Energy and Atmosphere

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PERPETUAL DRAFT, 160817b, 160906a in blue

Introduction

This article looks at the energy dynamics of the Earth's atmosphere. Since the role of radiative gasses (RGs, note a) has become a political issue that is undermining the stability of industrial economies and denying the many benefits of cheap and reliable energy to billions of people, the precise nature of the energy dynamics of our atmosphere has become a trillion dollar question.

The fundamental dynamic process is the creation of the lapse rate – the rate that the temperature drops with increasing altitude in the troposphere – below the tropopause marked by a dotted line in Figure 1 where the Earth curve follows a straight line. The tropopause is not a fixed height. It can vary from close to zero altitude at the poles to over 20 km at the equator. It varies in time, and thunderstorms can push it up locally. A typical height is said to be 11 km.

Some people think that the lapse rate is entirely due to radiative gasses and without them the atmosphere would have a constant temperature all the way up – be isothermal. It is a plausible first assumption, since we know that hot air rises. We might even expect to have cold air at the bottom and hot at the top, except that the atmosphere is mainly heated from the bottom. The problem is that these views are based on thermodynamics for laboratory conditions, which generally ignores gravity because the effect of gravity over small height changes is negligible.

The initial focus of this article is the affect of gravity on the lapse rate. I also discuss the significance of water vapour, the dominant radiative gas, and how the water cycle provides the Earth with a thermostat.

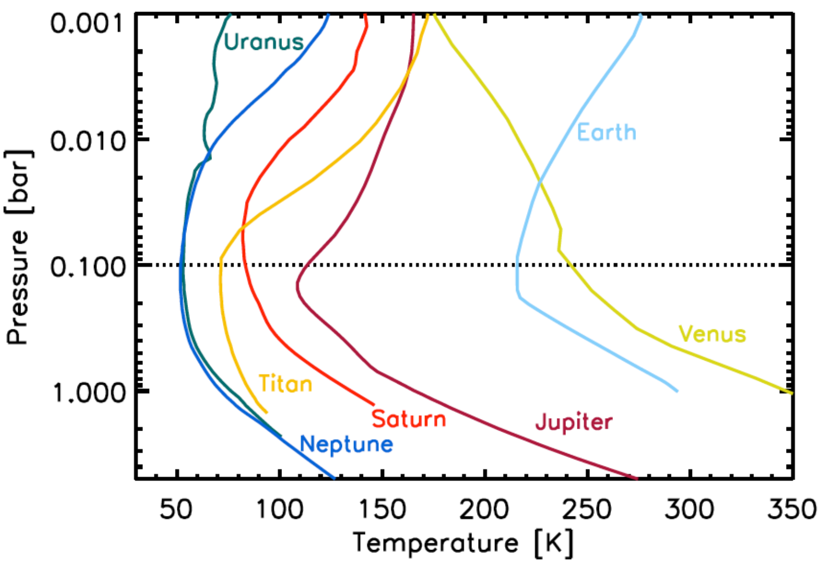

Figure 1: Atmospheric temperatures (1)

There are several definitions of lapse rate and some confusion in their use, so I'll start by giving definitions as I prefer to use them:

- Dry adiabatic lapse rate, DALR or ALR: with no radiative gasses
- Gravitational lapse rate, GLR: my preferred name for ALR
- Moist lapse rate, MLR: air with moisture levels below saturation
- Saturated lapse rate, SLR: air with water vapour at saturation levels
- Environmental lapse rate, ELR: an actual lapse rate at a particular place and time

The conventional determination of ALR:

The ALR is usually calculated from the thermodynamics of a parcel of air rising up through the troposphere. The ‘adiabatic’ means no energy is lost or gained by the gas parcel, which excludes radiative gasses which would transfer infrared energy in and out of the parcel, so the ‘dry’ is superfluous. The ALR applies only to an idealised mixture of gasses such as nitrogen and oxygen that are not radiative at atmospheric temperatures, so it is a theoretical abstraction. It provides the foundation of the actual lapse rate, which is modified by the addition of RGs. Thermodynamics gives a formula for calculating the lapse rate:

$$\Gamma_{th} = g/c_p \qquad \text{(E1)}$$

Where g is the gravitational acceleration and c_p is the specific heat of air at constant pressure – a measure of the amount of energy needed to raise the temperature of the gas.

I find the derivation of this formula too opaque. It hides the basic physics, which has caused a great deal of confusion and controversy (note b). After being resolved over a century ago, the issue has surfaced again in recent years in an effort to exaggerate the role of radiative gasses.

