A physicist's view on atmospheric and climate models

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- Introduction, aims
- The gardener's greenhouse, greenhouse effect, greenhouse gases, climate change in a shoebox
- Radiative equilibrium of objects in the sun
- Textbook absorption / re-radiation (A/RR) theory
- The "convective" part of simple "radiative-convective" models
- Textbook Consensus Radiation Transfer (CRT) theory
- Hard science physics radiation transfer and fluid-kinetic theory and discussion
- More questions about the consensus view on climate

“Greenhouse” does not occur in a greenhouse

- Experiments have shown that the “greenhouse” effect is not the warming mechanism in a greenhouse. The mechanism is suppression of convection.
  - R.W. Wood Philosophical magazine 19 (1909) 319-320.
  - http://www.drroyspencer.com/2013/08/revisiting-woods-1909-greenhouse-box-experiment-part-i/
  - http://www.principia-scientific.org/the-famous-wood-s-experiment-fully-explained.html
- This fact is well-known to *Consensus Climatologists* (CC’s):
  - “The next 18 pages of GT09 are devoted to showing that the atmospheric greenhouse effect relies on different physical processes than the warming in a glass greenhouse. This is a well-known fact that can be found even in popular expositions of the atmospheric greenhouse effect and is mentioned on p. 115 of the 2007 IPCC report.[13]” [Halpern et al. (2010); Gerlich & Tscheuschner (2009)]
  - “Radiation from the atmosphere back towards the surface raises its temperature above (…), giving rise to what we (somewhat inaccurately) call the greenhouse effect. [Vardavas & Taylor (2007)]
  - “the analogy should not be taken too far , but the term is too well-ingrained in the popular literature to ignore it altogether). [Taylor (2005)]
- The physics of the “greenhouse box” or of the “climate change in a shoebox” is much more complex than the simple absorption/re-radiation scheme and is even not well understood [Berto, et al (2014); Buxton (2014); Wagoner (2010)]

Temperature of a surface S at ground in the sun without convection

- Power radiated normally on a flat disk of radius R_d

$$P_s = \sigma T_s^4 \frac{R_s^2}{d_{se}^2} S(1-\alpha_e)(1-\varepsilon_e)$$

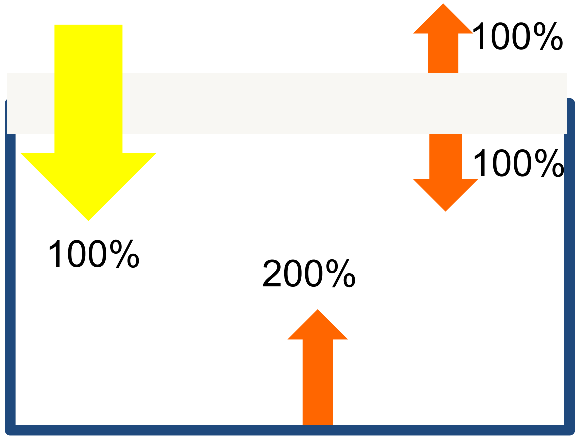
$$\alpha_e = 0.3; \quad \varepsilon_e = 0.25$$

- Power radiated by the disk

$$P_d = \sigma T_d^4 \; S$$

$$P_d = P_s \quad \Rightarrow \quad T_d = 62°\mathrm{C}$$

Temperature on the ground of the Gardener's greenhouse according to the "greenhouse effect"



$$T_d = 2^{1/4}(273 + 62) - 273 = 125°\mathrm{C}$$

This is (schematically) the way atmospheric models incorporate radiative balance (without water feedback [Berger & Tricot (1992)])

Questions and terminology

- Why should the simplistic absorption/re-radiation scheme work better in the very complex situation of the atmosphere than in box experiments?
- Why should we believe that this many orders of magnitude more complex problem is fully understood and accurately predictable while it is not in the simple “box” situations?
- Why do consensus climatologists insist on continuing to call a cat a dog?

- “Greenhouse effect” is a misnomer for the absorption/re-radiation (A/RR) mechanism advocated by CC
- A greenhouse gas is a gas that one can find in a greenhouse. Irrelevant to atmosphere or climate.
- I call a gas that has (does not have) radiation lines in the infrared an infrared active gas or IRA gas or IRAG (an infrared inert gas or IRI gas or IRIG)

