The current Global Climate Models (GCMs) divide the Earth's atmosphere into multiple stacked 3-dimensional grid boxes.

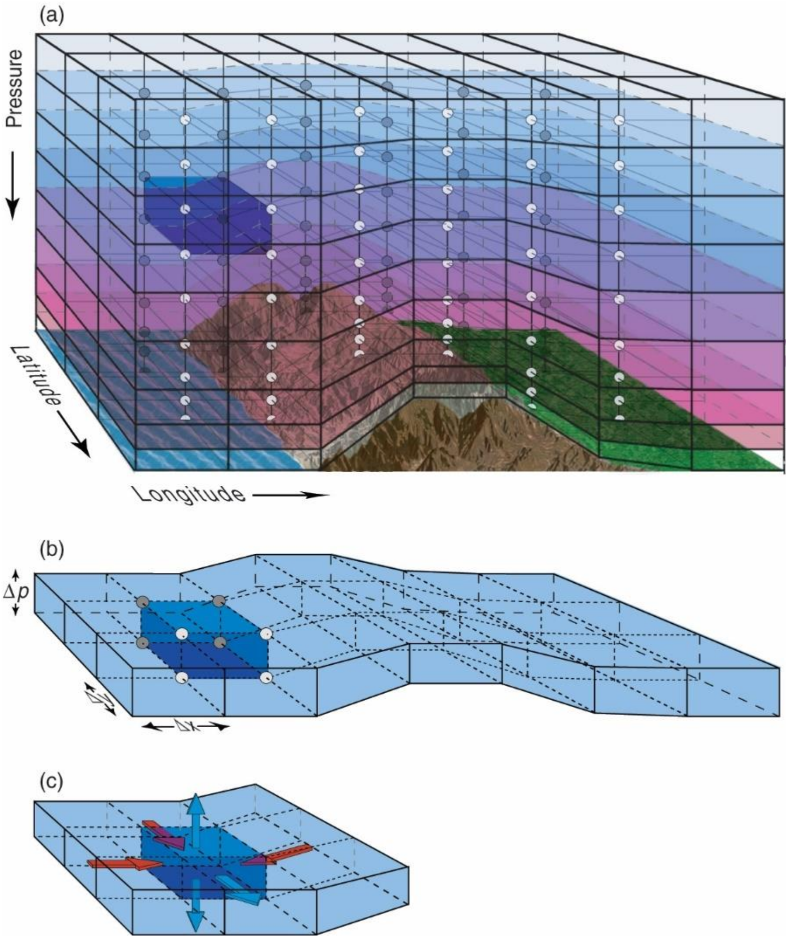

Figure 1. A schematic illustrating how GCMs divide the Earth's atmosphere into multiple stacked 3-dimensional grid boxes. Taken from J. David Neelin's 2011 book - Fig 5.1

The distance up to the lower stratosphere is only 25-35km, but the distance from the equator to the poles is exactly 10,000km (the kilometre was originally defined as "1/10,000 times the distance from the equator to the North pole"!). However, because 99% of the mass of the atmosphere is contained in the troposphere/tropopause/stratosphere, and because modellers are mostly interested in the troposphere (where we live), the models split the atmosphere vertically into very small distances, e.g., 1-2 km. On the other hand, if the models were to apply that resolution horizontally, the computational power required would be astronomically larger than present. Instead, the model horizontal resolution is only about 150-250km.

The current Global Climate Models are built on the framework developed by Elsasser, 1942's Harvard monograph, "Heat Transfer by Infrared Radiation in the Atmosphere" – freely available to download here: https://archive.org/details/ElsasserFull1942

Elsasser seems to have been working within the paradigm of assuming that the atmospheric temperature profile is heavily determined by radiative fluxes. He therefore developed his framework without ever bothering to experimentally test whether or not this was a valid assumption. Instead, it was just an implicit assumption, and his interest was in determining how you would solve (from first principles) the “radiative transfer problem”, i.e., how radiative fluxes within the atmosphere influence (and determine) the atmospheric temperature profile.