Determination of the gravitational lapse rate:

Here I go down to the level of individual molecules and give an alternative derivation for the ALR. The basic physics is simple. If you throw a ball into the air its energy can be given as the sum of its energy of movement – its kinetic energy, E_K – and its gravitational potential energy, E_P, minus energy lost to friction with the air, which can be ignored if the ball is in a vacuum. It moves up until all its energy is potential energy, then starts to fall and regain it.

$$E = E_K + E_P = mv^2/2 + mgh \qquad \text{(E2)}$$

Where m is the mass of the ball, v is its velocity or speed, h is its height, and g is the gravitational acceleration.

An insight into the lapse rate problem can be gained from the fact that a ball falling in a vacuum from a hight of 11 km has a velocity at ground level of 464 m/s, which is precisely the mean velocity of air molecules at 20 C° (2), and 11 km is a typical hight of the tropopause. This, and the suggestive g in E1, was the starting point that prompted me to try the following analysis.

Between collisions, the molecules that constitute air behave just like the ball. Having a molecule falling in a vacuum may not seem relevant when we're considering the atmosphere, but between collisions with other molecules they actually are all falling in a vacuum, or close enough for a simple analysis. All the molecules are following a parabolic path and gaining a little downward energy between collisions. Those moving down will gain kinetic energy, and those moving up will lose it. This produces a gradient with the average kinetic energy of molecules decreasing with increasing altitude – in other words, a temperature gradient.

Eventually our falling molecule will hit other ones, and the energy it has gained in falling will be passed on to them. The gravitational energy will be thermalised – added to the random motion of other molecules, to their kinetic energy, until an equilibrium is established.

If you want to skip the detail, go to E5. The next step is the most technical one because we aren't dealing with billiard balls colliding. We have to divide the added energy among all the degrees of freedom of the molecules, f. This is the standard equipartition rule dictated by entropy – the energy will distribute between all possible modes for storing it. Nitrogen and oxygen have 5 degrees of freedom at atmospheric temperatures. That's 3 for the directions of motion and 2 for rotational motions – spin and tumbling – rotation around the axis joining the two atoms doesn't count. I'll call this f_m.

During a collision we also have to consider the resulting energy distribution between the two colliding molecules. That's four nuclei and around 30 electrons. This needs to be seen from a quantum mechanical perspective as the transient formation of a four atom molecule which passes –

slowly by atomic standards – through a sequence of vibrational and rotational quantum states as it tries to form then breaks up – a process which determines the final distribution of energy between the molecules, and gives 2 more degrees of freedom, f_c.

The temperature of a gas is related to its kinetic energy by:

$$E_K = fkT/2 \qquad \text{(E3)}$$

where T is the temperature and k is Boltzmann's constant. The energy gained by a molecule falling a distance Δh is mgΔh (the deltas indicating related changes) so partitioning this among the available degrees of freedom we get:

$$\Delta E = mg\Delta h = fk\Delta T/2 \qquad \text{(E4)}$$

After a little manipulation we have the temperature gradient or lapse rate as:

$$\Gamma_g = \Delta T/\Delta h = 2mg/(f_m + f_c)k \qquad \text{(E5)}$$

Plugging in some numbers, m is taken as the average mass of nitrogen and oxygen in air weighted by their relative proportions of 79:21.

Comparing the two approaches, using a value for g adjusted slightly for a mean troposphere altitude of 5.5 km reduces it by about 0.8% from the usual surface value, and c_p is taken as the measured value of 1.0035.

E1 gives 9.73 C°/km.

E5 gives 9.66 C°/km.

Within 1% difference they are close, given that the real world doesn't usually comply exactly with simple physical theory. In note (c) I demonstrate the theoretical equivalence of the gravitational lapse rate and the conventional derivation, so if the theoretical value for c_p is used in E1 the two approaches give exactly the same result. That these two distinct approaches can be shown to reduce to the same dependence on g provides confirmation of the role of gravity.

Moist air

Here we allow a little water vapour but not enough to bring it to the dew point. Radiative gasses pick up internal rotational or vibrational energy through collisions with other molecules or, occasionally, by absorbing an infrared photon. They almost immediately lose it in subsequent collisions or as an emitted a photon. They don't 'trap' or 'store' energy. They pass it straight on. While a significant portion of atmospheric energy passes through radiative transfers, at any one moment the amount is small. They are a rapid conduit, not a reservoir.

