Energy and Atmosphere

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Introduction

This article looks at the energy dynamics of the Earth's atmosphere. Since the role of radiative gasses 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. I start with a brief summary of the role of a planetary atmosphere then look deeper at key issues.

Radiative gasses

All gasses can radiate at high temperatures. Radiatively active gasses (RGs), as relevant here, are ones that can have internal 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.

The Earth's atmosphere in stages

This is a hypothetical scenario that allows us to build up a picture, step by step, of how having an atmosphere can influence a planet. As a starting point we consider how the Earth's temperature might vary through the daily cycle if it was an airless, rocky planet much like the moon. During the day, the sun heats up a surface layer of the rock which cools through infrared radiation. The temperature follows the sun's irradiation almost directly, rising and plunging over a range of hundreds of degrees.

If we add a radiatively inert atmosphere, its only means of gaining and losing heat would be thermal conduction through direct contact with the Earth's surface. The heat capacity of a square meter column of the Earth's atmosphere is equivalent to that of about 12 tonnes of granite, so far greater than a thin layer of rock heated by the sun. While the surface would still go through a temperature cycle, the atmosphere would achieve an equilibrium where the mean lower atmosphere matched the mean surface temperature – give-or-take geography and atmospheric circulation. It would act as a buffer that would stabilise surface temperatures – cooling the surface during the day and warming it at night. This is discussed further in note (a) with some simple calculations.

All molecules are radiatively active if the energy is high enough. A realistic atmosphere, such as a nitrogen and oxygen mix, absorbs some energy from the light and UV components of incoming solar radiation, but still can't lose heat through infrared radiation.

We now add water vapour to the atmosphere at typical Earth levels of up to 4%, but ignore the effects of condensation. Water molecules are kicked into excited states by collisions with nitrogen or oxygen molecules which lose some kinetic energy in the collision. Most of this energy will return to kinetic in subsequent collisions. Otherwise, the energy is radiated in a random direction as an infrared photon, which creates a radiation flux that travels much faster and further than molecular movement. Their mean free path (mfp) is typically 50 metres in the surface atmosphere, increasing with altitude as the density of the air decreases and collisions are less frequent. A small part of this energy escapes to space, a smaller part is absorbed by the Earth's surface, leading to a net transfer to space.

This radiative flux greatly increases the thermal coupling between the surface and near-surface atmosphere, adding to the transfer via direct thermal conduction and reducing the daily temperature cycle of the surface, tying it closer to the temperature of the lower atmosphere. Due to the highly nonlinear nature of radiant emission, this will have a net heating effect on the surface as described in note (a).

The increase in mfp with altitude means there is a small upward bias in photon transmission through the atmosphere's photon sea created by molecular collisions. This net upward transfer of energy largely substiutes the direct infrared radiation from surface to space, adding a slight delay in the order of milliseconds. Heat is not 'trapped', as is commonly claimed, just slowed a little. It's a rapid conduit, not a reservoir.

For the next stage in the transition towards our current atmosphere we add our present distribution of liquid water over 70% of the rocky surface. This changes things dramatically. First, rather than just heating a thin surface layer of rock that can radiate heat rapidly, the sun's rays penetrate deep into the oceans, heating water that retains its heat until physical mixing brings it to the surface. In the upper 'mixing layer' this happens in days to months. Some is mixed deeper and can travel for centuries in deep ocean currents before surfacing.

At the surface of the oceans and wet land we now have evaporative cooling which extracts heat of vaporisation and cools the surface just as sweat cools our skin. Water vapour is lighter than air and reduces the air density. The lighter air rises, creating convection. As it rises it eventually cools to the point where liquid water condenses out to form clouds and dumps the heat of vaporisation into the upper atmosphere. The main impact of clouds is to reduce incoming solar radiation by reflecting it back out to space.

Most of the heating is in equatorial regions. The rising air creates the major Hadley circulation cells that carry heat polewards in the upper troposphere. The radiating upper air cools and becomes more dense as it travels, eventually sinking back to surface level and returning to equatorial regions.

Water isn't the only radiative gas in our atmosphere, but it dominates. The next in significance is carbon dioxide. It's main impact is in the upper atmosphere where most of the water vapour has condensed out. This impact is cooling. Its influence in the lower atmosphere is discussed later.

