Annex A - Why don't complete radiation balance diagrams allow us to reason qualitatively about the influence of CO2?

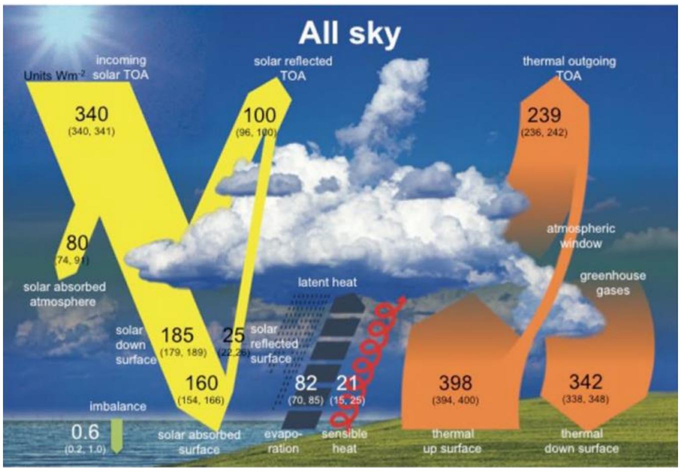


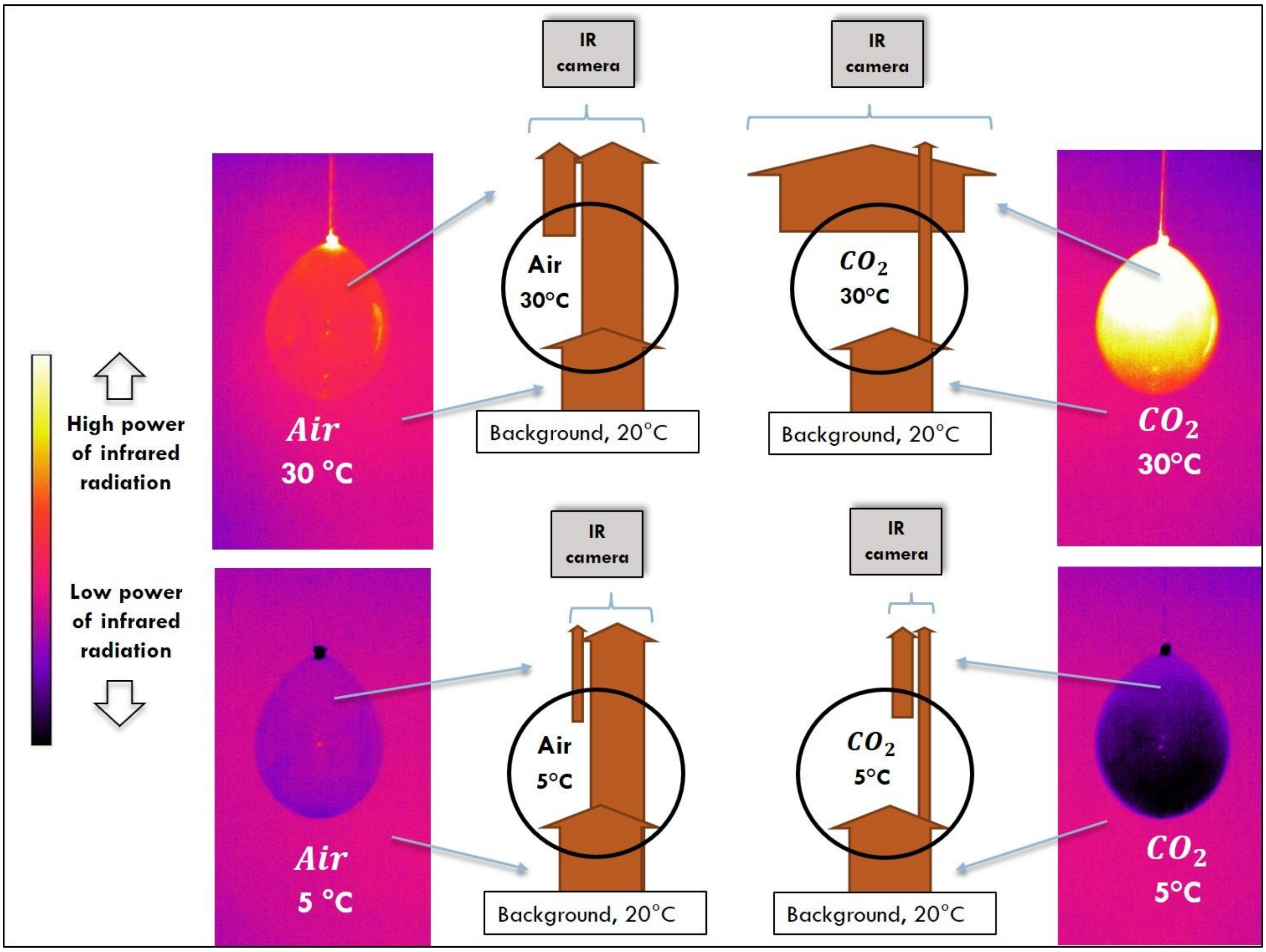
Diagram taken from Figure 7.2 of the 6th IPCC report, chapter 7, p.7-177. Values correspond to power in W/m². The pairs of values in brackets represent the uncertainty interval.