In Section 1 of his monograph, he makes several assumptions and approximations. Some of these are reasonable and correct. Others seemed reasonable, but we are now finding that they turn out to have been incorrect.

The early climate modelling groups used Elsasser’s framework as their starting point for their “radiative physics” components (sometimes called “the physics module”). The current climate models used those earlier models as their starting point. In this way, the atmospheric physics used by the climate science community are to this day heavily influenced by Elsasser – even if most modern climate scientists probably haven’t even read Elsasser, 1942. One of the consequences of Elsasser’s influence is the way in which technical discussions on atmospheric physics often refer to “Kirchoff’s laws” (as opposed to Einstein’s more comprehensive and accurate laws on radiation) and Schwarzschild's equation.

The influence of CO2 on atmospheric temperatures in the GCM world is a natural consequence of Elsasser’s framework. The exact influence, e.g., climate sensitivity, comes down to how it is implemented and the various feedbacks, parameterisations, adjustments, etc. But, the fact that CO2 causes the model world’s troposphere to heat and the model world’s stratosphere to cool is inevitable under Elsasser’s framework.

However, is Elsasser’s framework an accurate way to describe what is happening in the real world? Empirically, we are finding that is NOT. But, what specifically is wrong with the framework? This was not immediately obvious to us, as the assumptions and approximations Elsasser used initially seemed reasonable. But, the realisation that there was something empirically wrong with his framework prompted us to look carefully, line by line.

On careful inspection, we identified several key assumptions that we now realise are wrong **and** inappropriate. Other assumptions are wrong, but don’t majorly alter the overall results. Other assumptions are ok. These are all in Section 1 of Elsasser, 1942, if you want to check for yourself.

Key Elsasser assumptions #1: Kirchoff’s law

Elsasser uses what he calls “Kirchoff’s law”. This was an odd choice to make in 1942 as Einstein had superseded Kirchoff’s early insights into radiation. Elsasser seems to have rebranded Kirchoff’s 19th century insights in terms of early 20th century understanding, but missed some of the extra insights that Einstein had identified.

First, here is how Elsasser describes Kirchoff’s law:

“The ratio of emission and fractional absorption in any direction of a slab of any thickness in thermodynamic equilibrium equals the blackbody intensity” (p9)

The context in which he was giving this definition was that he was starting off with the simpler system of a beam of radiation passing through slab of material *which is in thermodynamic equilibrium*:

"Now in thermodynamic equilibrium the total intensity of the beam after passing through the slab must be the same as the intensity of the beam before it strikes the slab. Indeed, if this were not the case, the slab would gain or lose energy at the expense of the wall towards which the beam is directed, and we would have a steady flow of energy between two bodies of the same temperature, which is again in contradiction of the second law of thermodynamics." (p8)

Essentially, what he was saying was that if the system is in thermodynamic equilibrium, the flux of the radiation through the slab is independent of the concentration of the absorbers.

As we will see below, Elsasser believed the atmosphere was **not** in thermodynamic equilibrium. But, let us suppose he agreed that the atmosphere was in thermodynamic equilibrium (which he didn't!). This would mean that the net flux of the radiation through a given part of the atmosphere would be independent of the concentration of the greenhouse gases. One of the mechanisms by which the ground cools is by IR radiation, and similarly hot parts of the atmosphere are also cooling by IR radiation. However, at any given point in the atmosphere, "The ratio of emission and fractional absorption … equals the blackbody intensity". In other words, the GHGs don't change the net fluxes.

This is what we're finding. More on that below, but let's add a comment on Einstein.

Key Elsasser assumptions #2: Re-emission is spherically symmetric

Gustav Kirchoff (1824-1887) was a 19th century German physicist who identified several key concepts about the properties of radiation. This is separate from his insights into electricity and thermochemistry. He was a very prolific polymath who worked in a lot of fields.

However, Kirchoff died in 1887, and so his work all pre-dated the development of quantum theory.

One of Albert Einstein's many contributions to science was his work which described spectroscopy from a quantum perspective. His 1921 Nobel Prize actually singled out some of this work. It was awarded "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect."