Finally, we add Life. Early on, it added the oxygen to our atmosphere. Now, its plants have changed the surface albedo – the amount of the sun's energy reflected back to space. Through transpiration they also add to evaporation in increasing the input of water vapour to the atmosphere. Some plants and algae produce aerosols that seed clouds – terrestrial plants increasing their chances of rain – marine biota reducing the incidence of destructive UV.

The artificial balancing act

The first point I want to make about Figure 1a, and others like it, is to do with accuracy and honesty. In the lower left is a figure of 0.6±0.4 W/m^2 for the energy imbalance implicitly due to carbon dioxide – a crucial figure in the whole CO2 debate. But it is clearly a manufactured figure that can't possibly be deduced from the other figures in the diagram.

The differences between total ingoing and outgoing radiation at the top of the atmosphere and at the surface are both 1 W/m^2 which approximately match the imbalance presumed to be lost at sea, but the errors in these values are ±5 and ±25 W/m^2 respectively. At best these estimates give an error range ten times the ±0.4 W/m^2 in the diagram for the imbalance, and eight times the imbalance itself. The explanation for the incompatibility of the imbalance with the rest of the diagram comes buried in the text, which says:

> "*The difference between the net absorbed solar radiation, which amounts to 240 Wm², and the 239 Wm² outgoing thermal radiation takes into account in a rounded way the approx. 0.6 Wm² global energy imbalance inferred from ocean heat content measurements.*"

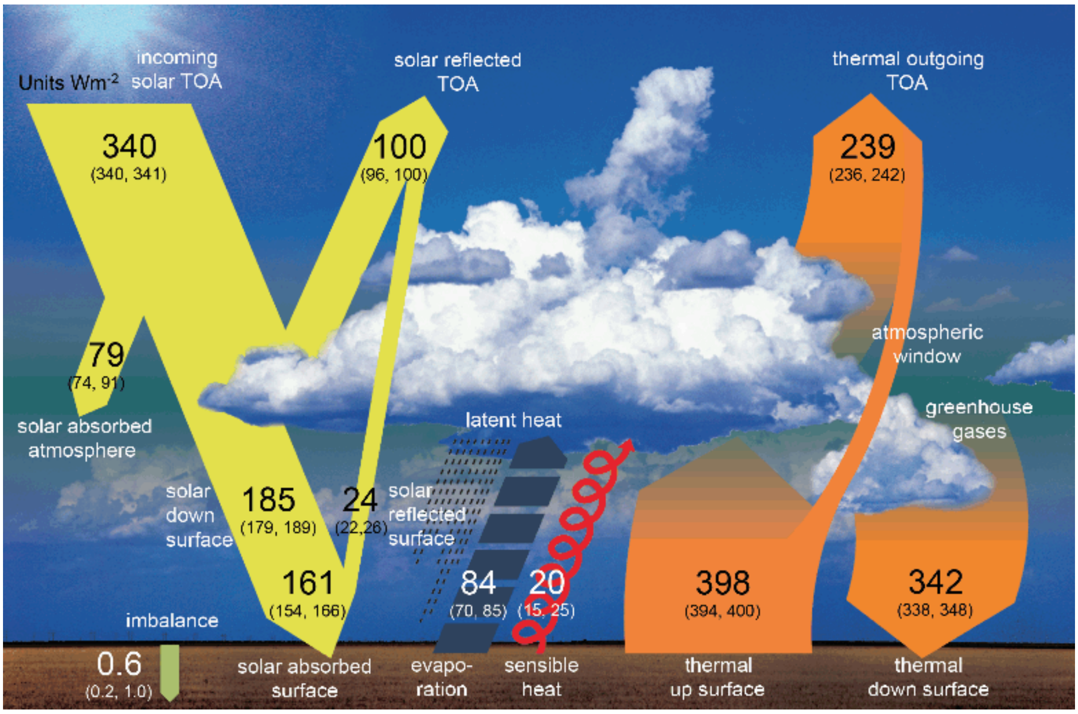

Figure 1a: The energy balance of the Earth's atmosphere and surface (1).

Silly me for initially assuming that the dataset was coherent. This is IPCC work, and they use the same trick with their version of the Earth's carbon cycle (2) and with temperature data in the infamous 'hockey stick' diagram. That makes their three principal datasets a Dodgy Data Trifecta.

