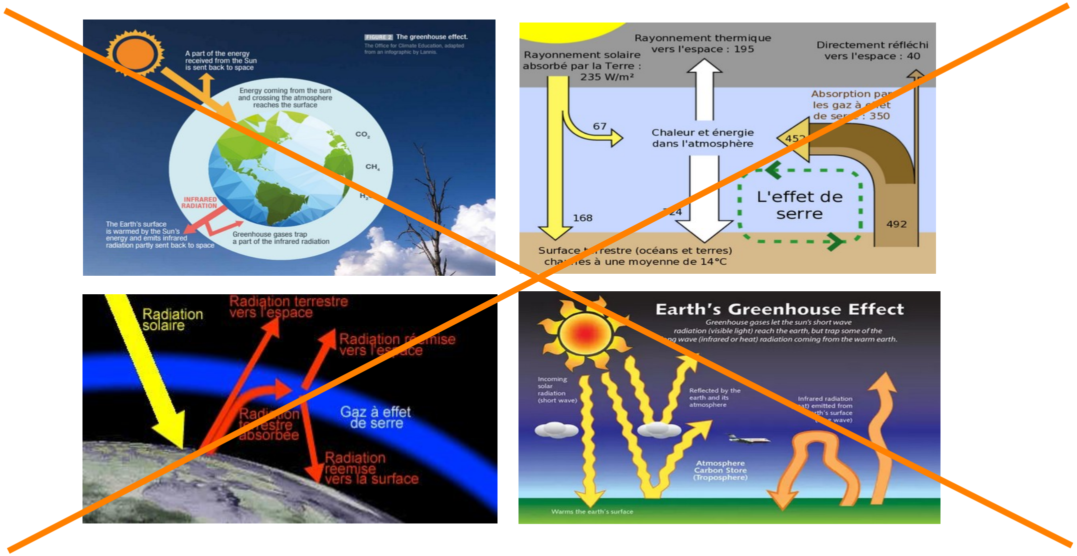
Towards a more correct and relevant explanation of the greenhouse effect

Jean-Louis Dufresne
jean-louis.dufresne@lmd.ipsl.fr

Laboratoire de Météorologie Dynamique et Institut Pierre-Simon Laplace

in collaboration with Valentin Maron and Lionel Pelissier,
EFTS (Education, Formation, Travail, Savoirs) and INSPE, Université Toulouse

Séminaire,UFR TEB, 14 February 2025



Presenting the greenhouse effect as an atmosphere that warms the surface by emitting infrared radiation towards the surface:

• Is inconsistent (false) with the definition of its measure: $G = F_s - F_e$

• Logically leads one to question the role of CO_2 in the greenhouse effect (saturation effect), to fail to understand why high clouds have a greater greenhouse effect than low clouds, etc.

• Doesn't allow for an answer to these legitimate questions.

Programme d’enseignement scientifique de Terminale (section 2.2, p.9)

"Lorsque la concentration des GES augmente, l’atmosphère absorbe davantage le rayonnement thermique infrarouge émis par la surface de la Terre. **Il en résulte une augmentation de la puissance radiative reçue par la surface terrestre de l’atmosphère.** Cette puissance additionnelle entraîne une perturbation de l’équilibre radiatif qui existait à l’ère préindustrielle […] ce qui se traduit par une augmentation de la température moyenne à la surface de la Terre […]" (MEN 2023, p.9)

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IV. Focus on the CO_2 greenhouse effect

V. From radiative forcing to surface temperature change

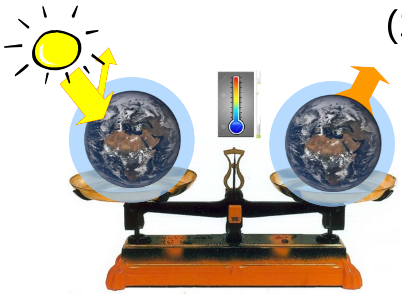
Emergence of climate physics

J. Fourier, 1824: *Mémoire sur les températures du globe terrestre et des espaces planétaires*

(https://www.academie-sciences.fr/pdf/dossiers/Fourier/Fourier_pdf/Mem1827_p569_604.pdf)
English traduction in American Journal of Science, Vol. 32, N°1, 1837.
+ R. Pierrehumbert https://geosci.uchicago.edu/~rtp1/papers/Fourier1827Trans.pdf

Joseph Fourier
(1768-1830)

- ➢ He consider the Earth like any other planet
- ➢The **energy balance equation** drives the temperature of all the planets
- ➢ **The major heat transfers are**
  1. Solar radiation
  2. Infra-red radiation
  3. Diffusion with the interior of Earth



- ➢ The **heat diffusion** with the interior of Earth has a **negligible impact** on the surface temperature
- ➢ Contradicts the thermal death of Earth

He formulated what would later be called the 'greenhouse effect'. *«C'est ainsi que la température est augmentée par l'interposition de l'atmosphère, parce que la chaleur trouve moins d'obstacle pour pénétrer l'air, étant à l'état de lumière, qu'elle n'en trouve pour repasser dans l'air lorsqu'elle est convertie en chaleur obscure »*

"it is thus that the temperature is augmented by the interposition of the atmosphere, because the heat has less trouble penetrating the air when it is in the form of light, than it has exiting back through the air after it has been converted to dark heat."

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He ***envisages the importance of any change of the sun.*** *«Les moindres variations de la distance de cet astre à la Terre occasionneraient des changements très considérables dans les températures, l'excentricité de l'orbite terrestre donnerait naissance à diverses saisons. »*

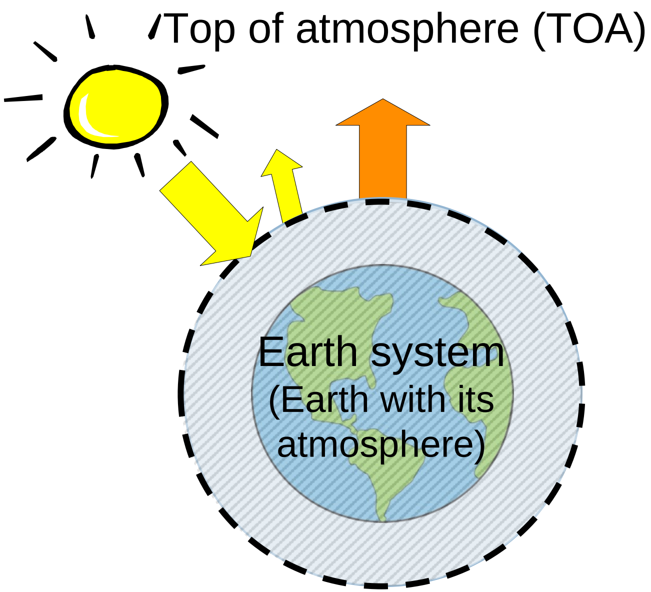
"The least variation of the distance of the Earth from this star would lead to considerable changes in the temperature, and the eccentricity of the Earth's orbit would give rise to new forms of seasonal variations"