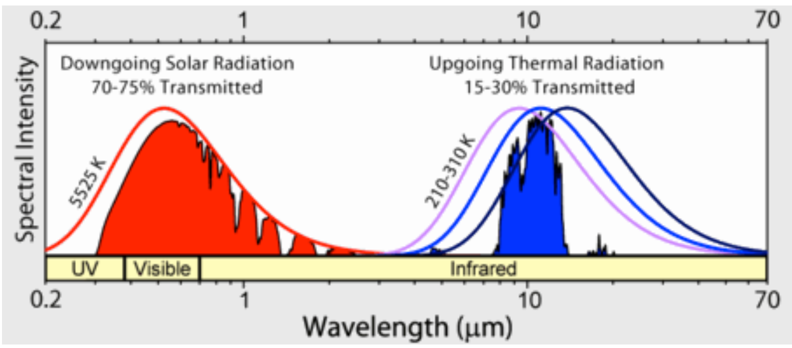

Figure 2: Atmospheric transmission. A micron, 1 µm = 10^{-6} metres (3)

Figure 2, others like it, and the narratives that go with them about RGs trapping heat in the atmosphere are misleading. The diagram only shows direct radiation through the atmosphere. Apart from energy that may be transported for centuries in deep ocean currents, and a little energy used in chemical reactions, all heat arriving from the sun is rapidly radiated back out into space.

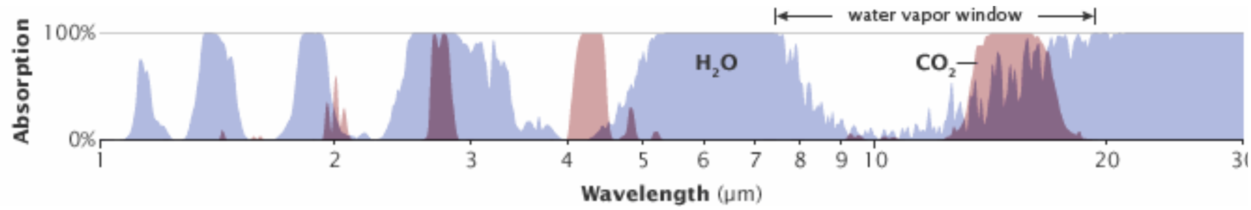

Figure 3: Absorption spectra of water vapour and carbon dioxide (3)

Discussion of the energy dynamics of the atmosphere often focuses on the absorption spectra of water vapour and carbon dioxide – how CO2 partly fills gaps in the absorption spectrum of water, as shown in Figure 3. To me, such diagrams just demonstrate the dominance of water. It is the excitation of RGs in collisions with nitrogen and oxygen and subsequent emission of photons that is the most significant aspect of radiative dynamics.

A photon can carry energy large distances by molecular standards, and does so at the speed of light, which is effectively instantaneous. The distance one travels on average – its mean free path or mfp – depends heavily on its energy, which depends on the emission spectrum of the source. The source is usually water molecules, or other RGs such as carbon dioxide where the air is too cold to contain much water vapour, or ozone above the tropopause. Some are emitted as broadband radiation from the Earth's surface with a temperature dependent bell curve spectrum as shown in Figure 2.

At ground level, infrared photons that reach wet surfaces are not significantly absorbed. At dry surfaces they are absorbed by the top layer of molecules, heating them, and with some of the heat conducting deeper. Others are being emitted, and between them they improve the thermal coupling between the surface and the near surface atmosphere.

Since the surface is primarily being heated by short wavelength light and UV energy, the net effect of infrared radiation is to pass surface heat to the lower atmosphere, warming it. Hot air rises, so the heat is transferred to the upper atmosphere by convection, where RGs radiate it to space.

At low altitudes the average transit zone of photons can be viewed as a fuzzy sphere with mfp radius in the order of tens of metres. As we look higher and the air density drops, the mfp and radius increase. As the change in air density over the mfp becomes significant, the sphere turns egg shaped – pointy end up.