More generally, I can't believe that any of these figures have the accuracy claimed. They are based on a mix of model outputs (with 15 W/m² spread between models) and a sprinkling of surface station data of variable reliability and time span. The abstract of the paper admits that the figures are set by the proscribed imbalance:

> "*Considering an imbalance of 0.6 Wm-2, the global mean sensible and latent heat fluxes are estimated at 20 and 84 Wm-2, respectively, to close the surface energy balance.*"

To repeat what I said in my carbon cycle paper: "The fluxes have been made up to fit this net value. In financial accounting, every cent is countable and a strict balance is a desirable goal. Here we are dealing with science and engineering where even countable values are rarely precisely known. Things never add up exactly. Mining geologists would end up in prison for such deception."

The second point worth noting is that there is an energy flux missing from the diagram: the heat transferred through time by ocean currents. The main Ocean Conveyor currents (Thermohaline circulation) transport deep water for up to a millennium. We are now receiving both heat and CO2 from water that downwelled during the Medieval Warm Period.

It is estimated that the ocean surface has recently shown an increase of about 10^{22} Joules per year which is $3x10^{14}$ Watts, or **equivalent to** 0.6 W/m² of the atmospheric radiation budget. How much of this heat has been passed on from the MWP and is now being passed on to the next period that historians call a 'climate optimum', with a top-up from the current peak? It may have little to do with the radiation budget.

Another temporal feature that is missing here is the diernal cycle. The significance of this was discussed in the previous section and in note (a).

The atmosphere's temperature lapse rate

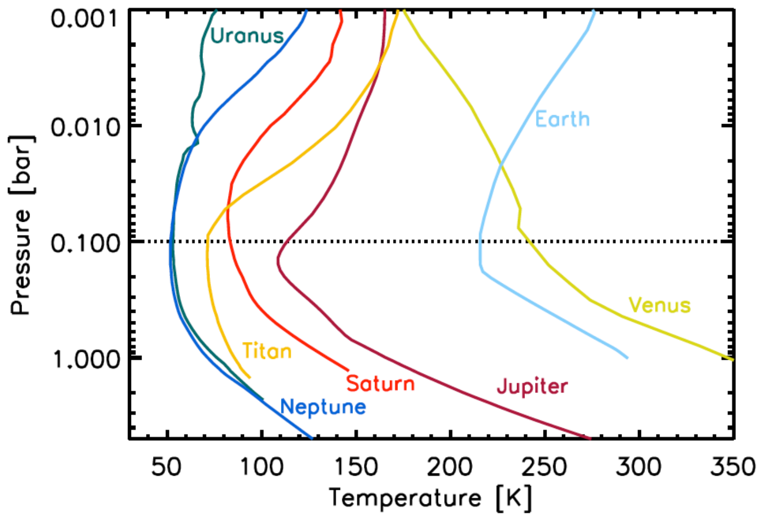

Figure 1: Atmospheric temperatures (3)

The fundamental thermodynamic process in the atmosphere is the creation of the lapse rate – the rate at which 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. On Earth, 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. This view maximises the significance of RGs. 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.

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 ALR is usually calculated from the thermodynamics of a parcel of air rising up through the troposphere. This terminology is wrong. 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. 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:

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

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.

In (4) I derive an expression for the adiabatic lapse rate from basic molecular mechanics:

$$\Gamma_g = 2mg/5k \qquad (E2)$$

where m is the average mass of nitrogen and oxygen molecules in air and k is Boltzmann's constant. I also show that these two equations are ultimately identical.

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.

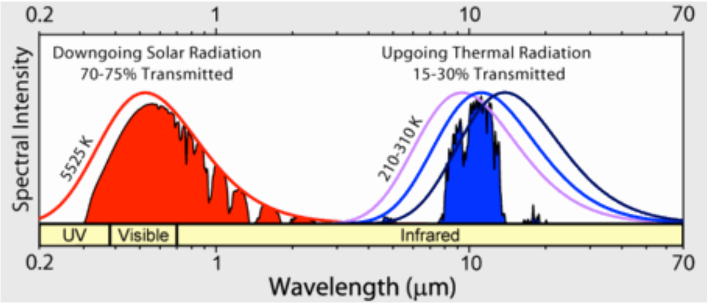

Figure 2: Atmospheric transmission. A micron, 1 μm = 10^{-6} metres (5)

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.