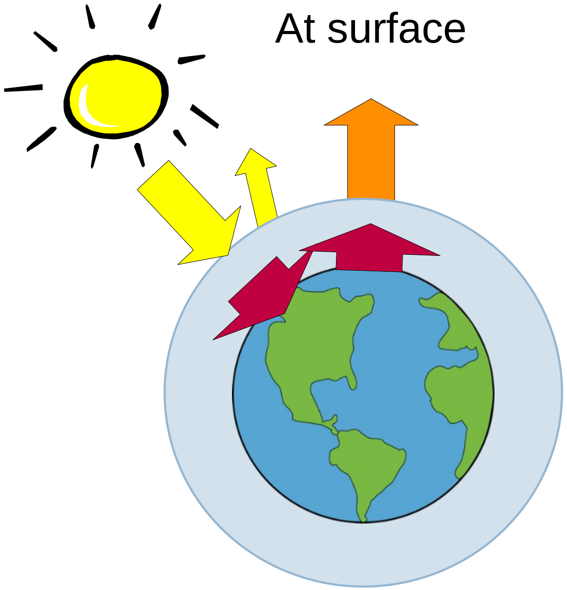
He refuted this possibility, which led him to assume the existence of a "temperature of space", which he took to be equal to that of the poles in winter.

He ***envisages that climate may change***: *« L'établissement et le progrès des sociétés humaines, l'action des forces naturelles peuvent changer notablement, et dans de vastes contrées, l'état de la surface du sol, la distribution des eaux et les grands mouvements de l'air. De tels effets sont propres à faire varier, dans le cours de plusieurs siècles, le degré de la chaleur moyenne; car les expressions analytiques comprennent des coefficients qui se rapportent à l'état superficiel et qui influent beaucoup sur la valeur de la température.»*

"The establishment and progress of human societies, and the action of natural forces, can notably change the state of the ground surface over vast regions, as well as the distribution of waters and the great movements of the air. Such effects have the ability to make the mean degree of heat vary over the course of several centuries, for the analytic expressions contain coefficients which depend on the state of the surface, and which greatly influence the temperature."

Energy budget at the surface or at the top of atmosphere?





Steady state (energy equilibrium): the energy balance is zero at both interfaces.

- The Earth (and other planets) is an open system with the rest of the universe
- Incoming solar radiation is independent of the radiation emitted by the Earth

- Atmosphere and surface are two open systems
- Strong energy coupling between surface and atmosphe

Single column model (from the 60's)

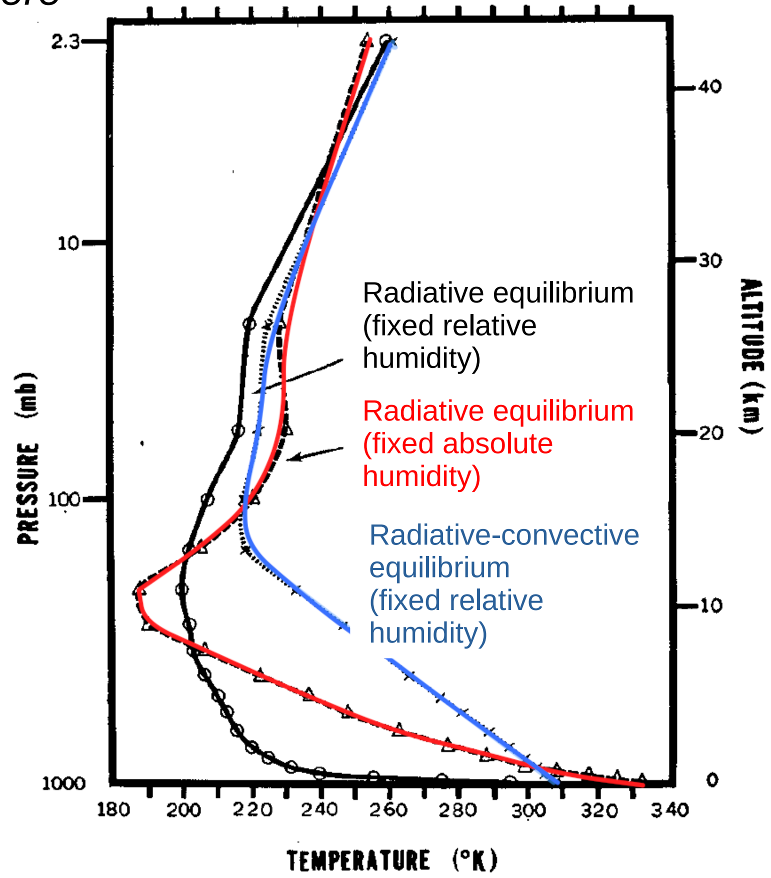
Manabe and Wetherald, 1967: *Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity*

Vertical temperature profile at

- ***radiative*** equilibrium with **fixed relative humidity**
- ***radiative*** equilibrium with **fixed absolute humidity**
- ***radiative-convective*** equilibrium at ***fixed relative humidity***

This article was very influential as it showed:

- **Fundamental role of convection**
- Large difference whether absolute or relative humidity is kept constant
- That for a given CO_2 variation:
  - ***its effect on radiative fluxes had to be considered at the top of the atmosphere, not at the surface (same for other perturbations)***
  - the variation in surface temperature was twice as high if relative humidity was kept constant and not absolute humidity
  - surface and tropospheric temperatures vary in the opposite direction to that of the stratosphere

