Radiative Delay in Planetary Atmospheres

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Abstract:

It is said that radiative gasses (RGs, or greenhouse gasses) trap heat radiated from the Earth's surface causing it's temperature to rise by 33 K above the theoretical temperature with no atmosphere. The word 'trap' is misleading. RGs delay the radiative transmission of heat from surface to space. I estimate this delay and conclude that its average impact on atmospheric temperatures, the Radiative Delay Effect (RDE), is in the order of 0.14 [0.1 to 1] K.

Introduction:

The objective of this work was to quantify the rate at which radiative processes can transfer energy through the atmosphere. Specifically, it considers vertical transfer from the Earth's surface to space, which involves changes in the density, temperature, and the concentration of RGs – primarily water vapour, which condenses as the temperature drops with altitude.

The transfer rate also varies with photon wavelength. In this analysis I am ignoring the spectral aspect of the problem, which dominates most discussion of the topic. I show that to be a negligible aspect of a small effect.

Some regions of the IR energy spectrum are not strongly absorbed by RGs, so about 12% of the energy radiated from the Earth's surface passes through the atmosphere at the speed of light unimpeded. The energy involved in the remainder takes a slower journey. It is the latter flow we are concerned with here.

The atmosphere is not opaque to infrared (IR) radiation, but can be considered as translucent. It is thermoluminescent, so little of the IR photon sea that bathes our atmosphere originates from the surface. It is generated by collisions between RG molecules and other molecules.

Some of the energy of motion – kinetic energy – of the molecules is absorbed by the RG molecules, bumping them into excited energy states. This excitation energy is usually lost back to kinetic energy in a subsequent collision, since the natural lifetime of the excited states is typically far longer than the mean time between molecular collisions.

Occasionally, the excited state may decay naturally, or be stimulated by a weak collision, to produce an IR photon. Since photons travel further and faster than molecules between collisions, they can transfer energy faster than mechanical thermal conduction.

The Process:

The procedure used is to consider a sequence of photons moving up through the atmosphere. The first, emitted near ground level, will travel an average 50 m, which is assumed to be the mean free path (mfp) of an IR photon at ground level (1) before being absorbed by another RG molecule. The next, emitted upward from 50 m, travels a slightly greater distance, since the mfp increases as molecular density decreases with altitude.

These stages are repeated until an average photon escapes to space. Since photons travel at the speed of light their transit time can be ignored. The delay comes from the mean time between photons being emitted, per RG molecule, that move upward by at least one mfp.

Gas molecules emit photons equally in all directions. Half will move upward, and some fraction of these will reach a plane surface one mfp above the source. This fraction, a specific molecular emission rate (SMER), could be calculated from molecular physics and laboratory measurements, but fortunately we don't have to rely on totally theoretical calculations because at the Earth's surface we have direct measurements of the downward radiative flux from the atmosphere.

An estimate for the SMER can be made by first taking the surface incident radiation of 340 W/m^2 (2) and dividing it by the energy of an average IR photon to get the number of incident photons per second. We can assume that, on average, these are emitted from a 1 m^2 column of air, the height of which is approximately the mfp. From the absolute humidity we get the number of water molecules in this column, and hence the number of photons emitted per water molecule per second that reach the ground. The simplifying assumptions made here are discussed in note (3), and allowed for in the final error range.

From radiative symmetry we can use this value in the upward sequence. At each stage, the emission rate is adjusted for the reduction in air density, temperature and composition. The delay accumulates over the stages in the upward transit to space.

The average upward energy flux through the atmosphere is around 200 W/m². This is accumulated over the total delay as increased heat in the 10 tonnes of atmosphere per m² of surface, raising its temperature. To put this into a common perspective, it is equivalent to a 200 W light bulb heating the air in a gym.

Calculations were performed using the OCM workbench (4). An annotated expansion of the code is given in (5).

