-2020	114-205
3.39	$\alpha.ln(C/C_0)_e$ - ΔF, W/m^2 radiative forcing (c.±50% on ΔT)	3.6-4.2
1360.8	S - W/m^2 solar irradiance constant (NASA, from space)	1360-1365
0.35	a - Earth's avg albedo (various, incl. NASA, ±7% on ΔT)	0.25-0.35

Table 1. Calculation of greenhouse effect caused by anthropogenic emissions from 1850 to 2020 (see Fig. 2). Further explanation is provided in the text above.

The current annual rate of greenhouse gas emissions is around 59 Gt CO_2e, of which 38 Gt comes from fossil fuels (UNEP, 2020). At this rate, it will take 9-10 years to add another 550-600 Gt CO_2e to the atmosphere, the estimated remaining budget before temperatures rise beyond the UN's preferred limit of

1.5°C (Masson-Delmotte et al., 2018). A doubling in atmospheric CO_2 since 1850 (an additional 155 ppm) would occur around 2060, associated with at total warming of ≥2.6°C based on a historical rise of 1.2°C with an increase of 284 CO_2 to 414 ppm CO_2 (Fig. 3).

Feedbacks and lag times

What is more worrying when considering climate models is that atmospheric warming cause feedbacks which are not fully accounted for. For example, as ice melts the Earth's albedo decreases and more CH_4, CO_2 and water vapour are released as the land and oceans get warmer, therefore enhancing the greenhouse effect and possibly ultimately leading to a tipping point (e.g. Duffy et al., 2021). Also, the latent heat of fusion involved in melting ice means that there is a certain lag in the time between the onset of warming and the full impact (IPCC, 2019).

Unequal impacts on climate change

There are compelling reasons to reduce emissions but the severity of the challenge becomes clear when the carbon footprint of a modern society is considered. It is easiest to illustrate the problem at the per capita scale. Thus, the average British person is responsible for adding around 17 tonnes (t) of CO_2 to the atmosphere per year from their use of power and vehicles and consumption of food and material products (Tukker et al., 2014). This is considerably more than the direct emissions from within the UK (5.6 t CO_2 in 2019), which are mostly related to energy use, reflecting the fact that manufactured goods are imported from countries where the emissions occur. Even so, the world average carbon dioxide emissions per capita is just under 6 t CO_2, the same as China's. To put 17 t CO_2 in context, this is equivalent to the carbon in 40 barrels of crude oil, in 310,000 cubic feet of gas or in 25 large trees. As an example of the emissions that are often overlooked, the manufacture of one car results in the production of between 15 t and 40 t CO_2, depending on the type of car. In this respect, most electric cars lie at the higher end of this range because the production of lithium-ion batteries has a large environmental impact (Hall and Lutsey, 2018).

Conclusions

Both from theoretical considerations and empirical data, human emissions of greenhouse gases are having an impact on global temperatures. Approximately 2200 Gt CO_2e have been emitted since 1850 causing a rise of around 1.2°C. Another 550-600 Gt CO_2e, equivalent to another 10 years of emissions at current rates, will get us to the aspirational limit of 1.5°C. The developed world is responsible for the majority of these emissions, either directly or indirectly, and it is therefore imperative that countries such as those around the North Sea lead the way in drastically reducing the use of fossil fuels, the main source of emissions.

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