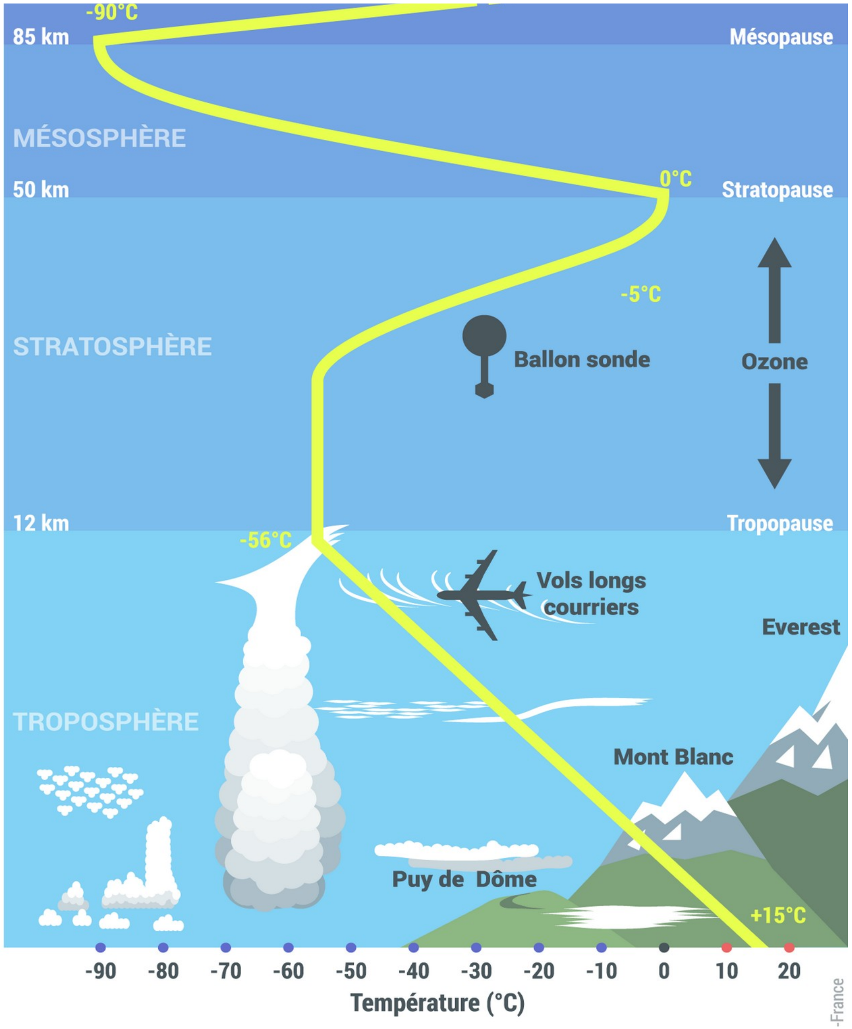


[Manabe and Wetherald, 1967]

Vertical profile of the atmosphere

Stratosphere:
- *Radiative equilibrium*
- Temperature driven by radiation

Troposphere:
- *Radiative-convective equilibrium*
- ***Temperature profile driven by the thermodynamic***



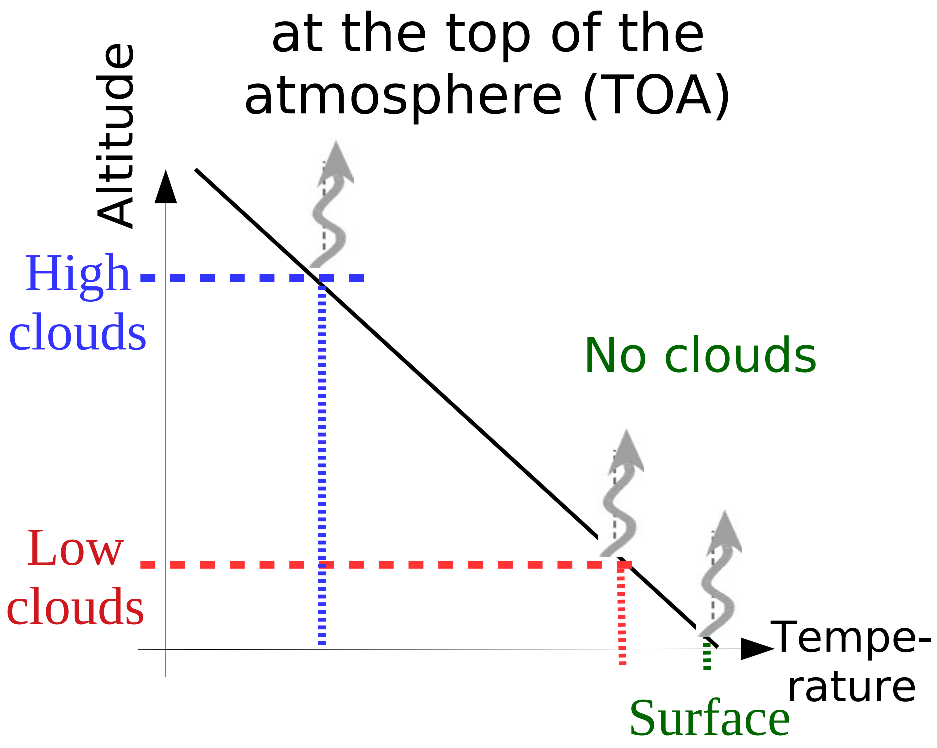
Fraction of the total mass of air below this altitude

99.9%

80-90%

Impact of clouds on LW radiative flux

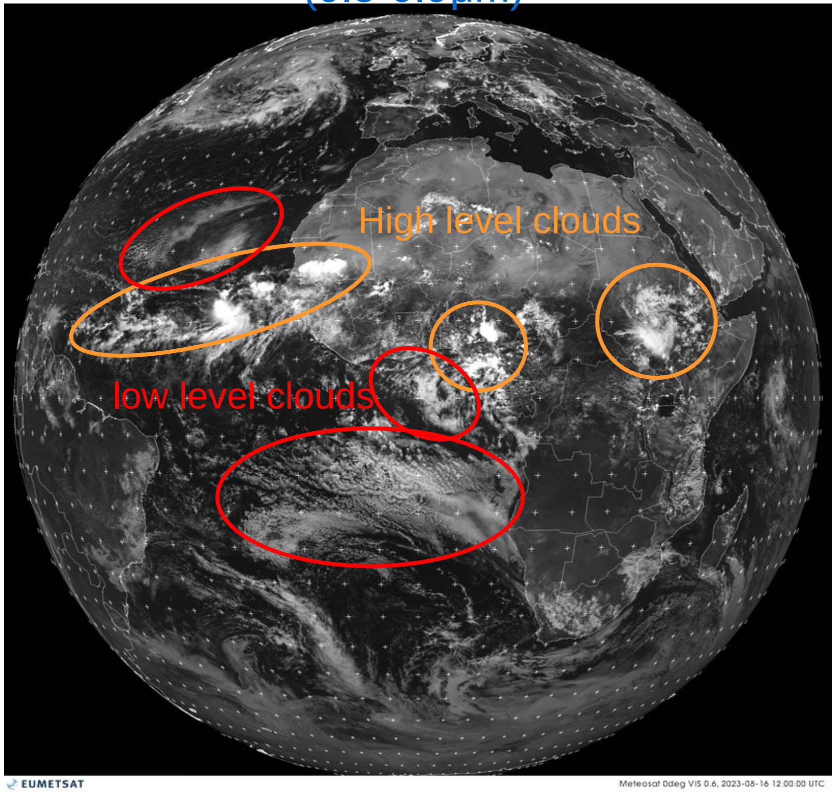
Simplification: **Clouds ≈ blackbody in the LW** ; no absorption in the SW
No LW absorption by the atmosphere



