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The physics of the greenhouse effect

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Introduction

Global warming is arguably one of the most pressing scientific issues of the last decades since it impinges directly on societal, economic, and environmental aspects of the world we live in. The fundamentals of the science underlying the forecasting of climate, and anthropogenic climate change, have been published and debated long before making headlines. In fact, the foundation of our understanding about the so-called "greenhouse effect" in relation to the earth's surface temperature is almost two centuries old. The greenhouse effect refers to the radiative process by which a planet's atmosphere warms the surface to a temperature above what it would be without it. The sensitivity of the earth's climate system to changes in atmospheric carbon dioxide (CO_2) was estimated at the end of the nineteenth century with an earlier allusion to a greenhouse effect credited to the French physicist Fourier. The rise of the atmospheric CO_2 concentration was discovered about fifty years ago and the compelling evidence of anthropogenic climate change to global warming stated in the IPCC (2014) report.

The purpose of this short communication is to briefly overview some of the fundamentals behind the natural and anthropogenic greenhouse effect. Some values to quantify the magnitude of the natural and anthropogenic forcings using a simple but physically-based climate model are provided, and conclude with a short acknowledgement of the contributions of the first scientists whose pioneering and seminal works aspired to develop comprehensive numerical models to understand and forecast global warming and its consequences.

The greenhouse effect

The existence of the greenhouse effect was hypothesised by Joseph Fourier in his "*Mémoire sur la température du globe terrestre et des espaces planétaires*" in 1827. Fourier is often considered as one of the scientists behind the discovery of the greenhouse effect, an expression that he did not use but was introduced later. However, his work, even qualitative, shows that he grasped the essential principles of this effect. The evidence was further strengthened by John Tyndall in 1859 who measured the radiative properties of specific gases. The effect was more fully quantified by Svante Arrhenius in 1896 who made the first quantitative prediction of global warming due to a doubling of atmospheric CO_2.

The greenhouse effect refers to the complex phenomena starting with the passage of the sun radiation, referred here to as "short-waves" ($0.1\ \mu m < \lambda < 4\ \mu m$; λ being the wavelength) and the absorption by the surface of the earth, since the troposphere [1] interacts weakly with short-waves. As the surface warms it emits thermal infrared energy, referred here to as "long-waves" ($4\ \mu m < \lambda < 100\ \mu m$) that would reach space if some radiatively active gases, also called greenhouse gases (GHG), were not present to trap the heat and therefore warm the surface.

According to the Stefan-Boltzmann law developed in 1879, based on experimental measurements made by Tyndall, the total energy radiated per unit surface area of a black body across all wavelengths per unit time is directly proportional to the fourth power of its temperature. Also, the Wien displacement law (formulated around 1893) states that the black body radiation curve for different temperatures peaks at a wavelength inversely proportional its temperature. Therefore, the sun maximum energy emission wavelength peaks at around 0.5 μm, whereas all components of the climate system emit radiant energy in the long-wave of the electromagnetic spectrum, at around 10 μm.

All real bodies emit and absorb less radiant energy than the theoretical black body at the same temperature and wavelength. The ratio between radiant energy between a real and a black body defines its emissivity, ϵ, and therefore, its absorptivity. In the heat transfer field of study, Kirchhoff's law (circa 1860) of thermal radiation states that both properties are less than 1 and vary with wavelength. The range of variation of emissivity with wavelength is large for gases. Monoatomic gases absorb and emit radiant energy in very distinct spectral absorption lines resulting from quantized changes in electronic states. But, molecular gases produce spectral absorption and emission bands formed by a large number of very close lines. The location and strength of these bands depend on the molecular structure of the gas. Therefore, atmospheric absorptivity varies greatly with wavelength and has highly irregular and discontinuous patterns.

At the ground level, the variety of surface types has different broadband emissivities ϵ, e.g. 0.97 for open waters and 0.98 for vegetation. The net effect of the absorption and emission spectrum for long-wave terrestrial radiation in the troposphere results from the superposition of the absorption spectra for the entire vertical column of individual constituents of the atmosphere. Thermal vibrations and rotations of the molecules produce emission and absorption spectra with emissivity less than 1. The spectral distributions are explained by the fundamental principles of atomic physics and quantum mechanics, involving quantum-mechanical selection rules whose details is beyond the scope of this communication. The emission spectra of molecules are far more complex than those of atoms because they have more degrees of freedom. Diatomic molecules such as N_2 and O_2, composing more than 99% of the air, have no electric dipoles and therefore no vibrational or rotational spectra, but mainly electronic transition with emission and absorption spectra in the ultraviolet and visible bands of the solar spectrum. The principal atmospheric gases that are radiatively active in the long-waves are "greenhouse gases".