He wrote several papers on this (often in German), but his 1917 paper, "On the quantum theory of radiation" is probably the most relevant. In this paper, Einstein shows how the classical physics understanding of radiation, i.e., what Elsasser described as "Kirchoff's law", was incomplete.

With regards the absorption aspect, he agreed that the rate of absorption was a function of the concentration of absorbers and the amount of radiation passing through. But, he added the caveat that the frequency of the radiation had to coincide with a suitable quantum transition.

As for emission, he realised that there were two parts: spontaneous emission (similar to Kirchoff's emission) **and** stimulated emission (not considered by Kirchoff… or the current climate models!). Spontaneous emission is spherically symmetric (provided the molecule is isotropic) – just like the "Kirchoff's emission" implemented by the models. But, Einstein argued that – under thermodynamic equilibrium conditions - stimulated emission would be in the same direction as the direction of the absorbed radiation.

In the 1950s and 1960s, this led to the development of lasers. The term "LASER" was originally an acronym for "Light Amplification by Stimulated Emission of Radiation", but over time everyone started using it as a single word. The key bit to notice is the SE part of the acronym, i.e., "Stimulated Emission" – this concept was introduced by Einstein. [*As an aside, one of the most efficient types of laser for infrared frequencies is the CO2 laser (https://en.wikipedia.org/wiki/Carbon_dioxide_laser), which emits in the 9.6-10.8 micron ranges, since these are in the "atmospheric window" which isn't already swamped*]

This is important when you are measuring the IR spectra of the Earth's atmosphere (e.g., Figure 2), because the current climate models assume all emission is non-directional. However, in reality, the stimulated emission component is directional.