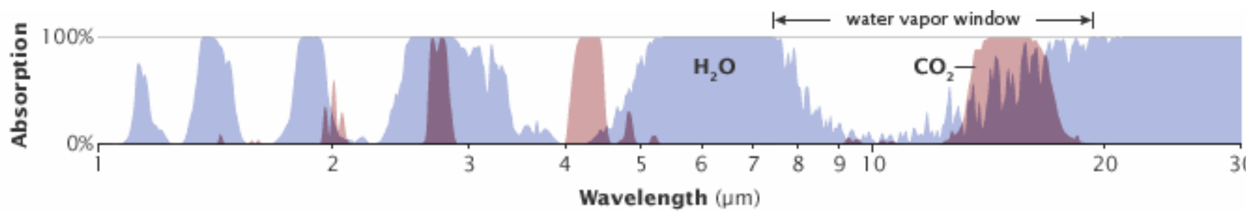

Figure 3: Absorption spectra of water vapour and carbon dioxide (5)

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.

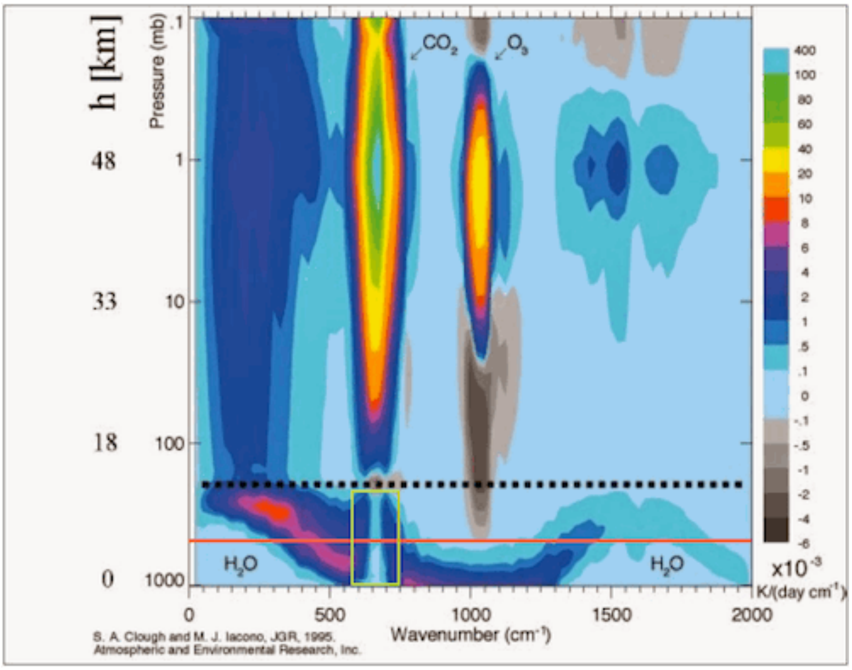

Figure 4: Modelled radiative cooling of the atmosphere

Since the surface is mainly 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 50 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.

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 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^o/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

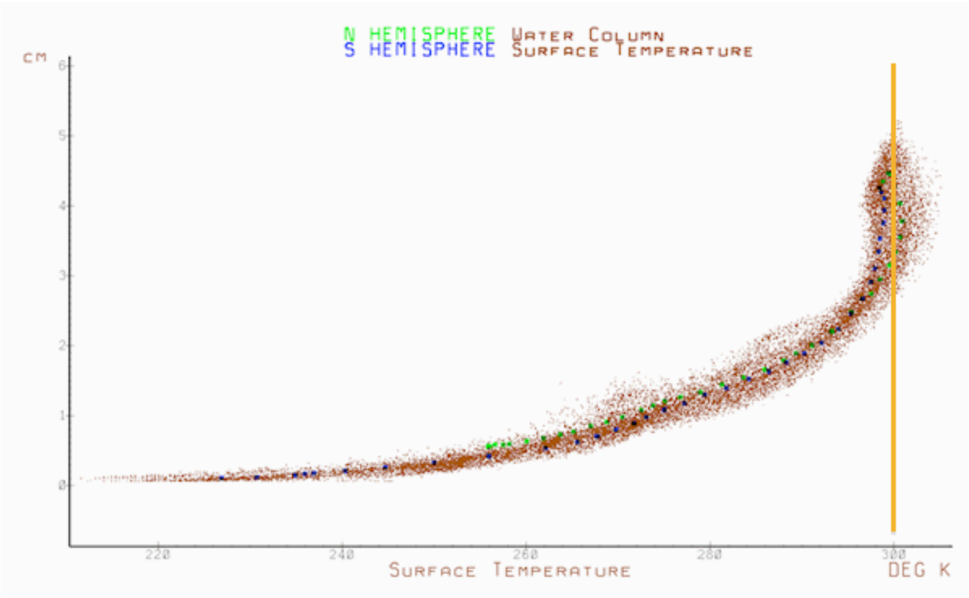

Figure 5: Atmospheric water column (cm) against surface temperature

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.