The radiative sun-earth balance

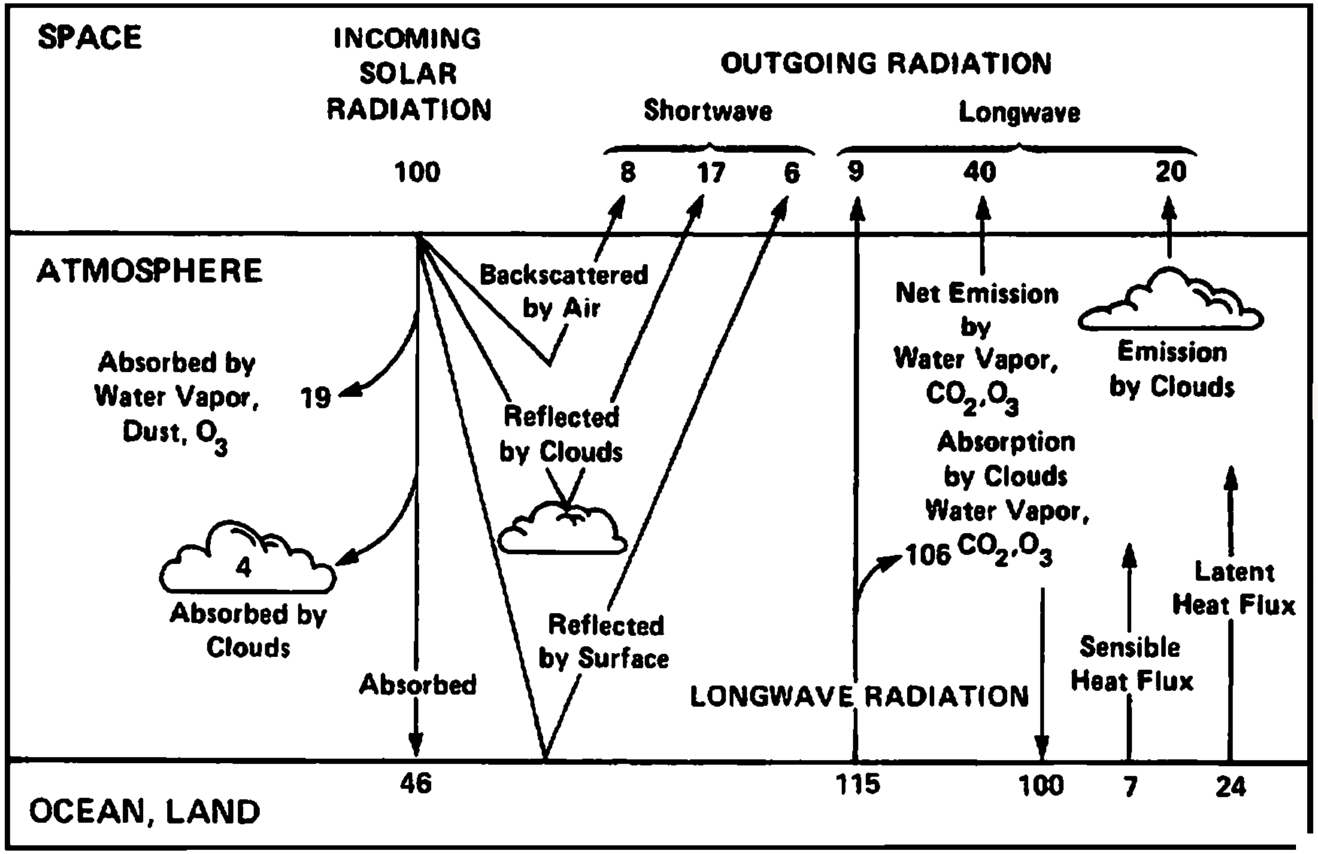
- Power radiated by the sun deposited on the earth surface: $$P_s = \sigma T_s^4 \frac{R_s^2}{d_{se}^2} \pi R_e^2 (1-\alpha_e)$$ $$\alpha_e = 0.3$$
- Power radiated by the earth $$P_e = \sigma T_e^4 4\pi R_e^2$$
- Balance $$P_e = P_s \quad \Rightarrow \quad T_e = 255\text{K} = -18°\text{C}$$ $$\sigma T^4 = 240 \text{ W/m}^2$$
- T_e is the "radiative" temperature of the earth
- Agrees with the radiated power flux measured by satellite
- However ground temperature □ 15°C $$\sigma T^4 = 390 \text{ W/m}^2$$

Greenhouse theory: the IR is absorbed by gases and re-radiated, partly to ground

Thermodynamic paradox:

A colder body

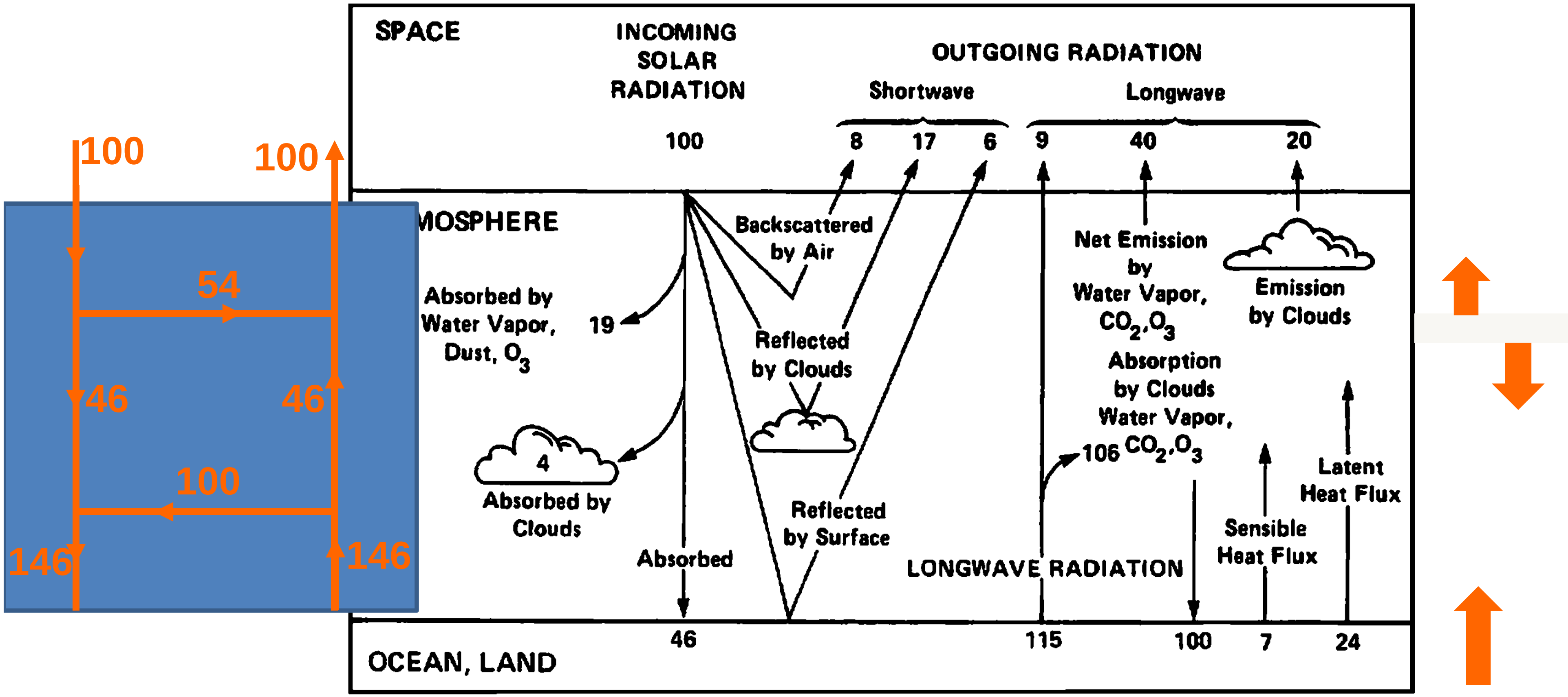
Heats a hotter one



Radiation Transfer theory

- CO_2 radiative forcing $\Delta F[W/m^2]=-6.3\ ln(C/C_0)$

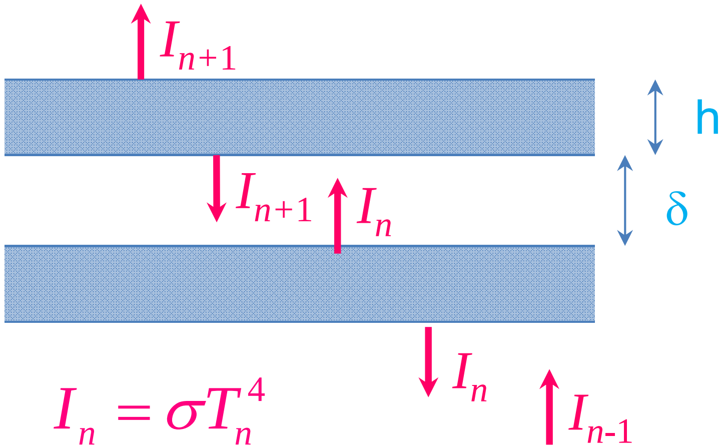
Greenhouse theory: the IR is absorbed by gases and re-radiated, partly to ground



Radiation Transfer theory

Textbook atmosphere in radiative equilibrium

"A third model for the vertical temperature profile is one that assumes dynamical processes are negligible compared to radiation, so the profile is determined by the equilibrium between the heating caused by the absorption of incoming solar radiation, the cooling to space by thermal infrared emission, and the radiative exchange between atmospheric layers at different heights. [Vardavas & Taylor (2007)]
Also in [Goody & Walker 1972], [Taylor 2005], [Halpern et al., 2010],



$$I_n = \sigma T_n^4$$

Conservation of power flux:

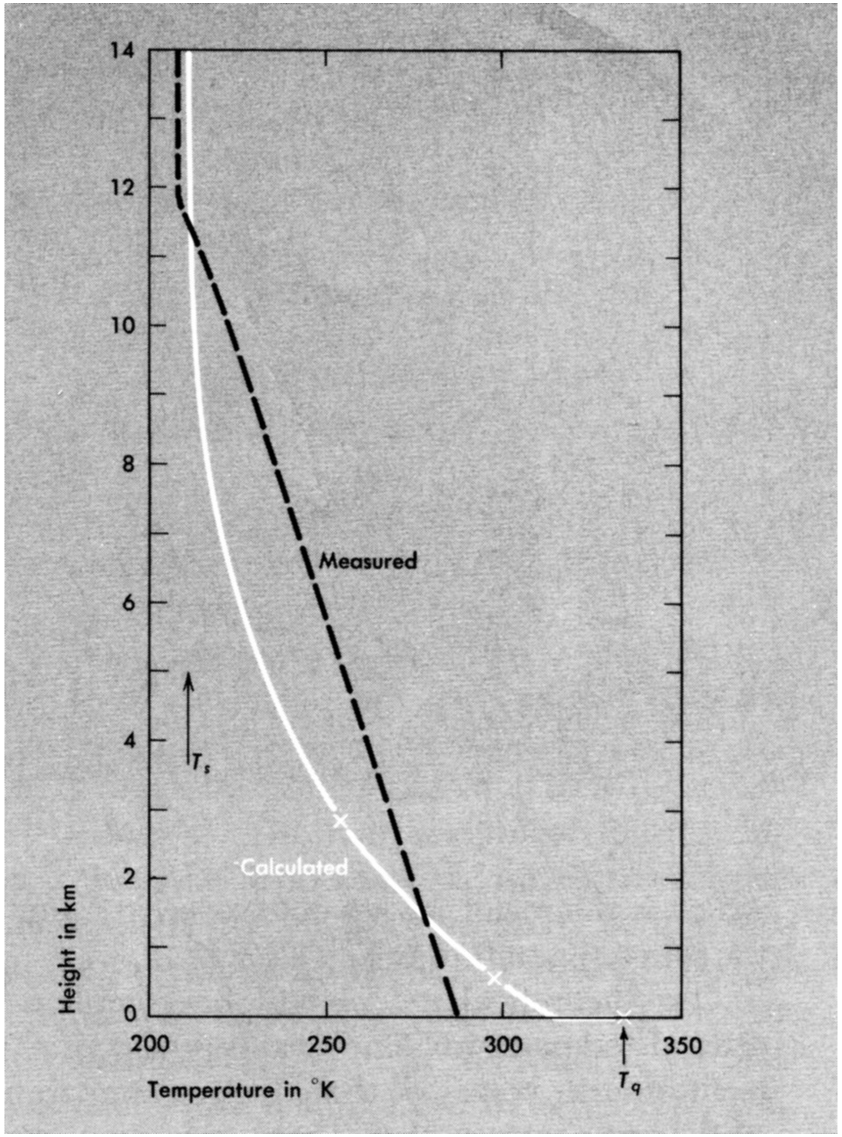
$$I_{n-1} - I_n = I_n - I_{n+1}$$

One can take $\delta \rightarrow 0$; then

$$I(z-h) - I(z) = I(z) - I(z+h)$$

$$\lim_{h\to 0} \frac{I(z+h) + I(z-h) - 2I(z)}{h^2} = \frac{d^2 I}{dz^2} = 0 \qquad \Rightarrow \qquad \frac{d^2}{dz^2} T^4(z) = 0$$

Textbook atmosphere in radiative equilibrium



[Goody & Walker 1972; Fig.3-8]

"…the true tropospheric profile is not the result of radiative equilibrium alone, since the radiative equilibrium profile is unstable against convection (super-adiabatic). If the air were as cool at say 5 km altitude as radiative equilibrium predicts, it would rapidly sink and be replaced by warmer air from below."
[Taylor 2005]

⇒ (1) The radiative flux unbalance present in the real *T(z)* profile is taken over by fluid (convective) power fluxes

⇒ (2) *T(z)* profiles differing from the actual (adiabatic) one are unstable

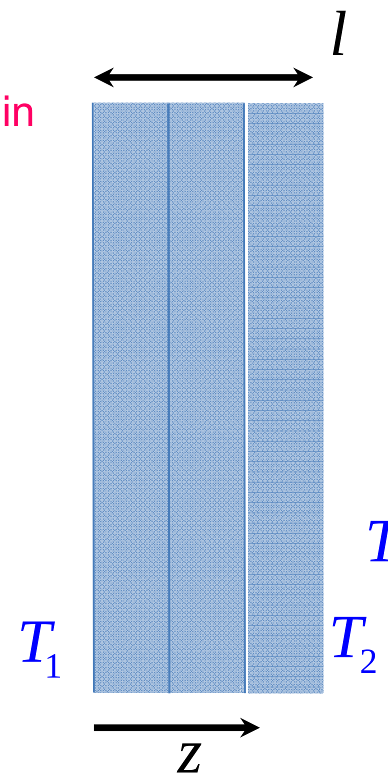
Textbook atmosphere in radiative equilibrium

⇒ (1) The radiative flux unbalance present in the real *T(z)* profile is taken over by fluid (convective) power fluxes

⇒ (2) *T(z)* profiles differing from the actual (adiabatic) one are unstable

The stability of an (inverted) temperature profile is determined not by adiabaticity or because it is the actually measured one but by the threshold conditions for the onset of Rayleigh-Bénard convection cells. The threshold results from the balance between the buoyancy force that tends to move the fluid upwards and the viscous force that opposes that motion.

Viscous forces are never invoked by CC in such stability discussions.



Glass layer, no convection in the material, radiative equilibrium must hold

$$\frac{d^2}{dz^2}T^4(z) = 0$$

$$T(z) = \left[T_1^4 + \frac{z}{l}(T_2^4 - T_1^4)\right]^{1/4}$$

Heat flux (z), not a static equilibrium

Fourier's law violated

$$\frac{d}{dz}\left(\kappa\frac{dT}{dz}\right) = 0$$

The “convective” part of simple (didactic) radiative-convective models – First version

- Thermodynamic analysis: the total internal energy (per unit mass) of gas should be conserved in the convective motion

$$dU = c_p dT + g dz = 0$$

- At equilibrium (+ moist air c_p nearly constant + initial condition)

$$\frac{dT}{dz} = -\frac{g}{c_p} \Rightarrow T = -6.5(z-5)-18 \quad [\text{km, °C}]$$

- T_e = -18°C at 5 km altitude

- Ground temperature: +14.5°C

The "convective" part of simple (didactic) radiative-convective models – Second version

- [Vardavas & Taylor (2007)], [Taylor 2005]
- Heat exchange between an atmosphere parcel and its surroundings (per mole) during its vertical motion: $dQ = C_v dT + pdV$
- Adiabatic motion: $dQ = C_v dT + pdV = 0$
- Ideal gas law: $pV = RT \quad \Rightarrow \quad \mathrm{p}dV + Vdp = (C_p - C_v)dT$
- Hydrostatic equation: $dp / dz = -\rho g = -Mg / V$
- Combining: $\dfrac{dT}{dz} = -\dfrac{Mg}{C_p} = -\dfrac{g}{c_p}$
- Or from fluid theory: $-\nabla p - \rho \mathbf{g} = 0 \; ; \; p = K\rho^{\gamma} \; ; \; p = nk_B T$

The "convective" part of simple (didactic) radiative-convective models – Fluid version

- The basis of fluid theory is Boltzmann's equation. Fluid theory follows by taking velocity moments (collisionless version)
- Zeroth-order: mass conservation $\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{v}) = \mathbf{0}$
- First order: hydrostatic equation $-\nabla p - \rho \mathbf{g} = 0$
- The second order (energy) moment: of the Boltzmann equation reads (scalar pressure approximation, no viscosity, approximate heat flux)

$$\frac{3}{2}\frac{Dp}{Dt} - \frac{5}{2}\frac{p}{\rho}\frac{D\rho}{Dt} + \nabla.(-\kappa\nabla T) = 0 \qquad \left(\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{u}.\nabla\right)$$