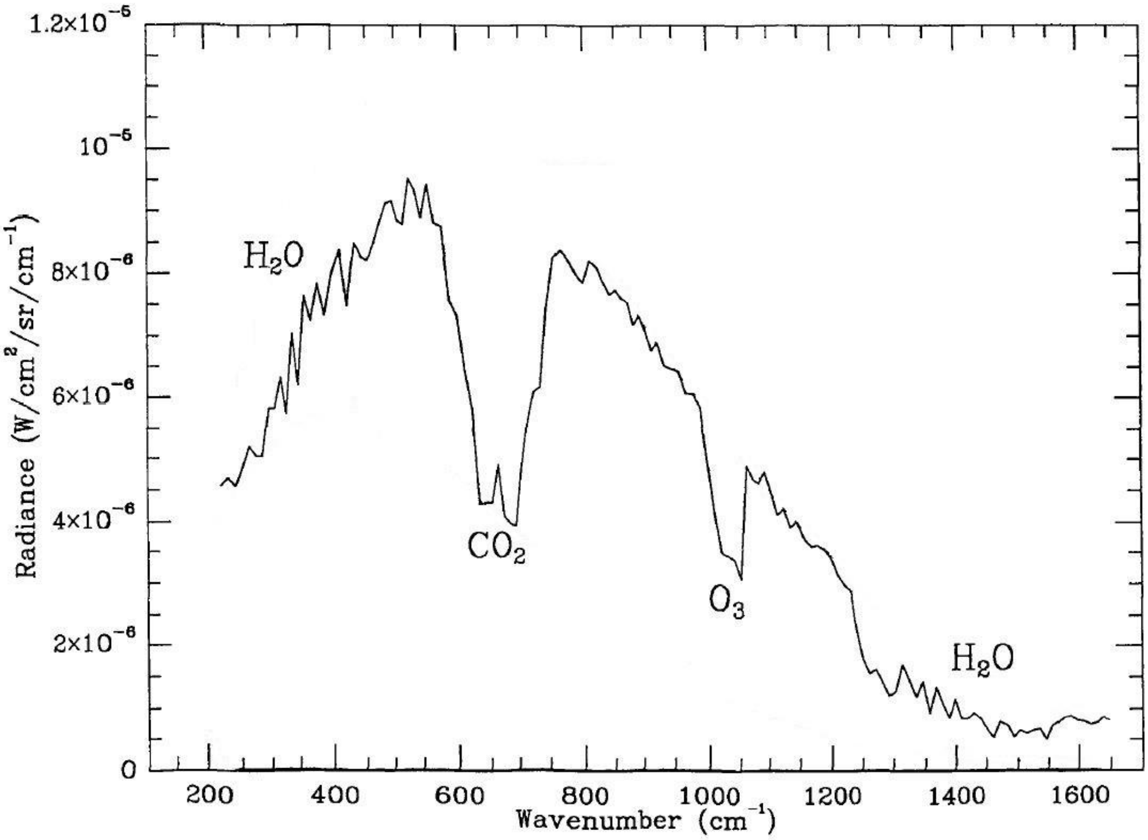

Figure 2. The infrared spectrum of the Earth's atmosphere as observed by the Mars probe in 1997 after leaving the Earth's orbit.

Under thermodynamic equilibrium, stimulated emission will on average transfer energy from hot regions to cold regions. Lasers overcome this tendency by artificially increasing the percentage of excited molecules of a cold gas.

At any rate, like Kirchoff's law, Einstein's laws also point out that – under conditions of thermodynamic equilibrium – the ratio of emission to fractional absorption is determined by the blackbody temperature (although he used Planck's law which wasn't developed until years after Kirchoff's death). In our context, that would mean the concentration of greenhouse gases would be irrelevant.

So, why does Elsasser's framework lead to a major role for greenhouse gases? Because he explicitly assumed that the atmosphere was a "stratified" system that was **not** in thermodynamic equilibrium.

Key Elsasser assumptions #3: The atmosphere is a “stratified” system that is **not** in thermodynamic equilibrium.

“We next consider radiation which is *not* in thermodynamic equilibrium with matter.” (p9, emphasis in original)

Elsasser treated the atmosphere as “a stratified medium” (p15) comprising multiple “slabs” of infinitesimally small thickness, and he explicitly assumed that these slabs were not in thermodynamic equilibrium. For this reason, instead of using “Kirchoff’s law” (or even Einstein’s laws), he used Schwarzchild’s equation: https://en.wikipedia.org/wiki/Schwarzschild%27s_equation_for_radiative_transfer

Schwarzchild’s equation describes the relationship between absorption and emission in a system that is **not** in thermodynamic equilibrium.

1. The rate of absorption is a function of the concentration of absorbers (i.e., greenhouse gases in our case) and the amount of radiation passing through. That is, it’s described by the Beer-Lambert law: https://en.wikipedia.org/wiki/Beer%E2%80%93Lambert_law
2. The rate of emission is a function of the temperature of the air (or rather T^4). That is, it’s described by the Stefan-Boltmann law: https://en.wikipedia.org/wiki/Stefan%E2%80%93Boltzmann_law

Elsasser explicitly assumed that the rate of absorption was largely independent of temperature (and we agree):

“We make the assumption, fundamental for all subsequent calculations, *that the absorption coefficient k does not depend on the temperature*. This is only approximately true in the atmosphere.” (p15, emphasis in original)

This is the origin of the influence of CO2 on atmospheric temperatures in the model world. Therefore, it is worth dwelling on this a bit more. This means that, under Elsasser’s framework, the rate of absorption in a given slab is a function of greenhouse gas concentrations, and the rate of emission is a function of the temperature of the slab.

The “radiative transfer problem” which Elsasser was trying to solve was essentially to integrate the fluxes of all infinitesimally small “slabs” from the surface to the top of the atmosphere. When the modellers try to implement this, they’re not able to make the slabs infinitesimally small. Instead, they make the vertical heights of the grid boxes as small as possible. The models treat each grid box as being in “Local Thermodynamic Equilibrium”. That is, within each grid box, the energy is totally mixed… but the grid boxes are thermodynamically isolated from the ones above and below.