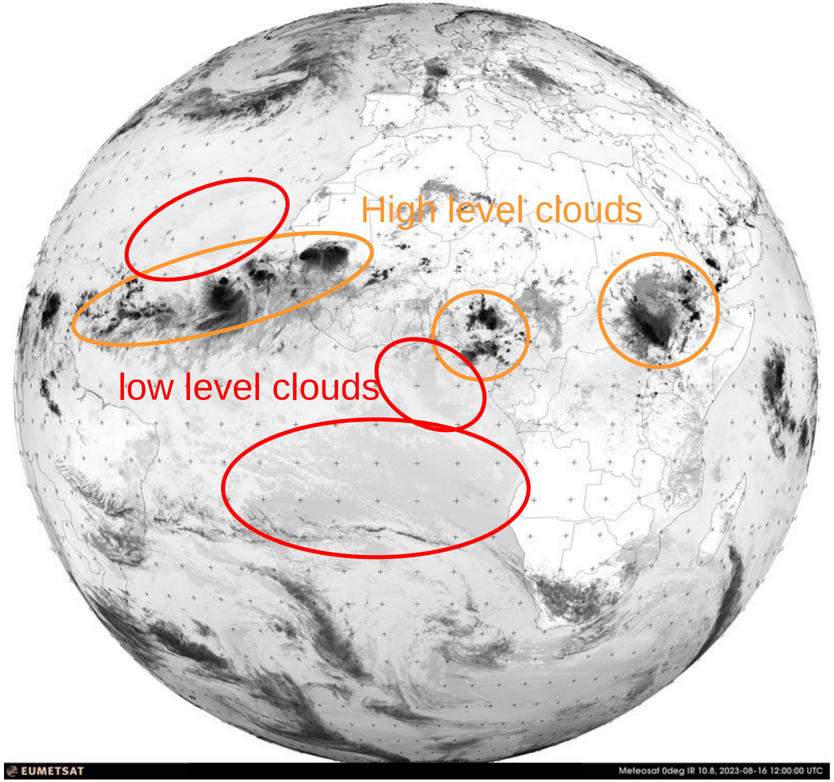
Observation from Meteosat satellite

Meteosat 0° observation on 2023-08-16

Visible
(0.5-0.9µm)



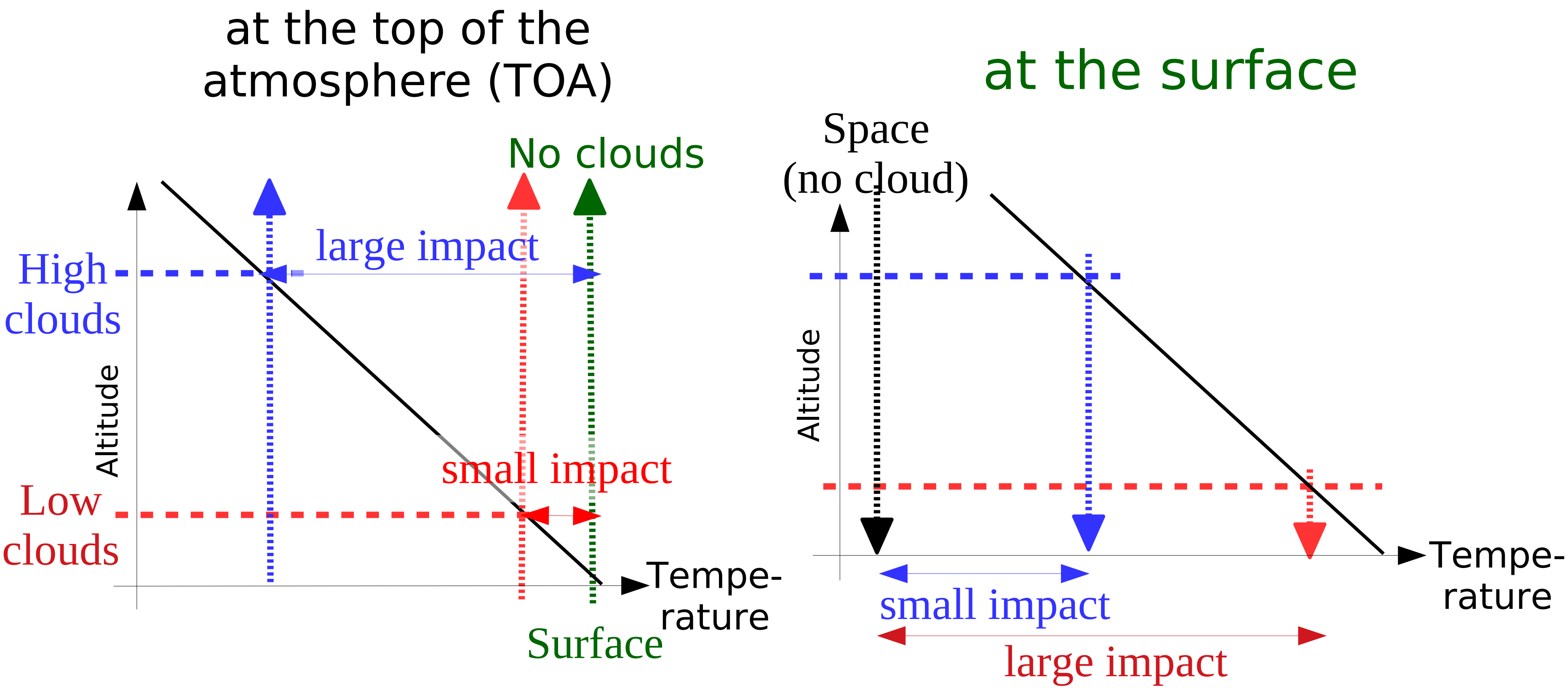
Atmospheric window
(10.5-12.5µm)