Although this diagram is very useful for understanding all the phenomena at play in the atmosphere, it does not, however, allow for valid reasoning on the effect of the increase in GHGs on global temperature. This representation effectively involves reasoning in parallel about the energy balance of the earth's surface and that of the atmosphere. However, the addition of GHGs has simultaneous, different and non-obvious consequences on the evolution of the three infrared powers involved in these two balances (the three orange arrows). In particular, for the infrared power emitted by the entire atmosphere towards the ground (right-hand arrow), more GHGs imply both more infrared emission and more absorption by the lower layers of the atmosphere. How, then, can we know whether the infrared power reaching the Earth's surface should ultimately increase or decrease when GHGs are added? This requires taking into account the dependence of emitted and absorbed infrared power on GHG concentration and temperature, both of which vary with altitude. At this stage, qualitative reasoning on the complete diagram is no longer technically possible, and indeed climate physicists do not need it, because they directly simulate all the phenomena taking place simultaneously in the atmosphere, taking into account all the dependencies between physical quantities.

When we want to reason qualitatively, by limiting the analysis to the radiation balance between the Earth system and Space [show diagram again], it is possible to develop a simpler and more coherent reasoning, without needing to take into account *or neglect* all the other phenomena. Furthermore, from an academic point of view, the definition of the extent of the greenhouse effect in IPCC reports does not directly involve either the absorption of infrared radiation by the atmosphere or the radiation emitted by the atmosphere towards the surface. The choice of a radiation balance restricted to the top of the atmosphere is therefore also closer to the official definition of the greenhouse effect.

Appendix B: Detailed interpretation of infrared images of hot and cold balloons

The infrared power measured for hot and cold balloons is the result of several components. Below we show the proportions of radiation emitted by the balloon (membrane + gas) and radiation transmitted by the balloon from the bottom.



In this representation, the radiation coming from the room, arriving at the camera by reflection from the membrane, is not shown, as it is the same in each case. For the component of radiation emitted by the balloon, there is no distinction between what is emitted by the membrane and what is emitted by the gas inside. When comparing air and CO balloons$_2$ at the same temperature, the difference can only be attributed to the parameter that changes: the nature of the gas (the component emitted by the membrane is the same in both cases, since it is at the same temperature). Finally, this representation requires the assumption that the absorption capacity (width of the transmitted arrow) does not depend on temperature (which is true for this temperature difference, but cannot be justified in this context). In the case of the cold CO_2 balloon, the fact that the outgoing radiation power is lower is therefore due to two phenomena: greater absorption of background radiation (less transmission) and lower emission, due to the lower temperature of the CO_2 . In the search for a minimalist explanation of the phenomenon, this more precise interpretation is not necessarily necessary for the rest of the reasoning, for the analogy with the Earth system. It is, however, necessary in order to respond to the "saturation argument" detailed above, in which the phenomenon of emission and its dependence on temperature is omitted. This is why it has been chosen, in the proposed logical structure, to demonstrate this phenomenon with the hot CO_2 balloon, even though it is not directly necessary for the rest of the reasoning.

Appendix C: Justification for extrapolating balloon observations to the atmosphere

A key stage in the proposed construction logic consists of extrapolating the influence of adding CO_2 to the atmosphere on the Earth's radiation balance, based on infrared observations of cold air and CO balloons$_2$. This extrapolation requires the potential effect of other characteristics of the atmosphere to be considered, in relation to the situation of the balloons. These justifications take up the central points developed in the content analysis section.