Just below 30 Cº evaporation suddenly increases (note c), 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.

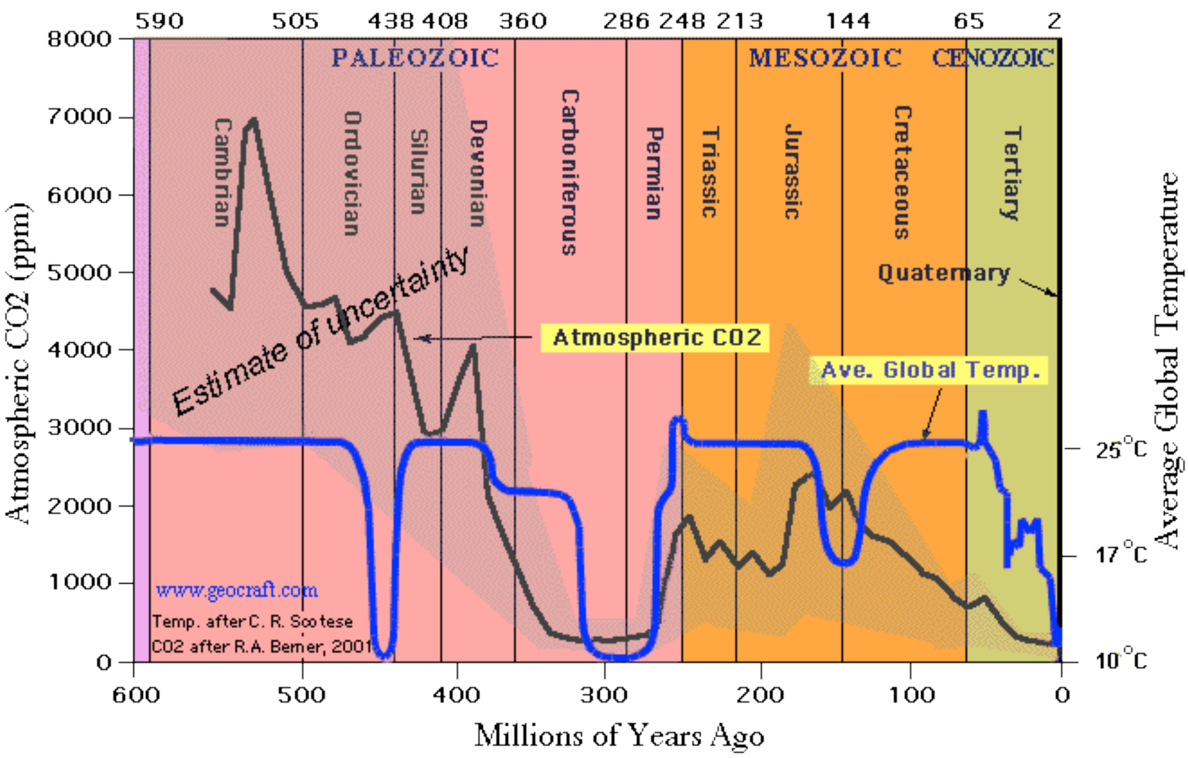

Figure 6: Ice core data for Temperature and atmospheric CO2 levels

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 d). Variations of a few percent in cloud cover are all that's needed to account for recent temperature changes.