Results:

A sample of the results is shown in Figure 1. Taking a typical surface temperature of 288 K (15 C) gives a saturation level of 10.6 g/kg and an RDE of 0.14 K. The contribution from CO_2 alone is 0.001 K.
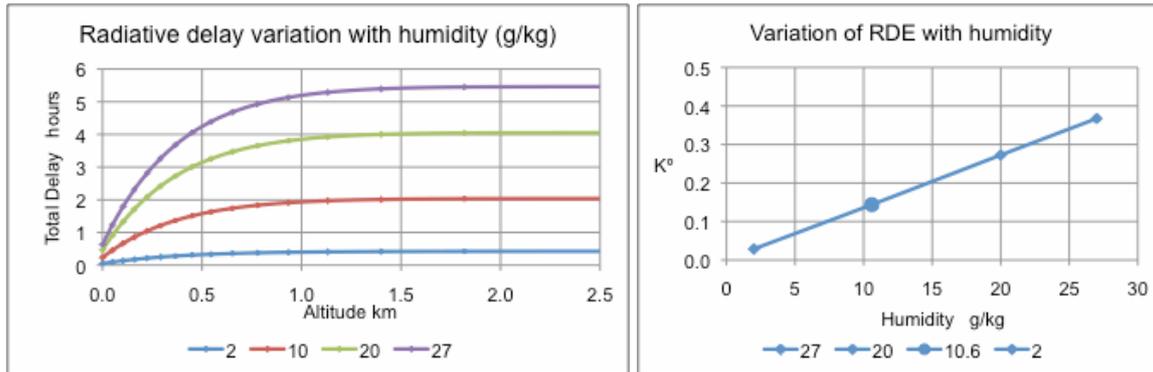

Figure 1a: IR transit delay for a condensing atmosphere and 288 K surface
1b: RDE with humidities ranging from 2 to 27 g/kg for 288 K surface

There are two distinct sources of uncertainty in these results. Wild et.al. (2) claim a 3% uncertainty for their surface radiation figures. The main uncertainty comes from theoretical simplifications discussed in note (3). To avoid adding unnecessary complexity to the calculations and discussion I concede an order of magnitude uncertainty from these and other approximations such as the appropriate choice of typical conditions.

Notes and References:

1: The choice of 50 m for surface IR mfp is a little arbitrary, having no provenance that I've found. I've seen values between 10 and 100+ m suggested, and any value in that range would do for this analysis. Within limits, it turns out to have no impact on the delay figures since its use in calculating IR emission rates at the surface is canceled by its use in determining the delay of the stages.

For example, halving the mfp halves the height of the air column assumed to be radiating to the surface and hence the number of RG molecules emitting. This doubles the estimate of the individual molecular emission rate. Its reciprocal, emission delay, is halved. So while the number of mfp stages doubles, the delay at each stage is halved, leaving the total delay unchanged.

2: Martin Wild et.al., *A new diagram of the global energy balance*, AIP Conf. Proc. 1531, 628 (2013)

3: Assuming that the IR incident on a square meter of the Earth's surface is coming from a single column of the atmosphere above it is clearly an abstraction. The patch of ground receives IR from the whole atmosphere within visual range, but on average about half comes from within the hemisphere with a radius equal to the IR mean free path.

It is an average figure and like any average must be viewed from some larger perspective. We could base the calculation on an area of 10,000 km² so that the 10 km height of the troposphere is just a thin layer, and lateral radiation in and out of the region is a negligible edge effect. Each square meter of surface is, on average, receiving 340 W of IR. This is also the amount that is, on average, radiated from the column above it.

To keep things simple, I am ignoring the fact that in the lower troposphere approximately half the upward heat transfer is through latent heat of vaporisation and convection. Including these would reduce the role of radiation and the value of the RDE by roughly a factor of two since, as can be seen in Figure 1a, most of the

delay occurs below 3km. I am also assuming water vapour saturation at all altitudes, which again overestimates the RDE.

The second law of thermodynamics and entropy require that the energy of the atmosphere be partitioned between sensible heat and gravitational potential energy. Since this point is strangely controversial, and famous physicists are quoted as ignoring the effect of gravity on atmospheric temperatures, I won't press it here. Its inclusion reduces the RDE.

I have chosen to avoid these complexities and have assigned a wide uncertainty range to the result to cover them and other factors.

4: The Open Climate Modeller (OCM) is a workbench for exploring the physics of planetary atmospheres. It follows the approach taken by Nikolov and Zeller (8) of starting with no atmosphere and building incrementally from there. It uses HTML and Javascript, so runs in a web browser from a public server or desktop. A version of OCM, along with an equivalent spreadsheet for the delay calculations (9), will be made available when this article is published to allow independent analysis of the results.