As a result, when considering the flux of IR through the grid boxes, the models use Schwarzchild’s equation instead of “Kirchoff’s law” (or Einstein’s laws). A schematic is shown in Figure 3(b) [*ignore Figure 2(a) for this discussion!*]

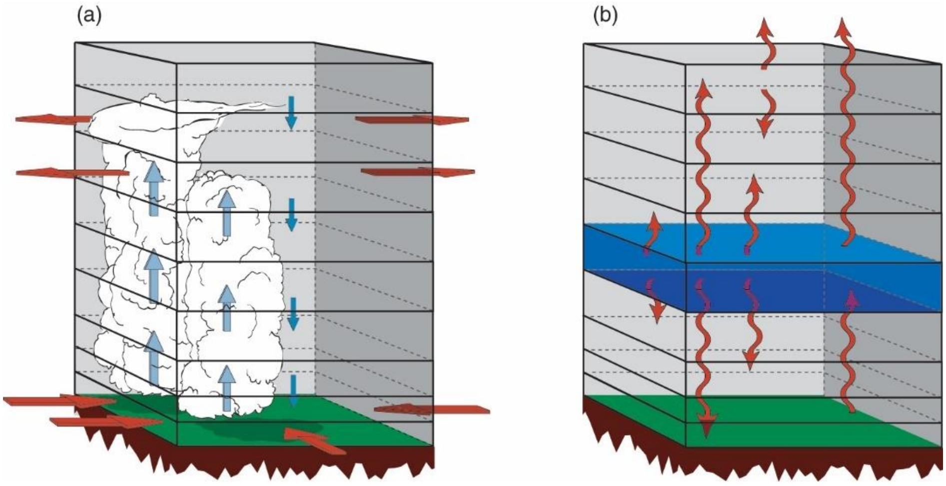

Figure 3. Schematics illustrating how energies are transmitted between grid boxes in current climate models. (a) illustrates the Arakawa convective adjustment for tall clouds which vertically span multiple grid boxes. The blue arrows indicate the transfer of energy via "convection"/precipitation/evaporation. This is a separate mechanism from the Manabe-Strickler "convective adjustment" which was developed to artificially make the modelled tropospheric lapse rates seem more realistic. (b) illustrates the radiative fluxes between layers. The red wavy lines indicate IR radiation. Taken from J. David Neelin's book - Fig 5.2

In the climate models, the net flux in a given time step for each layer is a function of the greenhouse gas concentration and the previous temperature of the grid box. The hotter the grid box, the more IR is emitted (using Stefan-Boltzmann law). The emitted IR is assumed to be uniform in direction (an extrapolation from Kirchoff's law), and so on average half of the IR continues upwards and half of the IR heads back down to Earth ("back radiation").

In the models – as in the real world - the Earth is heated up by incoming solar radiation. But, at the same time, the Earth cools to space (because space is so cold, i.e., ~4K). As the Sun has a surface temperature of ~6000K, the Sun's radiation is mostly ultraviolet/visible. However, because the Earth is only ~300K, it cools mostly via infrared radiation – see Figure 4.

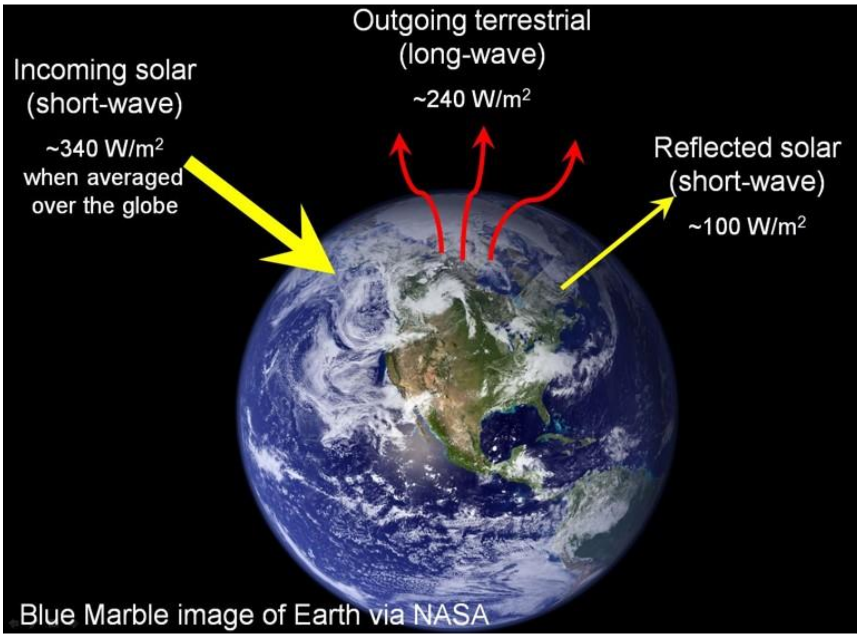

Figure 4. Standard estimates of the Earth's energy budget at the top of the atmosphere.