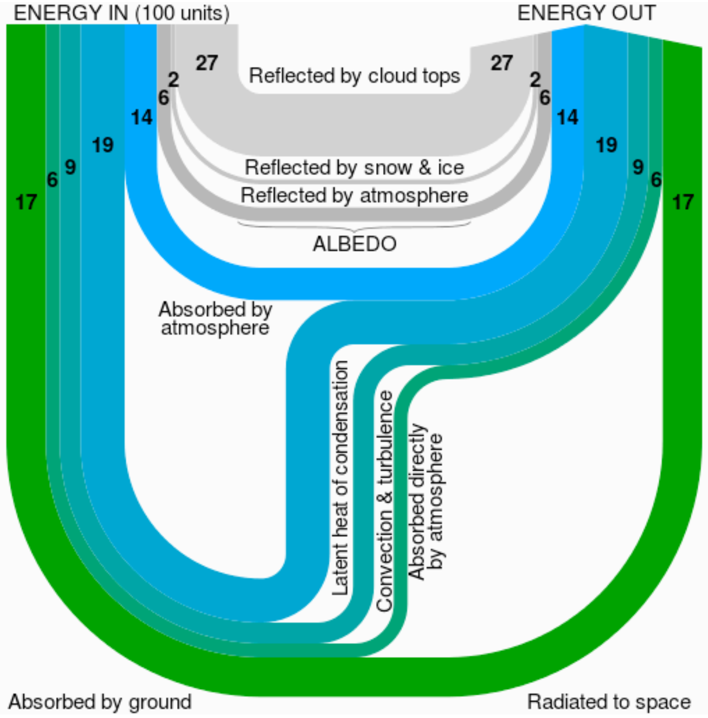

Figure 7: Earth heat balance – Sankey diagram (5)

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 Cº 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 cycles of the deep ocean currents – the Ocean Conveyor (note f).

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 (6) 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 CO_2 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: Atmospheric temperatures and radiance

a. Changes in radiance

Having a non-radiating atmosphere will increase the surface temperature of the planet. The atmosphere removing surface heat during the day and returning it at night reduces the daily mean energy radiated to space due to the fact that radiant emittance of a body rises to the fourth power of temperature.

$$E = \varepsilon\sigma T^4 \qquad \text{E13}$$

Here ε is the surface emissivity, σ is the Stefan–Boltzmann constant. This means that a small rise in nighttime surface temperature increases emission less than the same change in daytime temperature decreases it.

To roughly quantify this, if we take an area on a planet's surface that initially cycles between 200 and 300 Kº daily, and this range is changed to a 210 to 290 Kº by atmospheric redistribution, its emitted radiant energy will drop by 14%.

This analysis assumed that the atmospheric temperature was the surface mean as in E9. If it approached the limit given by E12 there would be no change in radiant emession.

b. Criticism of the GLR

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. The Earth's water thermostat

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° (7):

> *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 (8):

> *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 (9):

> *A clear nose* [turning point in the graph] *appears around T = 300 K, signalling 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 (10):

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.*

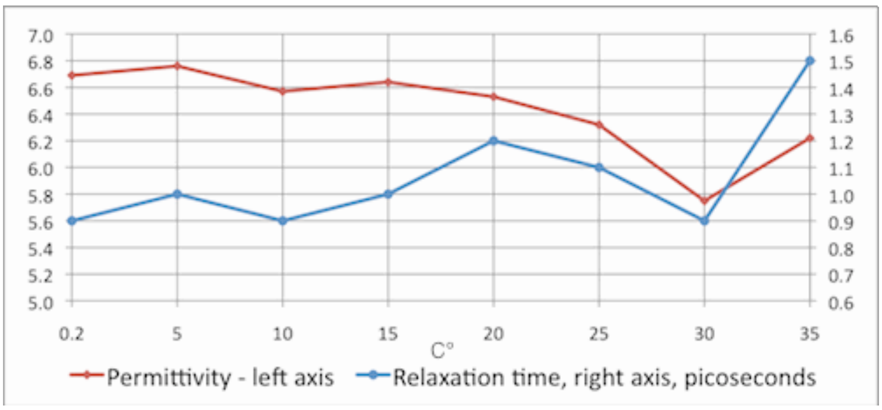

Figure 8: Anomalous dielectric behaviour of water (10)

Below 30 Cº, 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 Cº, 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 surfactants, 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.

d. Clouds

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 (11). It's an important point that this was an established and uncontroversial hypothesis long before it became politically significant.

Recently Svensmark (12) 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.

e. Terminology

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. Natural cycles

The major ocean currents have quasi-millennial timing of around 800 to 1000 years. Along with climate optima, they are probably best seen as geographical events that are influenced by weak external drivers that have a more regular cyclic pattern. What might those driver be?

I took a published model for sunspot cycles, and after a few hours of messing about with a spreadsheet, had it adapted to model southern ocean sea surface temperatures. For a more complete description see (13).

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