The first difference is the difference in concentration: 0.04% of CO_2 in the atmosphere, compared with 100% in the balloon. Taking into account the large difference in the volume of gas passed through in the two cases, we can determine that the balloon contains approximately 26g of CO_2 , whereas a vertical column of atmosphere 30cm in diameter contains approximately 424g. The addition of a balloon of CO_2 is therefore equivalent to the increase in the quantity of CO_2 in a column of atmosphere in around 10 years (between 2014 and 2024)[1] . Based on this comparison, we can see some important differences between the column and the balloon. In the atmospheric column :

1) The temperature and pressure of CO_2 decrease with altitude (whereas they are homogeneous in the balloon).
2) The atmospheric column also contains water vapour, which interacts with the same range of infrared radiation as CO $_2$
3) Adding 26g of CO_2 to the column increases its quantity from 424g to 450g, while the quantity in the flask increases from 0g to 26g.
4) The increase in the quantity of CO_2 in the atmosphere is gradual, whereas it is immediate when the balloon is added.

What influence could these different points have on the variation in outgoing infrared power to Space?

1) Effect of temperature and pressure gradient

Firstly, we can consider the influence of the temperature gradient in the column of atmosphere. A possible analogy is to imagine a superposition of increasingly cold balloons of CO_2 . As each balloon is colder than the previous one, the outgoing infrared power is a little lower after each new balloon encountered (from bottom to top). The temperature gradient therefore does not change the qualitative conclusion obtained with a balloon of homogeneous temperature (colder than the bottom): a drop in outgoing infrared power. However, this analogy does not take into account the

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[1] From the total mass of CO_2 in the atmosphere, we obtain the value of 6kg of CO_2 for a vertical column of atmosphere of 1m². A column 30cm in diameter (3.14 x 15² cm²) therefore contains 424g of CO_2 . Taking 14 litres as the volume of a 30cm diameter flask, we obtain 26g of CO_2 in the flask (1.87g/litres). The complete column of atmosphere therefore contains the same quantity of CO_2 as in 16 balloons of CO_2 . Since the quantity of CO_2 in the air balloon is negligible, the drop in infrared radiation leaving the cold CO_2 balloon is therefore due to the presence of 26g of additional (colder) CO_2 in its path. In the case of today's atmosphere, an increase of 26g of CO_2 in a column already containing 424g would correspond to an increase in concentration of around 6%, i.e. between 2014 and 2024 (according to the CO evolution curve$_2$: https://ourworldindata.org/grapher/global-co2-concentration).

decrease in pressure with altitude in the atmospheric column. Physically, the effect of the decrease in pressure is that the same mass of CO_2 absorbs less, but still continues to absorb. The qualitative conclusion is therefore once again the same as in the absence of a pressure gradient.

2) Presence of water vapour

Another major difference in the atmospheric column is the presence of other GHGs, in particular water vapour, which also absorbs infrared radiation over a wavelength range that partly overlaps that of CO_2 . As we have seen, water vapour is located in the lower atmosphere. Using the analogy of superimposed balloons, this would mean that water vapour is essentially present in the first balloons. However, the balloons above (containing only CO_2) are colder, as they are higher up. The infrared power coming out of these balloons is therefore lower than that coming out of the first balloons containing water vapour.

3) Saturation of the effect of CO_2 with its quantity

With the addition of a balloon, the radiation passes through 0 to 25g of CO_2 , compared with 424 to 450g in the case of a column of atmosphere. It might be assumed that above a certain quantity of CO_2 , the effect would be saturated, i.e. that the change from 424 to 450g would no longer have any influence on the drop in infrared power, even though one is observed when we go from 0 to 25g. However, as we saw in the content analysis section, this saturation effect only occurs in the presence of water vapour. In other words, in the previous analogy, for CO_2 balloons above those containing water vapour, adding an extra one would have the effect of reducing the outgoing infrared power, despite the quantity of CO_2 already present. This implication therefore remains qualitatively valid for an addition of CO_2 in a column of atmosphere, since it is distributed over the entire thickness, and therefore also above the water vapour.