5: Expanding the Javascript code for readability, with 0 subscripts denoting surface values

g	=	9.8	ms^{-2}	Gravitational force
cp	=	1003.5	J/kg.K	Heat capacity of air
N_A	=	6.022E+23	mol^{-1}	Avogadro's number
k_b	=	1.38065E-23	J/K	Boltzmann constant
mH2O	=	16	g/mol	H2O molar mass
mCO2	=	40	g/mol	CO2 molar mass
mAir	=	0.02896	kg/mol	Air molar mass
R	=	8.31447	J/mol.K	Universal gas constant
d	=	3.65E-10	m	Effective size of air molecules
$airT_0$	=	288	K	Surface temperature
$airP_0$	=	101,325	Pa	Surface air pressure
L	=	5.5, 7.7	K/km	Atmospheric temperature lapse rates
h	=	0 to 20000	m	Altitude
hc	=	1.9864E-25	J.m	Planck's constant * velocity of light
λ	=	1.6E-5	m	IR wavelength
$mfpIR_0$	=	50	m	IR mean free path at surface (1)
airMass	=	10300	kg/m^2	Mass of total air column over 1 m^2 of surface
rCO2	=	4E-4	kg/kg	Atmospheric CO2 level
r_e	=	0.29		Relative emissivities of water vapour and CO2 (10)
$humidity_0$	=	0.0106	kg/kg	Specific humidity at surface at 288 K
p_{sv0}	=	1371	Pa	Saturated vapour pressure at T= 288 K
E_{down}	=	340	Wm^{-2}	IR energy flux down to surface
E_{out}	=	200	Wm^{-2}	IR energy flux to space via atmosphere
Q_{phot}	=	1.2415E-20	J	Photon energy at 16 μm, hc/λ
airT	=	$airT_0$ - L * h / 1000	K	Air temperature at height h m
airP	=	$airP_0*(1 - g*h/(cp*airT_0))^{cp*mAir/R}$	Pa	Air pressure at height h
airD	=	airP / (287.06 * airT)	kg/m^3	Air density
CO2D	=	airD * 1000 * rCO2	g/m^3	CO2 density (g by N_A definition)
wvD	=	airD * 1000 * $humidity_0$ * p_{sv} / p_{sv0}	g/m^3	Water vapour density
tempR	=	$(airT / airT_0)^4$		Modifies emissivities
Nrad	=	(wvD + r_e * CO2D)		Density of radiative molecules
mfpIR	=	$mfpIR_0$ * tempR * Nrad0 / Nrad	m	IR mfp at height
p_{sv}	=	from Goff and Gratch equation	Pa	Saturated vapour pressure
N_{WV}	=	mfpIR * wvD * N_A / mH2O		Water molecules in mfp column

N_{CO2}	=	mfpIR * CO2D * N_A / mCO2		CO2 molecules in mfp column
$pFlux_0$	=	E_{down} / Q_{phot}	photons/s	Photon flux to surface

Primary calculation

$pFlux_0$	=	e_{wv0} * N_{wv0} + e_{CO20} * N_{CO20}	photons/s	e is the SMER
	=	e_{wv0} * (N_{wv0} + r_e * N_{CO20})		r_e = e_{CO2}/e_{wv}
e_{wv0}	=	$pFlux_0$ / (N_{wv0} + r_e * N_{CO20})	phot./molcule.s	Surface e
e_{wv}	=	$pFlux_0$ * tempR / (N_{wv} + r_e * N_{CO2})		N, T and e varying with height
$tDelay_h$	=	1 / e_{wv}	seconds	Specific emission delay per stage
	=	(N_{wv} + r_e * N_{CO2}) / ($pFlux_0$ * tempR)		
$tDelay_{tot}$	=	$\sum^h tDelay_h$	seconds	Delay summed over stages
Q_{delay}	=	E_{out} * $tDelay_{tot}$	J	Energy delayed
ΔT_{atm}	=	Q_{delay} / (cp * airMass)	K	Atmospheric temp increase

6: Engineering Toolbox, *Evaporation from water surfaces*.

7: Dai Davies, *Energy and Atmosphere*, brindabella.id.au/climarc/ Energy&Atmosphere.pdf

8: Ned Nikolov, Karl Zeller, *Unified Theory of Climate. Expanding the Concept of Atmospheric Greenhouse Effect Using Thermodynamic Principles: Implications for Predicting Future Climate Change*, http://www.wcrp-climate.org/conference2011/posters/C7/C7_Nikolov_M15A.pdf

9: RadiativeDelay.xlsx accompanying this document provides an alternative to OCM.

10: Paul D. Ronney, http://ronney.usc.edu/AME517F09/PlanckMeanAndLeckner.xls.

11: Leckner B., *Spectral and total emissivity of H2O and CO2*, Combustion and Flame, 19, 33, 1972