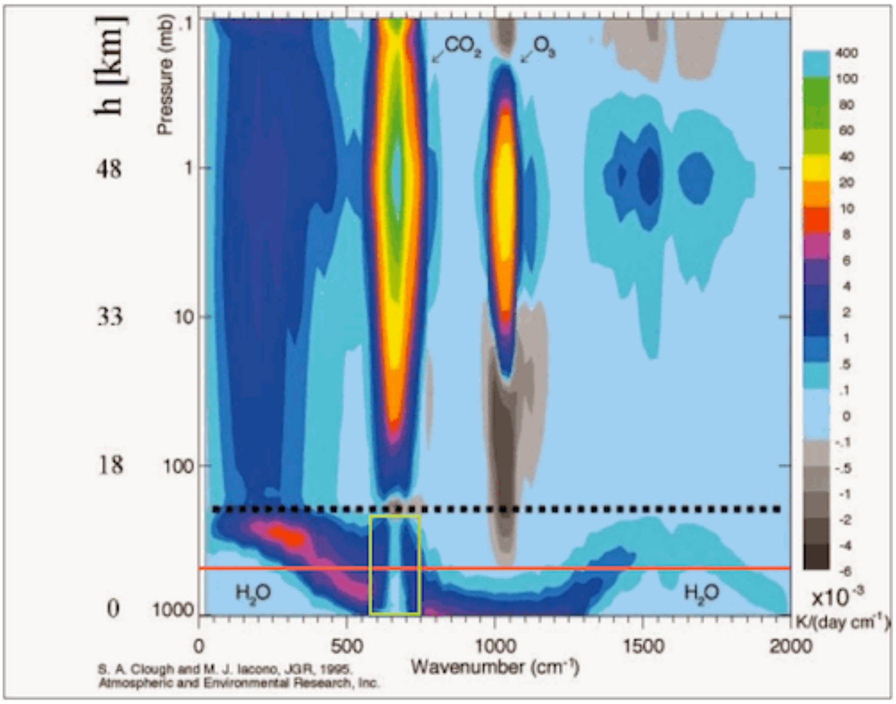

Figure 4: Modelled radiative cooling of the atmosphere

The red horizontal line in Figure 4 represents the mass centre of the atmosphere. Above it, a photon is more likely to escape to space than to reach ground level, though both are improbable. Our egg is still only about 100 to 200 m in radius. Near the tropopause, the top end of the egg is fuzzing its way out through the atmosphere, and average photons are escaping to space, as a few with the right energy have been doing all along – the blue in Figure 2. The net affect of RGs is to transport energy up through the troposphere and radiate it to space.

Figure 4 shows how the relative cooling affects of RGs, and heating in brown regions, vary with height and photon energy, or wavenumber, across the infrared spectrum. The strongest radiative cooling is performed by water vapour in the red regions of the lower left. The tropospheric impact of carbon dioxide can be seen inside the green rectangle as a perturbation of the water vapour background. It's saturated at its centre – the light vertical band – but adds to cooling in the bumps at its edges near the top of the troposphere where most of the water vapour has condensed out. It and ozone (O_3) are strongly active in the stratosphere above the tropopause, but the air is thin, so overall affect is less.

Water vapour increases the heat capacity of air slightly. At 4% it would drop the lapse rate given in E1 by 1.5%, but the system would no longer be adiabatic. The main affect of radiation on the lapse rate is to spread energy vertically, decreasing the temperature gradient by 3 to 4 C°/km or more.

Radiative transfer also spreads energy laterally, which allows energy to escape around clouds. This will be particularly significant with striated cirrus at high altitudes where the mfp is long.

Saturated air and the water thermostat

Earth is a water planet. Water dominates the energy transfers in the atmosphere and acts as a thermostat. This is dramatically illustrated in Figure 5, which shows the amount of water vapour in the atmosphere for varying surface temperatures in centimetres of water if condensed.