- Ideal gas law: $p = nk_B T = (\rho / m)k_B T$ (m molecular mass)
- Adiabatic assumption: heat flux vector = $\mathbf{Q} = -\kappa\nabla T = 0$

$$\frac{3}{2}\frac{Dp}{Dt} - \frac{5}{2}\frac{p}{\rho}\frac{D\rho}{Dt} = 0 \Rightarrow \frac{D(p\rho^{-\gamma})}{Dt} = 0;\ \gamma = \frac{5}{3} \quad \Rightarrow \quad p = K\rho^{\gamma};\ \ K \text{ constant}$$

- Leads to exactly the same law $\frac{dT}{dz} = -\frac{g}{c_p}$ as the two other derivations

Problems with the didactic convective model

- Theory is incomplete: K unknown (bc T=-18°C at z= 5 km)
- Because $dT/dz \neq 0$ the heat flux $Q = -\kappa dT/dz$ is non-zero
- Contradicts the adiabatic assumption and the static fluid assumption because $\kappa \propto \sqrt{T}$ according to kinetic theory and so $dQ/dz \neq 0$
- The divergence of the heat flux $\mathbf{Q}$ not balanced by anything
- At TOA conductive flux should be converted to radiative flux (IRA gases?)

The "convective" part of simple (didactic) radiative-convective models – Kinetic version

- Instead of starting with (truncated)ideal fluid equations start with Boltzmann's equation (1-D, collisionless) $$\frac{\partial f}{\partial t} + v_z \frac{\partial f}{\partial z} - g \frac{\partial f}{\partial v_z} = \mathbf{0}$$ (stationnary)
- General solution: $$f(z, v_z) = F(\frac{v_z^2}{2} + gz)$$
- Assume the distribution function at ground level is maxwellian:

$$f(z, v_z) = \left(\frac{m}{2\pi k_B T} \right)^{\frac{3}{2}} \exp \frac{-m(\frac{v_z^2}{2} + gz)}{k_B T}$$ (isothermal atmosphere)

- The canonical ensemble distribution of statistical mechanics says the same (atmosphere in contact with the ground heat reservoir): distribution is

$$f(z, \mathbf{v}) = A \exp[-\beta H]; \quad \beta = \frac{1}{k_B T}; \quad \text{hamiltonian } H = \frac{mv^2}{2} + mgz$$

- Also with rotations and vibrations: $$H = \frac{mv^2}{2} + mgz + \frac{1}{2} I \Omega^2 + \frac{p^2}{2\mu} + k \frac{q^2}{2}$$

The “convective” part of simple (didactic) radiative-convective models – tentative conclusion

- The thermodynamic adiabatic theory as well as the equivalent fluid theory is incomplete and inconsistent
- Kinetic theory as well at canonical ensemble statistical theory predict an isothermal atmosphere
- The latter result seems intuitively correct because these descriptions contain no mechanism capable to loose power flux to outer space.
- IRA gases are able to do that by radiating electromagnetic energy $\Rightarrow$ the model is lacking interaction terms with the photon gas (as well as collision terms)

The radiation transfer equation

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathbf{s}.\nabla I_\nu = \eta_\nu - \chi_\nu I_\nu$$

s direction of propagation

I_ν radiance [W/(m^{2}sr Hz)]; irradiance $\mathrm{F}_\nu = \pi I_\nu$ [W/(m^{2}Hz)]

Blackbody radiance (Planck's law) $B_\nu = \dfrac{2h\nu^3 / c^2}{e^{\frac{h\nu}{k_B T}} - 1}$

Stefan-Boltzmann's law $\int_0^\infty \pi B_\nu d\nu = \sigma T^4$ [W/m^2]

η_ν volume emission

χ_ν extinction coefficient: $\dfrac{dI_\nu}{ds} = -\chi_\nu I_\nu$

The consensus radiative transfer equation (CRTE)

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathbf{s}.\nabla I_\nu = \eta_\nu - \chi_\nu I_\nu$$

[Vardavas & Taylor 2007]
[Blundell & Blundell 2010]

$$\cos\theta \frac{\partial}{\partial z}$$

$$\chi_\nu = \kappa_\nu \text{ (absorption)} + \sigma_\nu \text{ (scattering)}$$

$$\eta_\nu = \varepsilon_\nu B_\nu; \quad \varepsilon_\nu = \text{ emission coefficient (no scattering)}$$

"In a state of thermodynamic equilibrium all processes are in equilibrium including *radiative equilibrium* (RE), and so the emitted and absorbed energy by the element of volume are equal $\eta_\nu = \chi_\nu I_\nu$
Thus, for a blackbody, the emission coefficient is identical to the absorption coefficient" [Vardavas & Taylor 2007]

$$\boxed{\varepsilon_\nu = \kappa_\nu}$$

"The amount of radiation it emits(*) at frequency ν will be proportional to its density and also κ_ν (because "good absorbers are good emitters)" [Blundell & Blundell 2010]; (*) the medium)

$$\langle\cos\theta\rangle = \mu_c \qquad \cos\theta \frac{\partial I_\nu}{\partial z} = \varepsilon_\nu (B_\nu - I_\nu)$$

Diffusivity approximation
or Schuster-Schwartzschild equation

A/RR theory: radiative equilibrium

$$\frac{dI_\nu^\uparrow}{dz} = \varepsilon_\nu B_\nu - \varepsilon_\nu I_\nu^\uparrow \quad (1) \qquad \frac{dI_\nu^\downarrow}{dz} = -\varepsilon_\nu B_\nu + \varepsilon_\nu I_\nu^\downarrow$$

Define $\chi = \int_0^z \varepsilon_\nu dz$:

$$\frac{dI_\nu^\uparrow}{d\chi} = B_\nu - I_\nu^\uparrow \qquad \frac{dI_\nu^\downarrow}{d\chi} = -B_\nu + I_\nu^\downarrow$$