According to Elsasser's framework, and hence the climate models, the presence of greenhouse gases alters the rates of this "infrared cooling" throughout the atmosphere. In particular, more CO2 is predicted to slow down the rate of infrared cooling in the troposphere – leading to tropospheric warming (or "global warming"). But, because the stratosphere is hotter (emits more) and the outgoing radiation from each grid box is less likely to be reabsorbed by the grid boxes above it, more CO2 is predicted to increase the rate of infrared cooling in the stratosphere, i.e., "stratospheric cooling".

Figure 5 shows the theoretical changes in infrared cooling that are expected from CO2 using Elsasser's framework. Figure 6 compares this to an equivalent curve for a GCM.

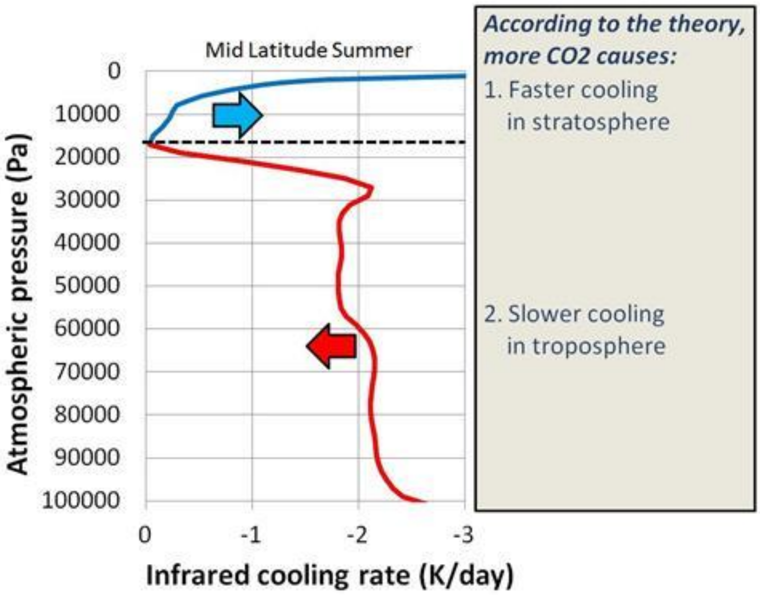

Figure 5. The theoretical infrared cooling rates for a mid-latitude summer atmosphere. Data is taken from the 1990 Intercomparison of Radiation Codes in Climate Models. https://cdiac.ess-dive.lbl.gov/ndps/db1002.html

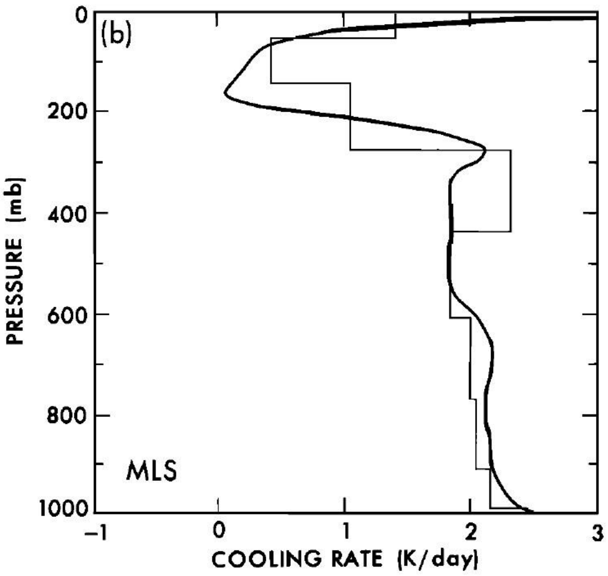

Figure 6. A comparison of the theoretical curve shown in Figure 5 (smooth thick line) to the equivalent curve for the Manabe & Stone Model III Global Climate Model (thin line).