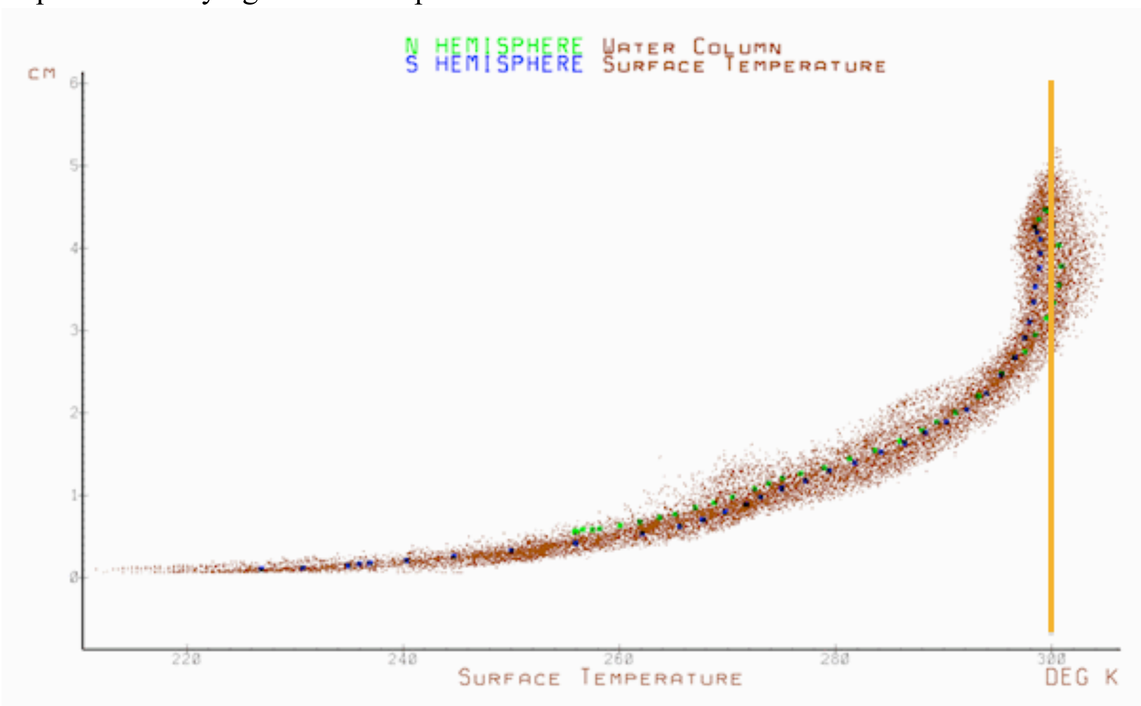

Figure 5: Atmospheric water column (cm) against surface temperature

Just below 30 C° evaporation suddenly increases (note d), and temperatures hit a limit as evaporative cooling soaks up heat as latent heat of vaporisation, just as sweat cools our skin. Water vapour is lighter than air, so the water rich air rises. As rising moist air cools, the relative humidity reaches 100% – saturation – and water starts to precipitate as clouds. In doing so it dumps the latent heat into the air of the upper troposphere where it's radiated to space.

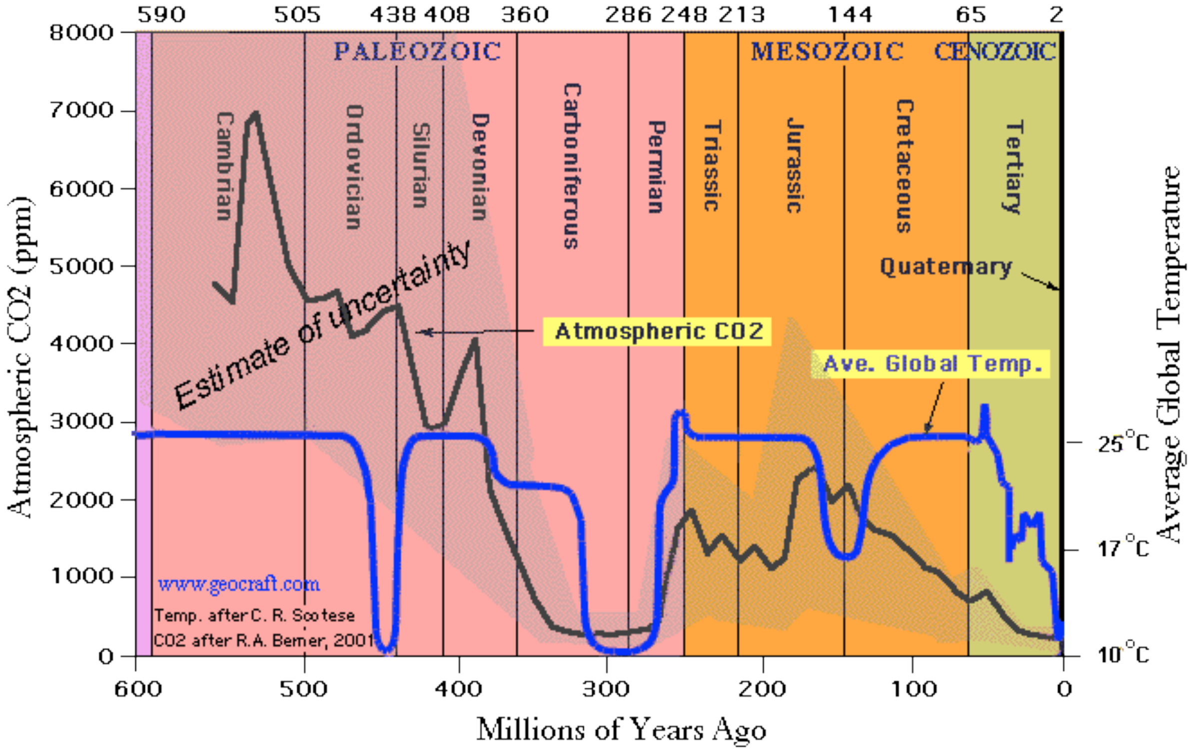

Figure 6: Ice core data for Temperature and atmospheric CO2 levels

The blue temperature plot in Figure 6 shows that the water thermostat has been consistently active, creating a ceiling for temperatures for over 600 million years.