Radiative equilibrium $\Rightarrow I_\nu^\uparrow - I_\nu^\downarrow = K = I_\nu^\uparrow(\chi_m) = I_\nu^\uparrow(0) - I_\nu^\downarrow(0)$

$$I_\nu^\uparrow + I_\nu^\downarrow = 2B_\nu \ ; \quad d(I_\nu^\uparrow + I_\nu^\downarrow)/d\chi = -K$$

$$\begin{cases} I_\nu^\uparrow = \frac{1}{2} I_\nu^\uparrow(\chi_m)(2 + \chi_m - \chi) \\ I_\nu^\downarrow = \frac{1}{2} I_\nu^\uparrow(\chi_m)(\chi_m - \chi) \end{cases}$$

$$\boxed{2B_\nu = I_\nu^\uparrow(\chi_m)(1 + \chi_m - \chi)}$$

$$\chi_m - \chi = \int_z^{z_m} \varepsilon_\nu dz$$

A/RR theory: radiative equilibrium
Consequences

$$\chi_m - \chi(z) = \int_z^{z_m} \varepsilon_\nu dz$$

$$2B_\nu = I_\nu^\uparrow(\chi_m)(1 + \chi_m - \chi) = \frac{4h\nu^3}{c^2} \frac{1}{e^{h\nu/k_B T} - 1}$$

T(z) is entirely determined by the absorption at frequency ν (!!?)

For global balance:

$$\sigma T^4 = \int_0^\infty I_\nu^\uparrow(\chi_m)[1 + \chi_m - \chi(z)]d\nu$$

Uniform absorption:

$$2\sigma T^4 = I_\nu^\uparrow(\chi_m)[1 + \varepsilon(z_m - z)] \quad \Rightarrow T = T_m[1 + \varepsilon(z_m - z)]^{1/4}$$

Radiative equilibrium does not make sense

CRT theory: solutions and use

$$\frac{dI_\nu^{\uparrow}}{dz} = \varepsilon_\nu B_\nu - \varepsilon_\nu I_\nu^{\uparrow} \qquad \frac{dI_\nu^{\downarrow}}{dz} = -\varepsilon_\nu B_\nu + \varepsilon_\nu I_\nu^{\downarrow} \qquad \chi = \int_0^z \varepsilon_\nu dz \qquad \text{TOA: } \chi_m = \int_0^{z_m} \varepsilon_\nu dz$$

Everything solvable by simple quadratures

Upwelling flux at TOA ($z = z_m$): $I_\nu^{\uparrow}(z_m) = B(0)e^{-\chi_m} + \int_0^{z_m} e^{-\chi(z')}\varepsilon(z')B(z')dz'$

$$\int_0^\infty I_\nu^{\uparrow}(z_m)d\nu = 240\ \text{W/m}^2 \ \text{ determines } T(0)$$

Downelling flux at ground ($z = 0$): $I_\nu^{\downarrow}(0) = \int_0^{z_m} e^{-\chi(z')}\varepsilon(z')B(z')dz'$ Schwartzschild-Milne formula

$$\int_0^\infty I_\nu^{\downarrow}(z_m)d\nu$$

Determines the "greenhouse gas" forcing (additional W/m^2 as if coming from sun)
May be used in conjunction with GCM's to take the "greenhouse effect" into account

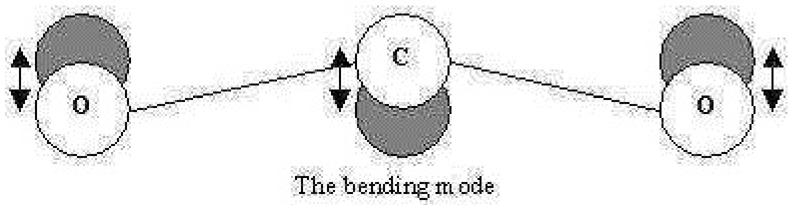
Disappearing / appearing volume power density $\frac{d}{dz}(I_\nu^{\uparrow} - I_\nu^{\downarrow}) \neq 0$