Because the theoretical calculations divide the atmosphere into infinitesimally small layers (or “slabs” in Elsasser’s terminology), they provide much smoother curves that the step-like equivalents in the Global Climate Models (Figure 6). However, as has computing power has increased over the decades, the modelling groups have made the size of the vertical grid boxes smaller and smaller.

This has meant that over time, the “infrared cooling rates” generated by the models have gotten closer and closer to the theoretically-derived curves. This has led the modellers to believe that their models are getting “more realistic”. However, nobody every bothered to check whether the Elsasser framework was accurately representing the real atmosphere.

Our research using weather balloons is suggesting that the atmosphere is mostly in thermodynamic equilibrium up to at least the lower stratosphere (where the balloons burst). This means that instead of using the Schwarzchild’s equation (for non-thermodynamic equilibrium conditions) to describe the radiative fluxes within the troposphere/tropopause/stratosphere, we should be using Einstein’s equations for thermodynamic equilibrium conditions… or at least Kirchoff’s law (for thermodynamic equilibrium conditions). This is illustrated schematically in Figure 7.

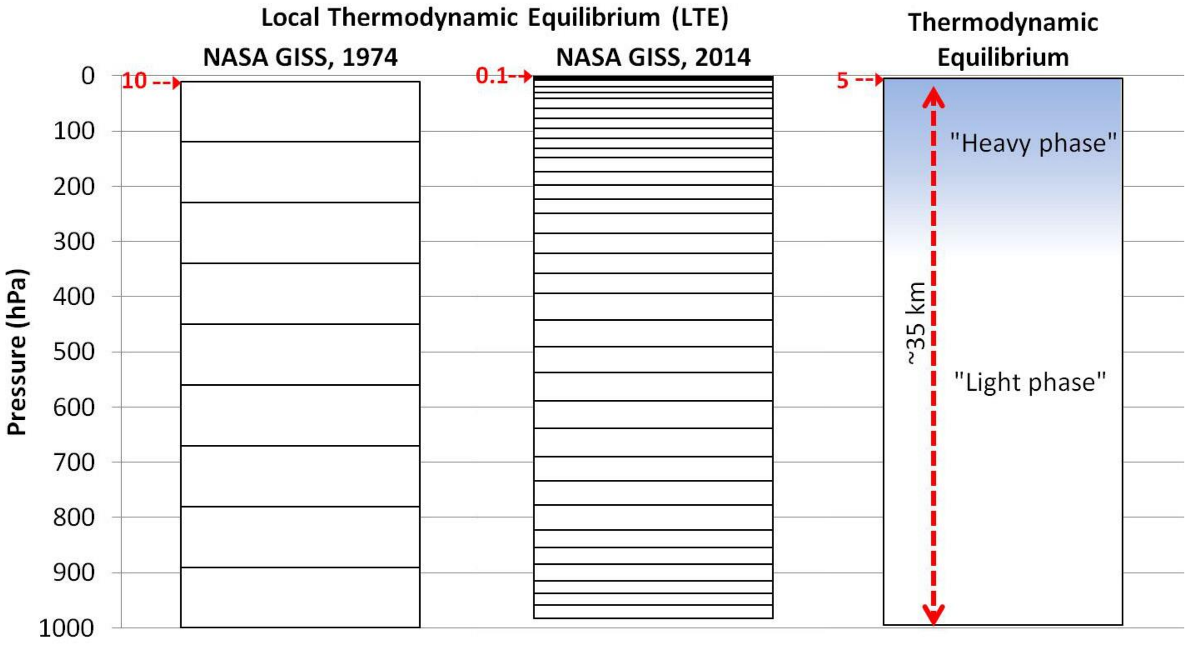

*Figure 7. Comparison of the two approaches. The GCM approach involves assuming each grid box is only in Local Thermodynamic Equilibrium (LTE). Due to computational limitations, early GCMs kept the vertical heights of each box to 2-3km, e.g., NASA GISS, 1974 had 9 layers. As computing power has increased, modellers have tried to reduce this height (e.g., see the middle panel corresponding to NASA GISS, 2014) with the ultimate aim of matching the theoretical calculation which assumes the atmosphere is divided into infinitely small layers each in LTE. Our approach (right panel) is the opposite. If the atmosphere maintains Thermodynamic Equilibrium over distances of 30-35 km, then the models should be **increasing** the vertical heights of the grid boxes to encompass the entire troposphere/tropopause/lower stratosphere. [Our balloon data only considers the first 30-35km and so we don’t yet know if TE continues above the lower stratosphere]. Note that because the horizontal grid box sizes of the GCMs are of the order of 150-200km, the GCMs are already effectively assuming that the atmosphere maintains TE **horizontally** over distances of 150-200km, i.e., throughout a given grid box. Our approach simply involves extending that assumption to also assume TE is maintained **vertically** over distances of at least 25-35km.*