Variations in solar activity – sunspots and flares – influence the Earth's magnetic field and its ability to deflect cosmic rays that aid cloud seeding and increases cloud cover (note f). Variations of a few percent in cloud cover are all that's needed to account for recent temperature changes.

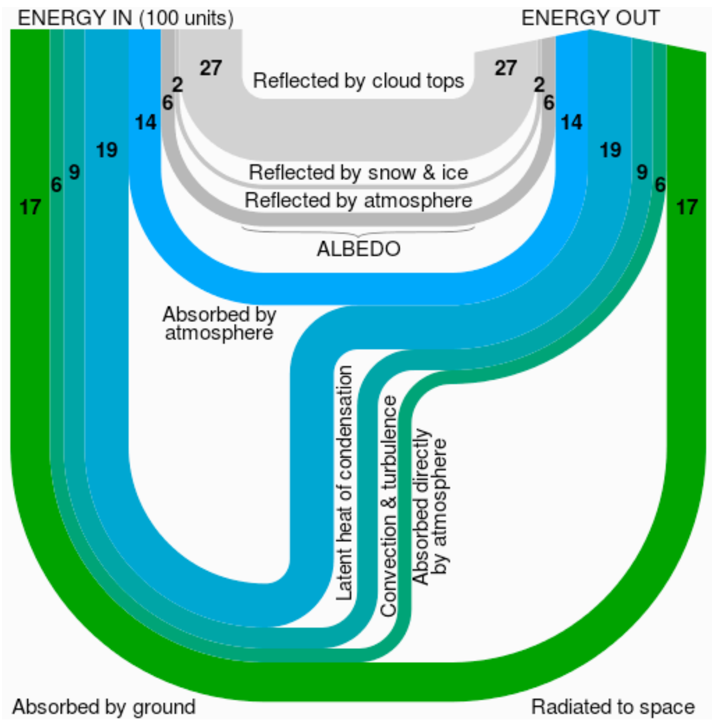

Figure 7: Earth heat balance – Sankey diagram (3)

From Figure 7, latent heat at 19% of energy transfer is second only to reflection from clouds. Along with convection they account for about 55% of upward heat transfer. Water not only acts as a thermostat, it's a powerful one – more than enough to counter any changes in the 17% radiated directly from the surface to space.

Combining the information in Figures 5 and 7, it's not just the relative sizes of the energy transfer channels that matter, but their dynamics, and how that dramatically changes at 30 C° with increased evaporation increasing cloud cover and the direct reflection of incoming energy from the sun before it reaches the lower atmosphere and surface.

The nature of the surface is important, too. The sun heats just a thin upper layer of solid surfaces and the heat is readily transferred to the atmosphere. Short wavelength – visible and UV – radiation from the sun penetrates deep into oceans, and can remain in the system for millennia in deep ocean currents.

Overview

The most fundamental of the many fatal mathematical flaws in the IPCC related modelling of atmospheric energy dynamics is to start with the impact of CO2 and assume water vapour as a dependent 'forcing' (note e). This has the tail trying to wag the dog. The impact of CO2 should be treated as a perturbation of the water cycle. When this is done, its affect is negligible.

Extensive analysis of radiosonde data over time, and an associated theoretical analysis, by Miskolczi (4) has shown that the water cycle adapts to maintain saturation – maximum impact – in the combined effects of water vapour and any other radiative gasses.

The sudden increase in evaporative cooling of warm water creating an upper bound for wet surface temperatures, along with the freezing point of water limiting ocean temperatures at the poles, anchor the overall surface temperature of the Earth. The Earth's orbit, variations in solar activity, and long term transport of heat in ocean currents, provide cyclic variations. The lapse rate just determines the height of the tropopause. The net affect of CO2 is to help cool the upper troposphere where water vapour levels are low.

The current small peak in temperatures is partly the result of heat returning from past millennial cycles – the historians' climate optima of the Medieval, Roman and earlier warm periods. As then, solar activity is now at low levels.

Notes:

a. All gasses can radiate at high temperatures. Radiatively active gasses (RGs), as relevant here, are ones that can have rotational or vibrational excited states at atmospheric temperatures, which can then emit that excitation energy as photons. The main RG is water vapour. Carbon dioxide and others play a minor role.

In political circles they are commonly referred to as 'greenhouse gasses'. Apart from being disingenuously evocative, it is wrong. Their action in the atmosphere doesn't resemble a greenhouse – a fact that even the IPCC admits.