The basic quantitative information on absorption spectra comes from laboratory experiments. To represent the effects of GHG in numerical models for weather prediction and climate simulation, knowledge of infrared absorption spectra for each gas is required. The most abundant greenhouse gas in the atmosphere is water vapour (H_2O) having rotational and vibrational states leading to complex and irregular absorption. It has a rotational band starting at 14

1 Troposphere: the lowest layer of the atmosphere where almost all weather phenomena take place. It contains approximately 75% of the atmosphere's mass and 99% of the total mass of water vapour and aerosols. The average depths of the troposphere are 17 km (~100 hPa) in the Tropics to 10 km (~250 hPa) in Polar regions. The tropopause meanwhile is the boundary between the troposphere and the stratosphere.

μm and centered at 65 μm, and several vibrational-rotational in the 1 μm - 8 μm band. Carbon dioxide (CO_2), which is naturally present in Earth's atmosphere but its concentration rose from pre-industrial levels of 280 ppmv to about 410 ppmv (July 2018; NOAA); with the increase mainly due to the use of fossil fuels and deforestation. Because CO_2 is a linear and symmetric molecule it only has vibrational bands causing absorption showing maxima at 2 μm, 3 μm and 4 μm, and in the 13 μm - 17 μm region. Ozone (O_3), which is abundant in the stratosphere, contributes to the absorption of long-wave radiation through vibrational-rotational states centered at 9.6 μm. Methane (CH_4) is another important greenhouse gas. Since it has even more atoms, its vibrations are complicated and centered around 7 μm. We should also mention that nitrous oxides (N_2O), plus a collection of man-made gases with more than 2 atoms also play a role. In the 8 μm - 12 μm region the atmosphere is almost transparent for long-wave terrestrial radiation in the absence of clouds, with the exception of the absorption by ozone. Interestingly enough, through absorption in this region, small increases of GHG may have a large impact on the climate.

Equilibrium of the global climatic system is achieved in the long term, so the short-wave radiation absorbed by the Earth and the atmosphere is returned back to space as long-wave radiation because practically all the energy exchange between the earth and outer space is achieved through radiative transfer. Therefore, in order to better understand the greenhouse effect, we first examine the global Earth's radiation balance at the top of the atmosphere (TOA) [2].

Radiation balance of the earth: a simple model

Meteorological satellites made significant scientific contributions to the measurements of the radiation budget in both the short-wave input and the long-wave output at TOA. Measurements of the planetary albedo [3], i.e. a mixture effect of surface and atmospheric reflection at TOA, combined with incoming solar radiation at TOA form the first component of the radiation budget. These indicate that the solar constant I_o is about 1370 Wm^{-2} and a planetary broadband albedo α of 30%, with contributions of about 26% from the atmosphere (air, clouds, and aerosols) and 4% from the surface. Long-wave radiation coming from outer space is not significant so only the emission by the earth-atmosphere system $R_L^{\uparrow}$ is considered. The earth is in radiative equilibrium so that the integration of the short-wave input minus that of the long-wave output at TOA approximately vanishes on the long term to produce a global all wave net radiation budget R_n close to zero, consequently

$$R_n = \frac{I_o}{4}(1-\alpha) - R_L^{\uparrow} \approx 0 \qquad (1)$$

with the factor one quarter coming from the integration over a disk for the short-wave and over a sphere for the long-wave radiation. If $R_n \neq 0$, the global Earth-atmosphere system would be subject to cooling or heating. With the accuracy of actual measurements this does not seem to be the case. The first term on the left hand side of ≈ in Eq. (1) is about 239.8 Wm^{-2}, a useful reference value for the study of the energetics of the global climate system. If we suppose that the global Earth-atmosphere system behaves like a black body, then T_e defines the effective radiating temperature computed using the Stefan-Boltzmann law as $R_L^{\uparrow} = \sigma T_e^4 = 239.8\ Wm^{-2}$, where σ is the Stefan-Boltzmann constant equal to 5.67×10^{-8} $Wm^{-2}K^{-4}$, so that T_e = 255 K or about -18°C, and that is the temperature at which satellites see the top of the atmosphere emitting long-wave radiation to space. Because the atmosphere emits in specific wavelength bands, the emission departs significantly from that of a black body.

An appraisal of the global greenhouse effect

Due to the existence of an atmosphere with greenhouse gases that absorb and emit in the long-wave spectrum, the global average surface temperature, T_{sfc}, is greater than it would be if the atmosphere were transparent with regards to the long-wave radiation, formally:

2 Top of the atmosphere: the actual altitude used for calculations varies depending on what parameter or specification is being analysed. For example, in radiation budget, TOA is considered ~20 km because above that altitude the optical mass of the atmosphere is negligible.