That is, instead of reducing the vertical heights of the grid boxes until they reach the idealized “infinitesimally small slabs” of Elsasser’s framework, the modellers should be increasing the vertical heights so that each grid box encompasses the troposphere, tropopause **and** stratosphere.

This is not as unprecedented as it might seem – after all, the Global Climate Models already effectively assume that the atmosphere is in thermodynamic equilibrium **horizontally** over distances of at least 150-200km, since that is the average horizontal grid box size. We're simply saying that the same assumption should be applied vertically over distances of at least 25-35km.

If this simple extrapolation is applied, then the models will no longer imply that the atmospheric temperature profiles are driven by the greenhouse gas concentrations. This is because they will be using Einstein's laws (or Kirchoff's law) for thermodynamic equilibrium conditions instead of Schwarzchild's equation for non-thermodynamic equilibrium.

Another way of understanding why this negates the role of greenhouse gases on atmospheric temperature profiles is by considering Figure 5. According to the climate models, increasing CO2 should cause the troposphere to get hotter, but simultaneously cause the stratosphere to get colder. That is, the predicted effect of increasing CO2 are opposite in the troposphere and stratosphere. However, if the tropopause and stratosphere are in thermodynamic equilibrium, then the opposing effects cancel each other out. In other words, CO2 is predicted to cause opposing thermodynamic instabilities in the troposphere and stratosphere. But, under thermodynamic equilibrium, any thermodynamic instabilities that are generated get redistributed between the troposphere and stratosphere.

The significance of the two linear segments of the D vs P plots

One reason why the following explanation hasn't been considered until now is that the standard explanation for the positive lapse rates in the tropopause/stratosphere has been one that uses radiative transfer theory. That is, it had been assumed that the tropopause and stratosphere were "stratified" and that the positive lapse rates were due to "ozone heating" from the ozone layer

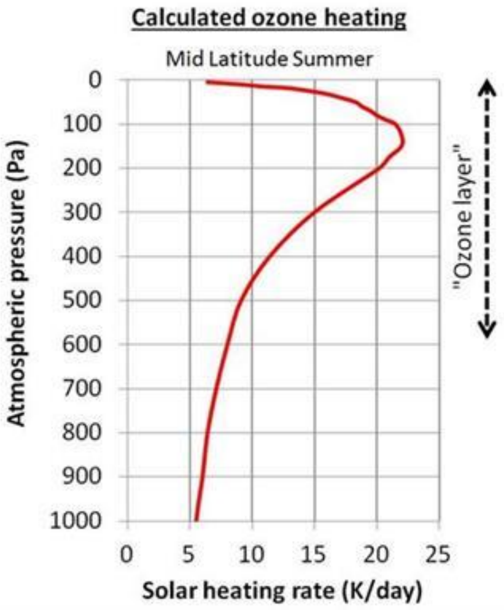

Figure 8. The calculated ozone heating rates for a mid-latitude summer, adapted from Figure 4 of Chou, 1992.

However, if the real reason for the change in lapse rate is a change in phase of the atmosphere, then this explanation is no longer relevant. In that case, we conclude that our proposed TE approach is more accurate than the current LTE approach.