Emission (brightness) temperature:
White: warm. Black: cold

http://www.meteo-spatiale.fr/src/autres_sources.php

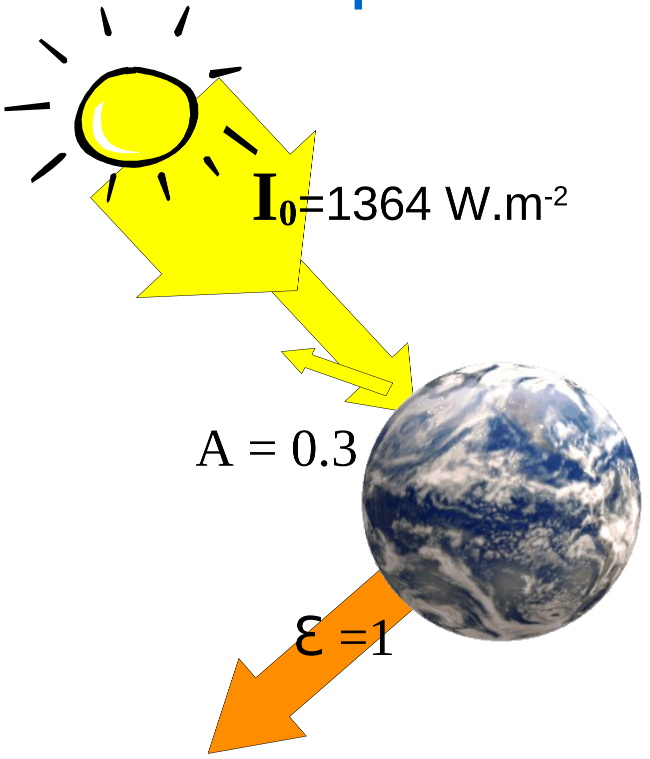
Impact of clouds on LW radiative flux



• The relative impact of high and low level clouds on radiative flux **is opposite at the TOA and at surface**

• For climate, the radiative budget at the TOA is central (cf. [Manabe & Wetherald, 1967])

Equilibrium temperature of planet Earth



Average incoming solar radiation on a **sphere:** $I_s = I_0/4$

We assume the surface temperature is uniform

absorbed solar (shortwave) radiation**:**
$F_a = (1\text{-}A)\ I_0/4 = 240 \text{W.m}^{-2}$

emitted terrestrial (longwave) radiation**:**
$F_e = \varepsilon\ \sigma\ T_e^4$

Steady state: the heat power gained by absorption is equal to that lost by emission: $\mathbf{F_a = F_e}$

$$\sigma \epsilon T_e^4 = (1 - A) I_0 / 4$$

T_e: Emission temperature

longwave radiation **emitted by the Earth** toward space:
F_e **= 240** W.m^{-2}

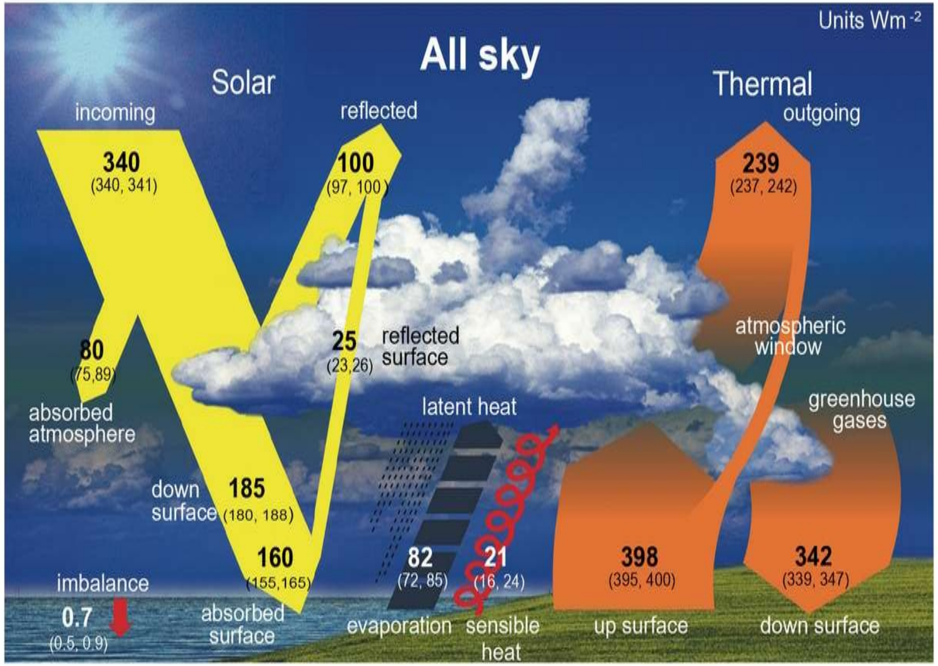
T_e= 255K (-18°C)

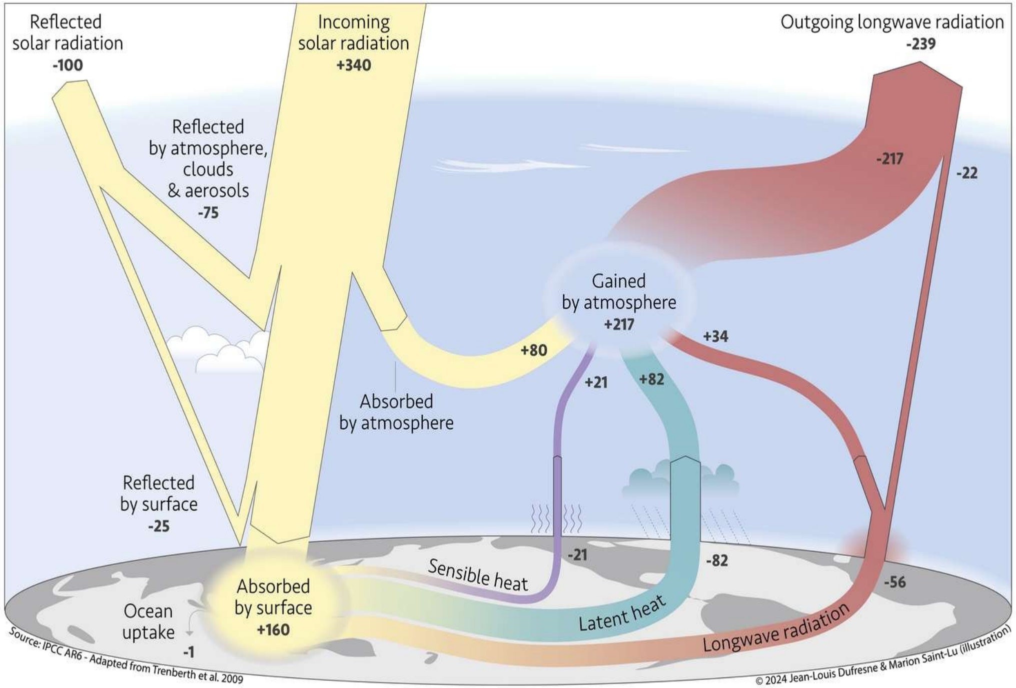
longwave radiation **emitted by surface:**
F_s **≈ 400** W.m^{-2}