3 Albedo: the measure of the diffuse reflection of solar radiation out of the total solar radiation received by the Earth.

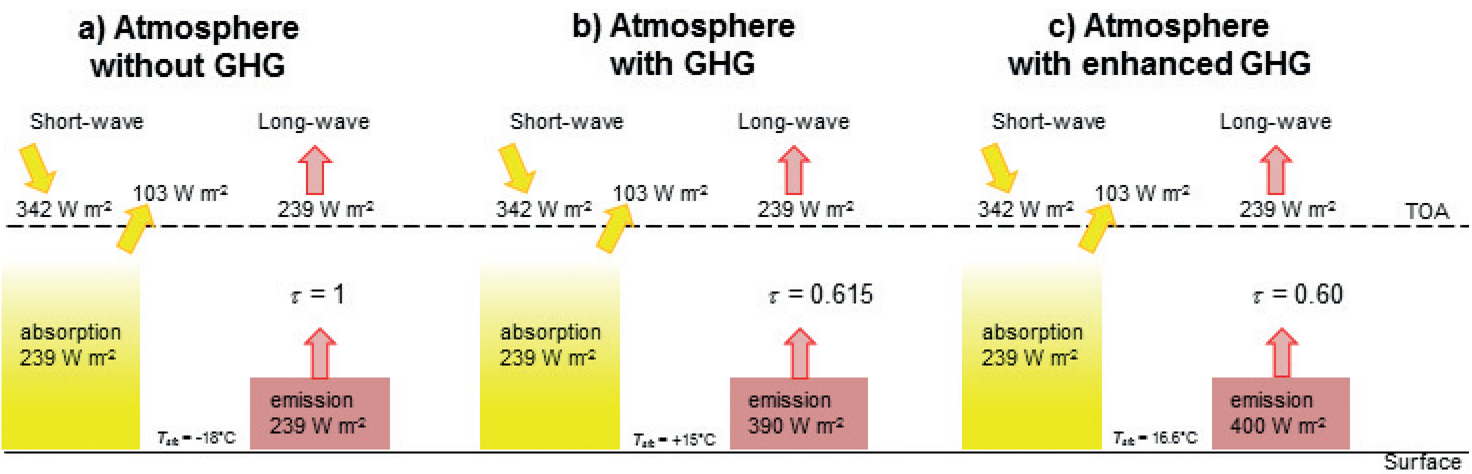

Figure 1. Schematic comparing short-wave and long-wave fluxes, atmospheric transmissivity in the long-wave, τ, and the global average surface temperature, T_{sfc}, at equilibrium for : a) an hypothetic earth's atmosphere without GHG, τ = 1 and T_{sfc} = -18°C; b) an atmosphere with GHG representative to that of the second half of the 20th century, τ = 0.615 and T_{sfc} = +15°C; c) an atmosphere with enhanced man-made GHG, τ = 0.60 and T_{sfc} = +16.6°C. The assumption made to estimate the magnitude of the greenhouse effect and its enhancement is that the same amount of short-wave is absorbed at the global earth-atmosphere system in each case based on Eq. (3).

$$T_{sfc} = T_e + \Delta T \qquad (2)$$

Long term meteorological observations indicate that the global average surface temperature is about 15°C. The value ΔT of 33°C in Eq. 2 is attributed to the greenhouse effect. At a temperature of 15°C, the surface emits 390 Wm^{-2} on the global average, whereas satellite measurements indicate that only 239.8 Wm^{-2} escape to space (see Fig 1b). The difference, termed G, between the surface emission and the total energy loss of about 150 Wm^{-2} is a metric for the greenhouse effect. The energy budget at TOA can also be characterised by an effective transmissivity factor of the atmosphere in the long-wave spectrum, τ, by connecting the absorbed solar radiation to the Earth's surface temperature using the following model

$$R_n = \frac{I_o}{4}(1-\alpha) - \varepsilon\tau\sigma T_{sfc}^4 = 0 \qquad (3)$$

therefore $\epsilon\tau$ = 0.61. Thus more efficient heat trapping in the long-wave, i.e. lower τ, produces higher T_{sfc} for given I_o and α. The contributions to the greenhouse effect on Earth are about 50% due to water vapour, 25% due to clouds, 19% due to CO_2, and 7% due to other GHG. From Eq. (3), one can easily note that if the earth's atmosphere is devoid of GHG as shown in Fig 1a, $\tau \rightarrow 1$ and the surface temperature tends to T_e. One may also show using a simple 2- layer radiative model that with an absorbing atmosphere in the long-wave, the surface temperature would be much higher than that of the atmosphere and the resulting temperature profile would be unstable. Thus, air parcels disturbed from a location close to the surface would be turbulent and carry energy upwards through sensible and latent heat fluxes. These turbulent fluxes mix the lower atmosphere and produce a lapse rate such as that observed on the global average.