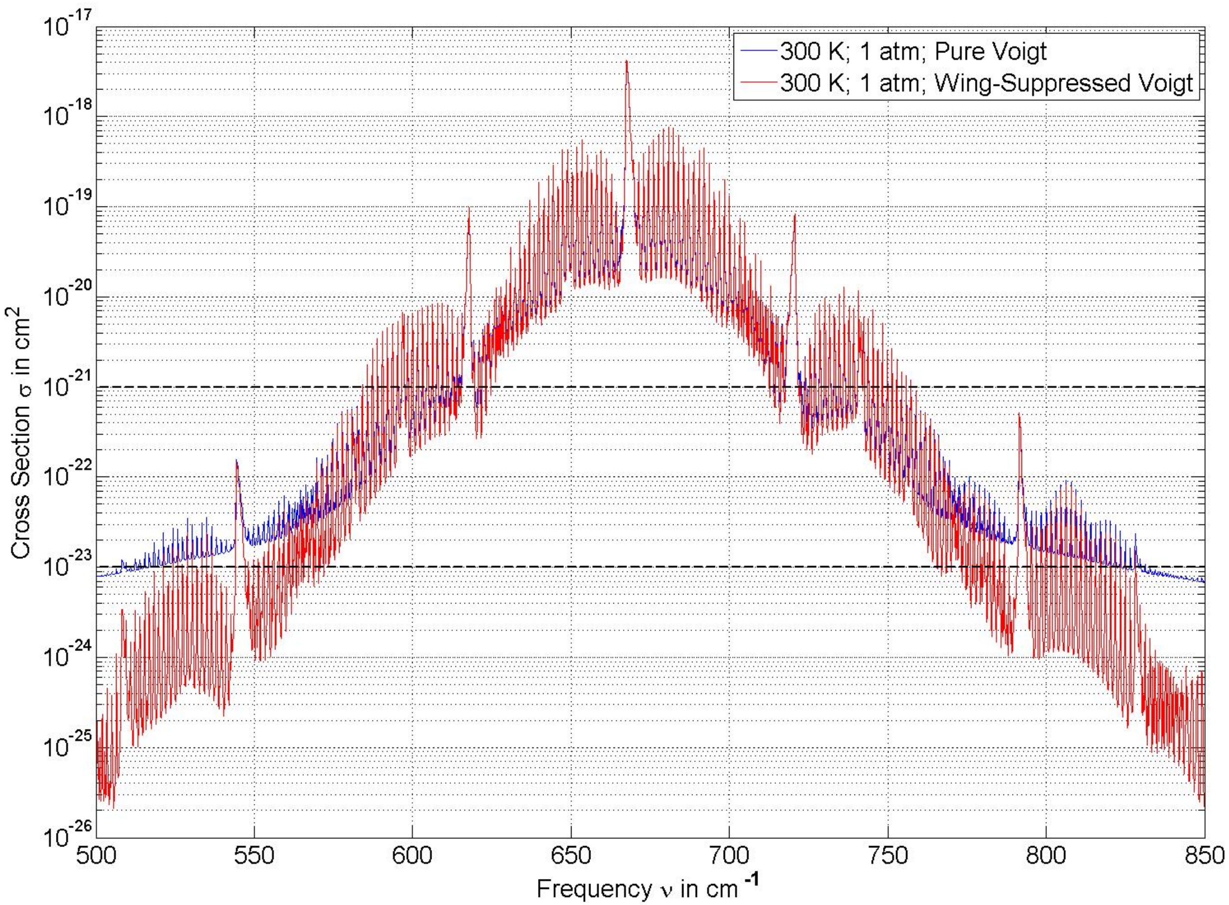
Not taken into account anywhere

Even CRT theory is complex and uncertain

Even using the above model frequency per frequency (LBL)

Bending mode giving rise to the 666 cm^{-1} (f/c) line:





Rotational sidebands

Collisional broadening

Doppler broadening

"Assuming Voigt line shapes greatly overestimates the net CO_2 cross section in the wings of the band". [Happer 2015]

The hard science version of radiative transfer equations

$f(\mathbf{p},\mathbf{r},t)$ Occupation number per energy level, per polarization ($\mathbf{p} = p\hat{\mathbf{s}}$; $p = h\nu / c$)

In thermal equilibrium: $f = f_0 = \dfrac{1}{e^{\frac{h\nu}{k_B T}} - 1}$ (Planck's distribution)

Density of states per unit volume F: $F d\nu = 2f\ d^3 p / h^3 = \dfrac{8\nu^2}{c^3} f d\nu$

Photon energy density: $U = h\nu F = \dfrac{8h\nu^3}{c^3} f$

Photon energy flux $I_\nu = \dfrac{c}{4} U = \dfrac{2h\nu^3}{c^2} f$; In thermal equilibrium: $\dfrac{2h\nu^3}{c^2} f_0 = \dfrac{2h\nu^3 / c^2}{e^{\frac{h\nu}{k_B T}} - 1} = B_\nu$

Kinetic equation for the photon density of states:

$$\frac{1}{c}\frac{\partial f}{\partial t} + \hat{\mathbf{s}}.\nabla f = \sum_{l<n} \Delta_{ln}; \quad \Delta_{ln} = N_n \sigma_{nl}(\nu)[1+f] - N_l \sigma_{ln}(\nu) f$$

[Liboff (2003), Pomraning (2003)]

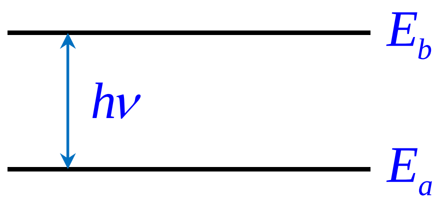
The hard science radiative transfer equations

$$\frac{1}{c}\frac{\partial f}{\partial t}+\hat{\mathbf{s}}.\nabla f=\sum_{l<n}\Delta_{ln};\quad \Delta_{ln}=N_n\sigma_{nl}(\nu)[1+f]-N_l\sigma_{ln}(\nu)f \qquad (1)$$

N_n Number density of molecules in the n-th excited state

σ_{ln} Cross-section for the transition $l\rightarrow n$ at frequency ν (for I_ν: Einstein coefficients)

Absorption / emission symmetry: $g_l\sigma_{ln}=g_n\sigma_{nl};\quad g_n$ degeneracy of the n-th state



Two-level system $\sum_{l<n}\Delta_{ln}=\Delta_{ab}=N_b\sigma_{ba}(\nu)[1+f]-N_a\sigma_{ab}(\nu)f$

Equilibrium: $\Delta_{ab}=0;\quad N_a=g_a e^{-E_a/(k_BT)}\Rightarrow f=f_0=\frac{1}{e^{h\nu/(k_BT)}-1}$

Eq. (1) is a generalization of Planck's law

Assume thermodynamic equilibrium: $\hat{\mathbf{s}}.\nabla f=g_b\sigma_{ba}e^{-E_a/(k_BT)}\left[\cancel{e^{-h\nu/(k_BT)}}(1+f)-f\right]$