Global mean surface temperature T_s ≈ 16.5°C

Greenhouse effect
$G = F_s\text{-}F_e \approx 160\ \text{Wm}^{-2}$

Energy flows in the Earth atmosphere





[IPCC AR6, ch7, 2021; Trenberth & Fasullo, 2012]

Same, redesigned by Saint-Lu & Dufresne

Also in Peixoto and Oort, 1992

Equilibrium temperature of planet Earth

The energy budget must be considered at the top of atmosphere, not at the surface

The link between the energy budget and the Earth's surface temperature will be decomposed into two parts:

- ***how the flux emitted by the Earth towards space depends on Earth’s state*** (including greenhouse gas concentration, surface and atmosphere temperature)
- ***how the Earth's temperature depends on its energy balance***

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Spontaneous emission of radiation

Planck law (“Black body” emission)

$$B_\lambda(T) = \frac{C_1\,\lambda^{-5}}{\pi\,\left(e^{C_2/\lambda T} - 1\right)}$$

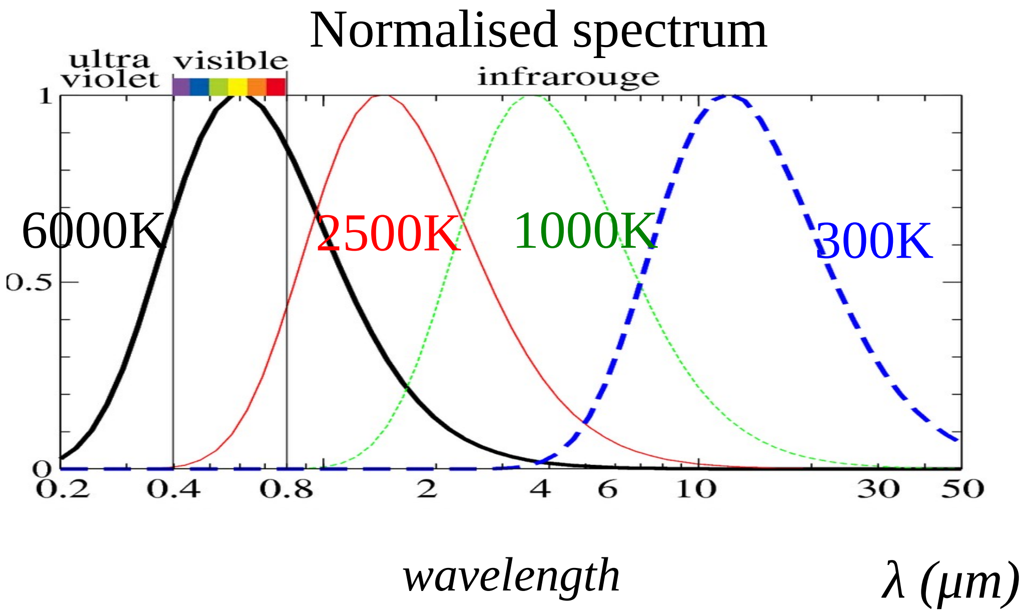
B_λ in W.m^{-2}.µm^{-1}.sr^{-1}

T in K, C_1 et C_2 are constants

Sun
T≈6000K

Lamp filament
T≈2500K

Lava
T≈1000K



Stefan-Boltzmann law (integral of the Planck law over the whole spectrum and over an hemisphere).

Power F lost by emission of radiation by a body of temperature T : $\boxed{F = \sigma T^4}$

With σ = 5,67 10^{-8} : Stefan-Boltzmann constant, F in W.m^{-2}, T in K

The flux emitted by a medium is an **increasing function of temperature**

Spontaneous emission of radiation

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B_λ in W.m^{-2}.µm^{-1}.sr^{-1}

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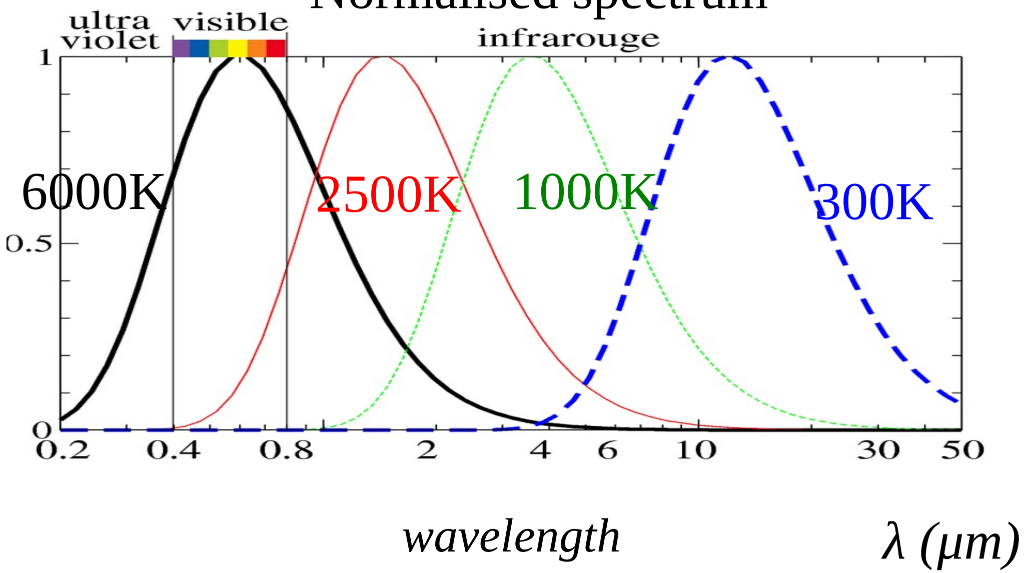
Normalised spectrum



Semi-transparent media:

$L_\lambda(T) = \varepsilon_\lambda\, B_\lambda(T)$ with ε_λ spectral emissivity

($0 \leq \varepsilon_\lambda \leq 1$; black body: $\varepsilon_\lambda = 1$)

Kirchhoff law: **emissivity ε_λ = absorptivity α_λ** at the spectral level

Stefan-Boltzmann law (integral of the Planck law over the whole spectrum and over an hemisphere).