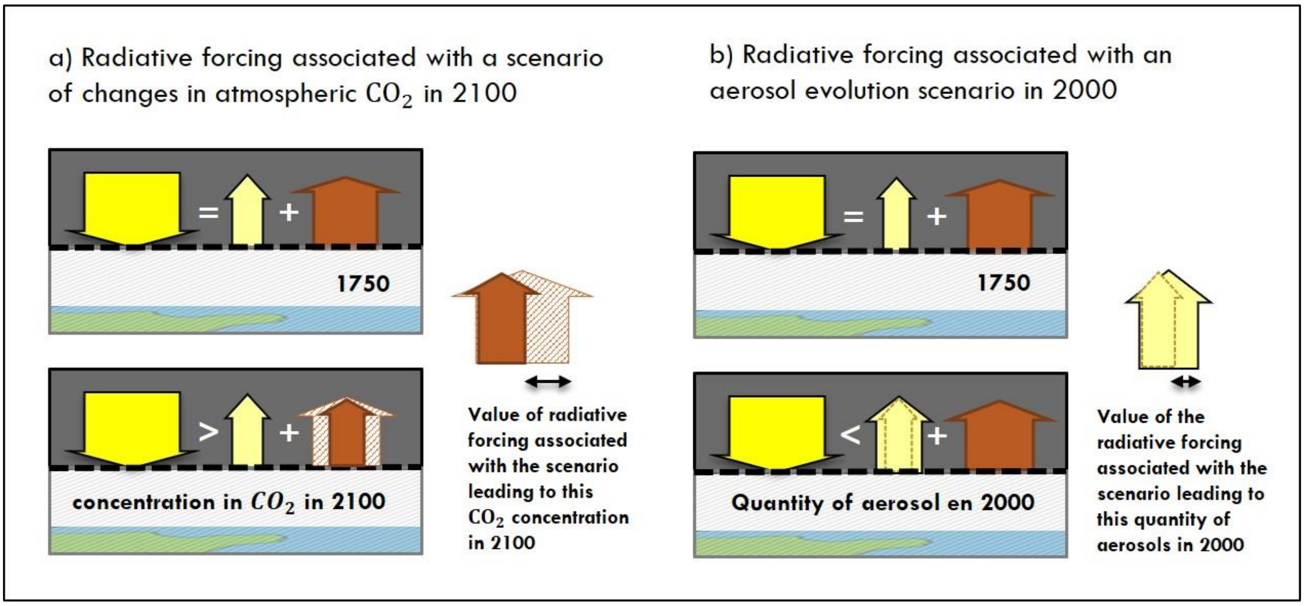
4) Gradual or instantaneous addition of CO_2

The final difference considered here between the addition of a balloon of CO_2 and the increase in its concentration in the atmosphere, and that in the latter occurs gradually, implying a progressive adjustment of the radiation powers involved in the balance. This continuous increase in concentration can, however, be modelled as a sum of small discontinuous increases, each of which would imply a small decrease in outgoing radiation, and thus a small rise in temperature.
In addition, the "one-off" addition of a certain quantity of CO_2 in the case of the balloon, and the representation of the drop in outgoing infrared power at that moment, can provide a definition of the concept of "radiative forcing" for non-specialists. For example, the radiative forcing associated with a CO evolution scenario$_2$ in 2100 can be obtained from the following calculation (see case a) in figure 23):

- The reference situation is 1750, where the incoming and outgoing radiation powers are equal.
- At a stroke, we replace the concentration of CO_2 by the value it would have in 2100, according to a certain scenario.

- At this point, the outgoing infrared radiation power decreases. The difference between the incoming and outgoing power corresponds to the "radiative forcing" in 2100 associated with this CO evolution scenario .$_2$

Using the same logic, we can define the radiative forcing associated with the change in any variable which has an influence on the radiation budget, at any time. Starting from a balanced budget, all we have to do is instantaneously replace the value of this variable at that moment (see case b) in figure 23, for the radiative forcing associated with aerosols in 2000).



This representation makes it possible to provide a definition of radiative forcing that is compatible with that used in climate physics. which is not the case with the definition given in the science curriculum for the final year of secondary school in France, or in many other popularisation resources, such as the Climate Fresk. Radiative forcing is defined as "the difference between the radiative energy received and the radiative energy emitted", without reference to temporality, which suggests a priori that it is a difference at a given moment. This definition, which corresponds in physics to that of "radiative imbalance", gives the idea - wrongly - that radiative forcing could be a measurable physical quantity. However, this is not the case, since its definition implies the effect of an instantaneous variation in the value of the parameter in question, even though its evolution is almost always progressive (except possibly in the case of a volcanic eruption). As we saw earlier, a gradual change in a parameter implies a gradual rebalancing of the radiation balance, so the notion of "radiative forcing" does not generally correspond to a measurable value, even indirectly. The usefulness of this quantity is that it allows the effect of several parameters to be compared in the same unit, using the same calculation rule. A more detailed presentation of the concept of radiative forcing is given in 'Horizons Climatiques' (Dion & Henrion, 2024, p68-70), following a collective reflection between the authors of the comic and this article.