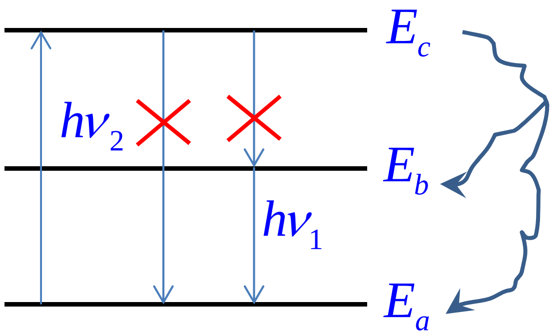
$$\neq\kappa_\nu(B_\nu-I_\nu)$$

"for the CO_2 transitions that are most significant in the thermal IR, the lifetimes(*) tend to range from a few milliseconds to a few tenths of a second. In contrast, the typical times between collisions (…) is well under 10^{-7}s." [Pierrehumbert 2011]

(*)of the excited states

The hard science radiative transfer equations

$$\frac{1}{c}\frac{\partial f}{\partial t} + \hat{\mathbf{s}}.\nabla f = \sum_{l<n} \Delta_{ln}; \quad \Delta_{ln} = N_n \sigma_{nl}(\nu)[1+f] - N_l \sigma_{ln}(\nu) f \qquad (1)$$



- The absorption / radiation process + mechanical collisions displace the radiation spectrum to other (lower) frequencies

- Single-frequency radiation transfer analysis makes no sense (LBL?)

What should be a correct description of a stationary-state equilibrium?

For each possible energy transition (vibration-rotation) of the IRA molecules (species a)

$$\hat{\mathbf{s}}.\nabla f = \sum_{l<n} \Delta_{lna}; \quad \Delta_{lna} = N_{na}\sigma_{nla}(\nu)[1+f] - N_{la}\sigma_{lna}(\nu) f$$

A Boltzmann equation determining each population density N_{na} (for each type of IRA molecule) and for each type of IRI molecules (species i) [all species s={a,i}]

$$\mathbf{v}.\nabla N_{na} - g\hat{\mathbf{z}}.\frac{\partial N_{na}}{\partial \mathbf{v}} = \sum_{l,s} K_e(N_{na}, N_{ls}) + \sum_{n'\neq n,l,s} C_i(N_{n'a}, N_{ls}) - \sum_{l,s} A_i(N_{na}, N_{ls})$$
$$+ \sum_{l\neq n} \{N_{la}\sigma_{lna}(\nu_{ln}) f(\nu_{ln}) - N_{na}\sigma_{nla}(\nu)[1+f(\nu_{nl})]\}$$

$K_e(N_{na}, N_{ls})$ elastic collision operator

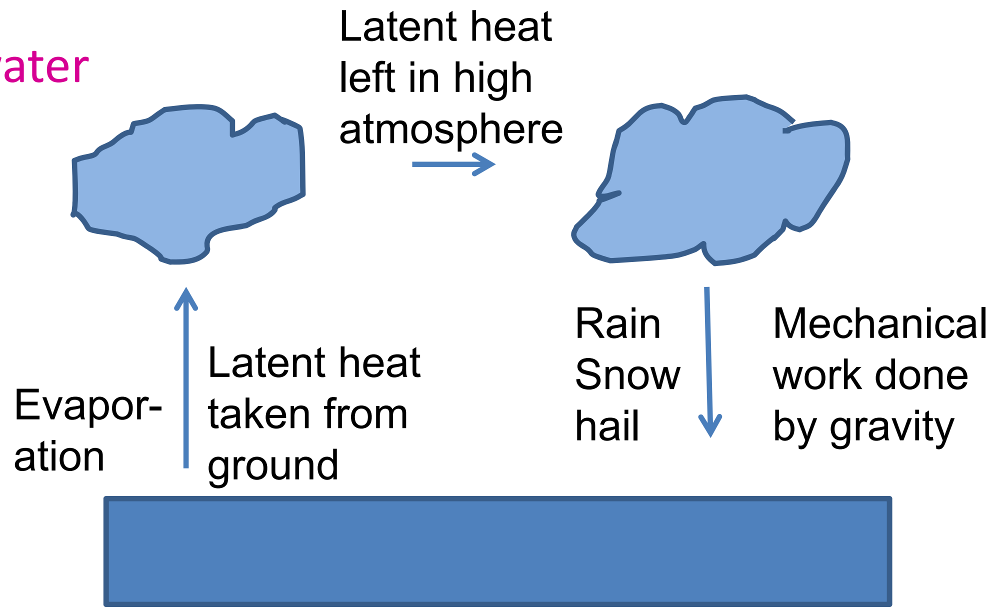
$C_i(N_{na}, N_{ls})$ creation of a state n of molecule of type a from a similar molecule in state n' by inelastic collision with a molecule of type s in state l

$A_i(N_{na}, N_{ls})$ annihilation of a state n of molecule of type a by inelastic collision with a molecule of type s in state l

This should be more correctly written to take into account that the interaction between a molecule at velocity $\mathbf{v}$ sees a photon of frequency ν propagating in direction $\hat{\mathbf{s}}$ at the Doppler-shifted frequency $\nu(1-\mathbf{v}.\hat{\mathbf{s}}/c)$

Summary

- CRT equations are incorrect, they do not conserve power flux
- Applied to the simple case of a glass thickness (no convective motion of material) they lead to absurd conclusions
- Correct equations describing a static atmospheric equilibrium can be written: correct RT equations + Boltzmann's equations for energy level populations of all gas components. Enormous system of equations. Does not imply IRA gases play no role.
- This system is consistent but
- Missing: liquid and solid phases of water



The water cycle refrigerator

Notice:
most ȻC accept A/RR picture

[Taylor 2009, Moran et al. 2015]

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Thank you for your attention