Power F lost by emission of radiation by a body of temperature T : $\boxed{F = \sigma T^4}$

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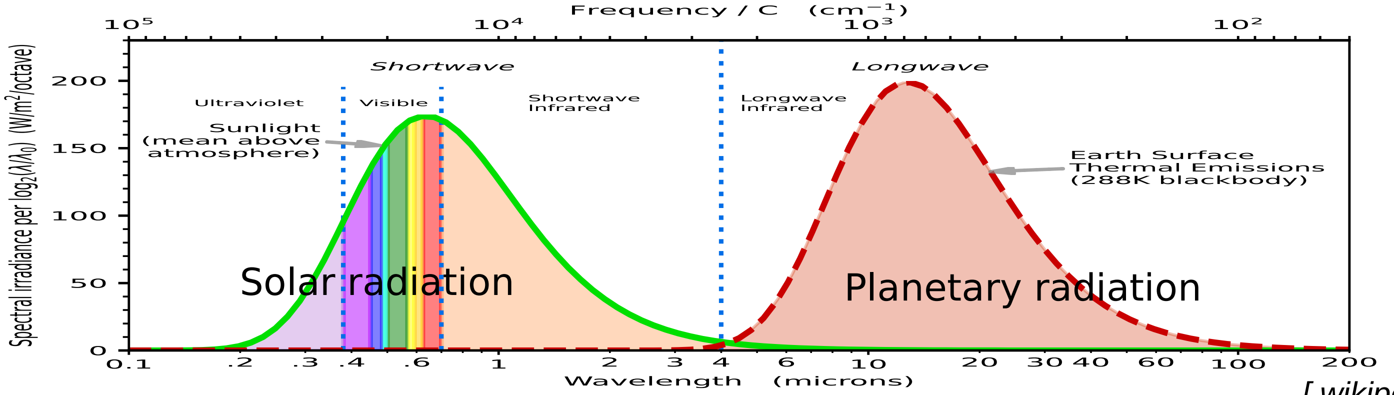
The flux emitted by a medium is an **increasing function of temperature**

Radiation absorption by the atmosphere



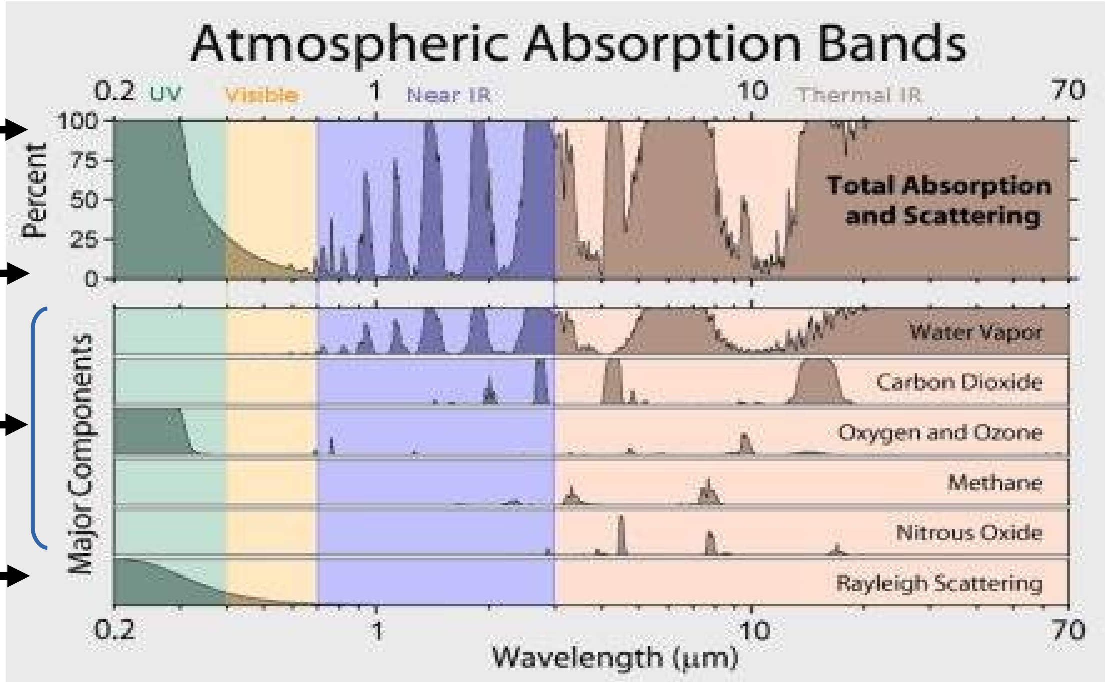
[wikipedia]