The anthropogenic contribution to the greenhouse effect

Charles Keeling set up an infrared spectroscope measuring atmospheric CO_2 at the Mauna Loa Observatory and later published his results (Keeling et al., 1976); this paper revealed for the first time the measurable increase in the atmospheric CO_2 as a result of the combustion of fossil fuels.

If the atmospheric concentration of CO_2 increases, the global mean direct radiative forcing of the surface-atmosphere system first results in the reduction of the TOA long-wave flux causing stronger infrared trapping holding all the other climate parameters fixed, such as I_o and α in Eq. (3). This is strictly an enhanced greenhouse effect above that occurring due to natural GHG concentrations as the atmosphere is more opaque in the long-waves.

Due to its major role in the global warming, let's focus on the CO_2 forcing [4]. Radiative calculations lead to an evaluation of perturbation in the long-wave emission to outer space with a change in the CO_2 concentration and yield a value of about -4 Wm^{-2} for a doubling of the atmospheric concentration of CO_2 (e.g. Dickinson and Cicerone, 1986). In other words, if the CO_2 is abruptly doubled, the long-wave flux would decrease by about 4 Wm^{-2} at the tropopause with heating increasing by the equivalent radiative forcing of 4 Wm^{-2}. According to the simple model (Eq. (3)), the climate system will re-establish a radiation balance by warming up the surface and the troposphere until it re-emits to space the excess 4 Wm^{-2}. The increase in long-wave emission induced by higher temperature balances its decrease caused by the lower value of τ, or likewise by the increase in atmospheric emissivity. Figure 2 shows the variation of the global average temperature as a function of the long-wave transmissivity using Eq. (3) and shows warming with increasing CO_2 (also shown in Fig. 1c). This simple analysis ignores the stratosphere which in fact will cool because of the increased CO_2 infrared emission. Although this does not alter the overall results described above and therefore will not be addressed here.

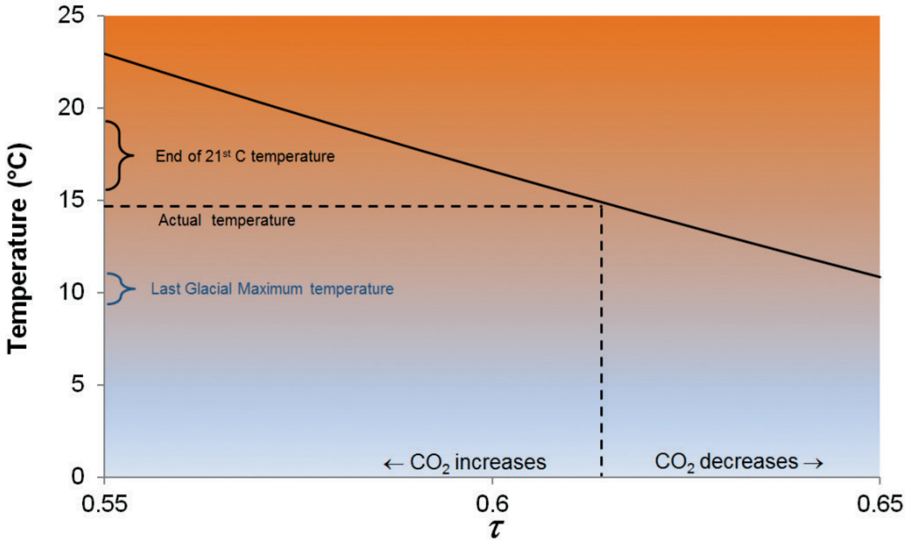

Figure 2. Global mean surface temperature as a function of atmospheric long-wave transmissivity τ. Actual conditions are depicted by the black dashed lines. As the CO_2 increases, long-wave opacity increases, i.e. transmissivity decreases and the surface warms up. By the end of the 21st century, the temperature will depend much on the emission scenario (e.g. IPCC 2014) but the CO_2 concentration will presumably be much more than twice the amount of pre-industrial period. Also shown, the last Glacial Maximum temperature for comparison.