We are, of course, talking about the low energy heat radiation you experience sitting in front of a heater, not dangerous, high energy, ionising radiation. But the mere mention of the word can cause concern for many people, and I suspect that this is a significant component of the CO2 scare.

b. An objection that has been raised against the gravitational lapse rate – an attempted refutation – is that you could use the temperature difference across a column of air to power a heat engine, and so get free energy – a perpetual motion machine. You could build such a machine, but the energy is not free. You'd just be drawing energy from the atmosphere as is done with geothermal energy drawing energy from deep hot rock. Gravity is not adding energy to the air, it's just redistributing it. It would be an extremely inefficient and expensive generator, even by today's standards.

Another objection is that the seas should likewise be colder at the top. A slight tendency will be there, but the bonds holding liquid water together are far stronger than gravity, and dominate. Seas are largely heated from the top, and warm water rises, so they tend to be stable.

c. Equating Γ_{th} with Γ_g for those who are comfortable with some simple algebra and cryptic physics. I'm assuming a perfect monomolecular gas.

Starting with E5: $\Gamma_g = 2mg/(f_m + f_c)k$.

Substituting M/N_A for m, where M is the molecular mass of the molecule and N_A is Avagadro's number gives:

$$\Gamma_g = 2Mg/N_A(f_m + f_c)k \qquad \text{E6}$$

Substituting R/N_A for k, where R is the gas constant, gives:

$$\Gamma_g = 2gM/(f_m + f_c)R \qquad \text{E7}$$

Now looking at the conventional derivation in E1: $\Gamma_{th} = g/c_p$.

We can derive a theoretical value for c_v starting with c_{vm}, the molecular heat capacity:

Combining $c_{vm} = f_m R/2$, $c_{pm} = R + c_{vm}$, and $c_p = c_{pm}/M$ gives:

$$c_p = (f_m + 2)R/2M \qquad \text{E8}$$

Substituting this in E1 we get:

$$\Gamma_{th} = 2gM/(f_m + 2)R \qquad \text{E9}$$

So with $f_c = 2$ in E7 we have:

$$\Gamma_g = \Gamma_{th} \qquad \text{E10}$$

The two derivations for the adiabatic lapse rate are theoretically equivalent.

d. In Figure 5, temperatures hit a wall at 30 C° and evaporation shoots up. The obvious question is why such an abrupt transition should exist. My starting point was noting that hurricanes only begin to form when the water surface temperature rises above 24 C°.

Liquid water has many anomalous properties. These are thought to come from the formation of transient nanoscale structures of up to a few hundred molecules. An anomaly that seems relevant here is the minimum in specific heat at around 35 C°. It is thought that between 0 and 35 Cº the nanostructures break down.

Another anomaly is water's high surface tension. Water molecules near the surface are more tightly, packed than in the bulk water. The molecules aren't just densely packed. Picosecond pulsed laser energy dumps show that energy can be carried into the whole layer almost instantly by quantum coherent vibrational states that penetrate the layer. [160822, removed speculation on deep surface layers, EZ-water]

A quick look through some of the literature on bulk water spectroscopy showed interest in water's structure at around 30 Cº. I don't claim to have a good grasp of this. I have had some experience in molecular spectroscopy – experimental work and quantum calculations for energy levels and decay rates, but it was in gas phase not liquid, and decades ago when spectroscopically useful lasers were simple DIY constructions and computer models were boxes of punch cards, so I won't risk interpretation, just a few quotes.

Rønne et.al. discuss water's behaviour at 30 C° (5):

> *The two lines intersect near 303 K. ... It is interesting to note that 303 K has proven to be a special temperature in various studies of water. ... Mizoguchi et al. have ... observed a kinklike behavior at ~303 K. In pressure dependent studies of the shear viscosity, water behaves like an abnormal liquid below 303 K and the specific heat capacity of water, Cp, has a minimum at 303 K. ... adding all these observations together we obtain indication of a changes in microscopic structure at ~303 K.*

From (6):

The power absorption coefficient and refractive index of water at temperatures of 4, 8.9, 30 and 50 °C have been measured … . The power absorption coefficient profile is observed to increase with increase in temperatures from 4 to 8.9 and then to 30 °C. This is followed by a decrease in the profile at 50 °C.

From (7):

A clear nose [turning point in the graph] *appears around T = 300 K, signaling the onset of the network of hydrogen bonds (HB)* [as temperature decreases]. *Indeed, strong directional interactions (such as the HB), impose a strong coupling between density and energy.*

From (8):

Buchner et.al. used a pulsed laser technique to measure electrical properties of water. Figure 8 shows a drop at 30 C° in permittivity (the ability of a substance to store electrical energy in an electric field) and relaxation time (the time taken to dissipate energy). In attempting to explain the data they refer to:

… a contribution of additional processes in the far infrared region, which cannot be resolved within the frequency range of our data.

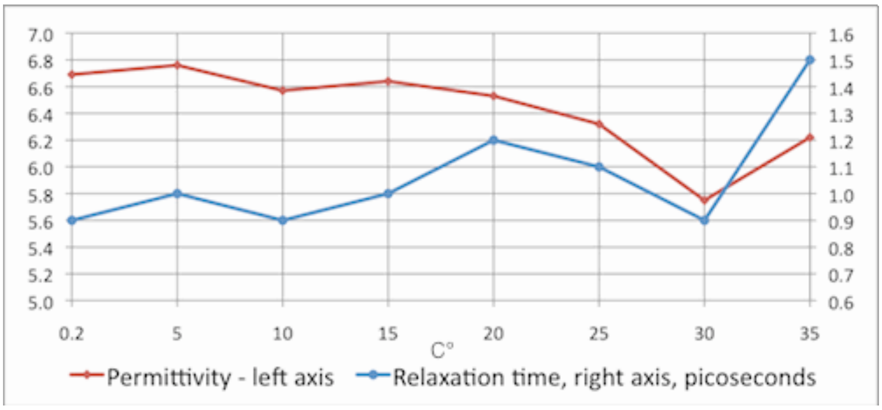

Figure 8: Anomalous dielectric behaviour of water (8)

Below 30 C°, the relaxation time has dropped by 33%. It then rises by at least 66%. This looks to me like the kind of transition point needed to explain the uptick in Figure 5.

At 30 C°, air molecules have, on average, 10% of the energy needed to remove a water molecule with some having much more. The rest comes from the thermal energy of the water, particularly those water molecules with higher than average kinetic energy. A 15μm photon can supply 20% of the energy needed, and while it is unlikely to be fully absorbed in a pure water surface, the radiation field at the surface may assist evaporation. Seawater has a fine surface layer of organic surficants, which are likely to absorb in the infrared, if only briefly.

Ejection of a water molecule from the surface will cool the water while increasing the density of water molecules in the air immediately above the surface, so increasing the emission of photons. This gives the possibility of a runaway radiative gas effect causing the runaway cooling seen in Figure 5. This will be limited by the fact that it is cooling the water, and convection is refreshing the air at the surface.

I try to form some kind of specific physical image, if only to show me how little a theory or mathematical model is actually telling us about the real world. Here, I can imagine the surface layer of the sea weakened by a nanoscale phase transition and with bombardment by air molecules and infrared photons creating small patches where the tightly bound surface layer is disrupted, exposing the more loosely bonded molecules of the bulk water, so increasing evaporation. As the water under the patches cools, the surface layer reforms.

e. Use of the word ‘forcing’ is a significant ambiguity this context. It suggests inevitable success for what is just an influence that may not overcome competing influences. In physics, you can apply a force to an object without necessarily moving it. In mathematics, unambiguous wording is essential.

That they chose to start with CO2 wasn't just a mathematical error. It was mandated by the UN in their brief for the IPCC that they just look at human impacts. Water is systematically ignored or is significance downgraded in IPCC reports. It's not even mentioned in lists of ‘greenhouse gasses’.

f. The precise effect of clouds on global temperature is still debated and is not well modelled. They reflect heat from the sun back into space. They also reflect heat radiated from the earth's surface and lower atmosphere back down. Any observant person who has spent time outdoors will be aware that a cloud blocking the sun during the day drops the temperature far more than clouds increase temperatures at night.

Australians, or those that live on the land, have always taken a keen interest in clouds. When one appears on the horizon, where it's heading, its size, and whether it's bringing rain are often anxiously discussed. In the early 1960s I heard about the Wilson cloud chamber. It had recently been replaced as the primary detector in particle physics experiments after nearly half a century of valuable service. Along with many amateur scientists I had a go at making one. I can't remember that mine actually worked, but I did see one working somewhere and remember the thin condensation trails it produced in the wake of a charged particle.

I remember hearing of discussions among physicists at ANU, or the CSIRO rainmakers, who were wondering about cosmic rays – high energy particles from outside the solar system – and their probable role in nucleating cloud formation. It was a reasonable hypothesis for anyone who had seen a cloud chamber (9). It's an important point that this was an established and uncontroversial hypothesis long before it became politically significant.

Recently Svensmark (10) and others have provided experimental verification of the hypothesis. The funny side was climate scientists adamant that the whole idea was preposterous. Presumably they've never heard about, let alone seen, a cloud chamber. This is a great illustration of the adage ‘*If you don't study history you are bound to repeat it.*’ In any case, the clue is in the name.

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