Feedback effects ensuing from the anthropogenic greenhouse effect

The global mean earth's surface temperature may be regarded as one of the responses of the climate system to forcings taking into consideration possible internal feedbacks. In fact, there are a large number of non-linear mechanisms operating within the various components of the climate system and subsystems. Actually, there are many positive and negative feedback mechanisms and there is compensation between them in the mean to prevent from a runaway situation such as that which presumably happened on Venus. There are some approaches published in the scientific literature to get some insight into the complex feedback mechanisms (Schlesinger 1988). Without going into the details, only a few examples can be given in this com-

4 Forcing: the change in net (down minus up) irradiance (solar plus longwave; in Wm^{-2}) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values. Radiative forcing is used to assess and compare the anthropogenic and natural drivers of climate change IPCC (2014).

munication to provide for some hints as to how the climate system reacts to a given perturbation. As described above, the infrared loss at TOA depends on the CO_2 concentration and the atmospheric temperature, but also on water vapour content because of the evaporation feedback with the inclusion of other known non-linear effects such as the temperature-albedo feedback. The simple model described above (Eq. 3) does not include feedback mechanisms and the direct radiative response is clearly positive with a sensitivity of 0.3 $KW^{-1}m^2$ at 288 K (15°C). The increase of GHG induces a positive feedback. The water vapour-greenhouse effect induces a positive feedback contribution due to the non-linear relation of the air moisture and temperature through the Clausius-Clapeyron equation which is a non-linear equation describing the rate of increase in vapour pressure per unit increase in temperature. An increase in temperature causes a melting of sea ice and snow cover that lowers the albedo and thereby increases the absorbed short-wave radiation, the whole process amplifying the surface warming, and thus producing positive feedback. On the other hand, the temperature long-wave radiation coupling in the atmosphere produces a negative feedback; as the temperature increases the atmosphere will loose more long-wave radiation to space thus reducing the temperature and thus weakening the initial perturbation. One should mention that cloud feedback is one of the largest sources of uncertainty in the theory of climate change. Clouds and aerosols reflect the incoming short-waves (parasol effect through the modulation of the planetary albedo) and absorb the long-waves emitted by the surface and emit energy to space from colder cloud tops (greenhouse effect). Therefore, while this greenhouse effect of clouds warms the planet, the albedo effect cools it. Modern three-dimensional numerical global climate models predict global warming of more than 2°C by the end of the XXI century depending on the GHG emission scenario (IPCC, 2014). Therefore, the climate system sensitivity with regards to GHG would be more than 0.3 $KW^{-1}m^2$, presumably in the range of 0.4 – 1.25 $KW^{-1}m^2$ due to numerous feedback processes. This shows the complexity of what might be an initial CO_2 forcing on the subtle energy balance of the earth-atmosphere system.

Conclusions

The physical processes of the greenhouse effect may be synthesised as follows: the incoming solar energy warms the surface, which in response to short-wave absorption emits long-wave energy that is then partially trapped by GHG primarily composed of water vapour and CO_2, with a smaller (< 5%) contribution from O_3, N_2O and CH_4, due to the interaction with the long-wave emission originating from the surface. Clouds also contribute significantly to the natural greenhouse effect. Several anthropogenic gases, however, such as the halocarbons also contribute. Tropospheric temperatures decrease with height, so that the GHG absorb more upward radiative flux than they emit upwards, consequently the metric *G* is positive. The net result of these absorption and emission processes is that part of the infrared radiation emitted by the surface is trapped, forces increased convection, and acts to warm the troposphere and surface until the long-wave emission to space balances the net incoming short-wave.

Following the seminal works undertaken more than a century ago, the development of the greenhouse theory reached higher rungs in the knowledge ladder. But as is often the case, many early works have been only valued in hindsight. Callendar in 1938 linked the increase in CO_2 concentration over the previous fifty years to rising temperatures. Plass (1956) calculated that the mean global surface temperature would increase by approx. 3.6°C if atmospheric carbon dioxide were to double. Möller (1963) provided the first model attempt and advocated that water vapour might also act as a positive climate feedback mechanism. The pioneering effort by Manabe and Wetherald (1967) provided quantitative results for carbon dioxide induced warming on the basis of a numerical one-dimensional radiative-convective model. One of the most significant advances in the CO_2 warming was the pioneering development by Manabe and Wetherald in early 1970s of a three-dimensional global climatic model. Since then, these models have increased the complexity and the reliability of their simulations allowing for the analysis of the impacts of global warming at a fine spatial resolution in order to address the most pressing issues for the decades to come, as presented in the numerous IPCC reports. The history of this sensational journey in research is presented by Weart (2008) and in a collection of papers in Archer and Pierrehumbert (2011).

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