Opaque

Transparent

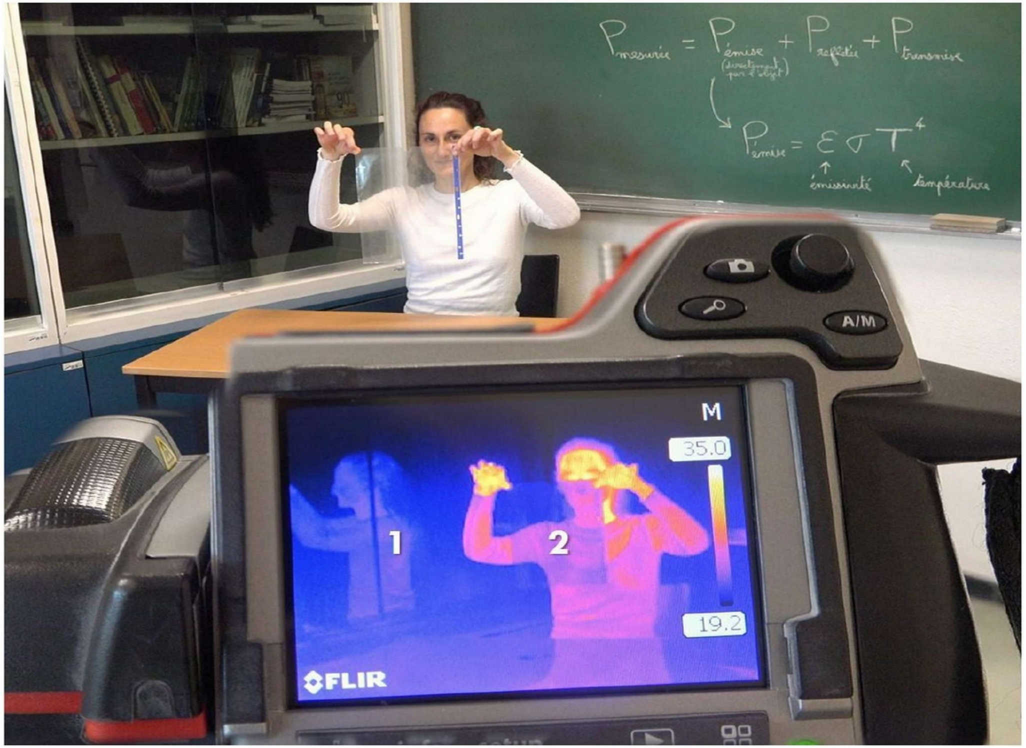
absorption

scattering



absorptivity

Spontaneous emission of radiation

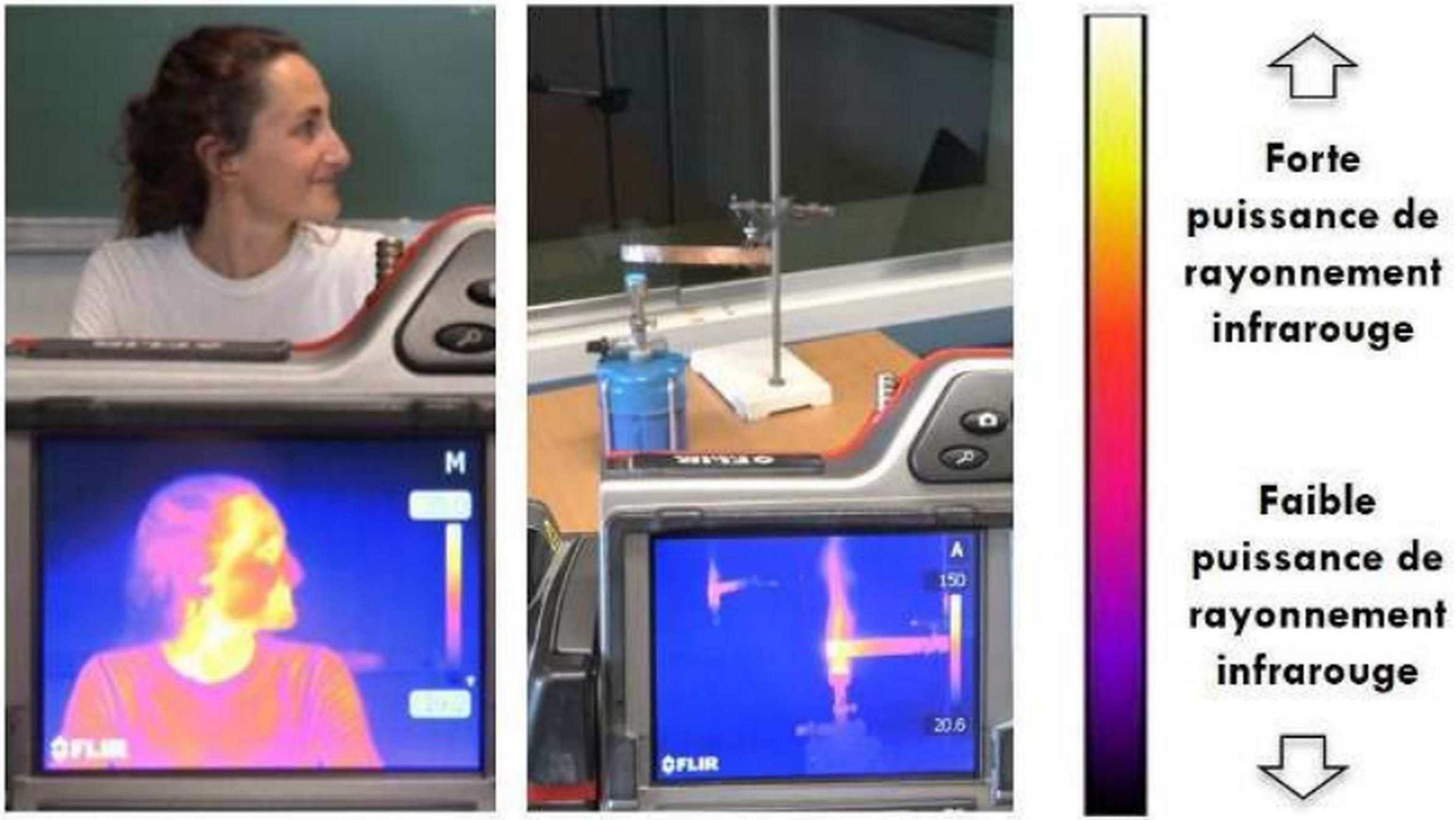


The flux emitted by a medium is an increasing function of temperature

The camera indicates a temperature, but it actually measures the power of the infrared radiation it receives.

This radiation is partially reflected by a pane of glass, like visible radiation.

[Maron et al., 2025]



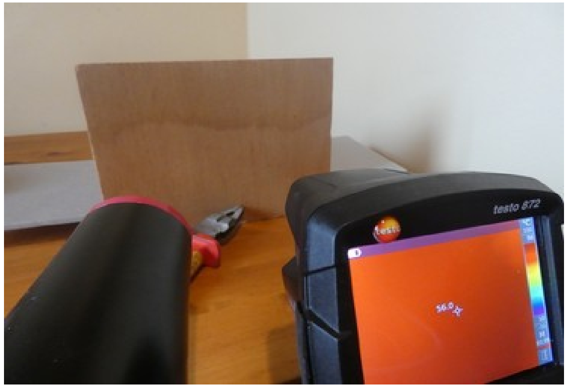
A : Plus la température d'un objet est élevée, plus la puissance de rayonnement infrarouge qu'il émet est grande.

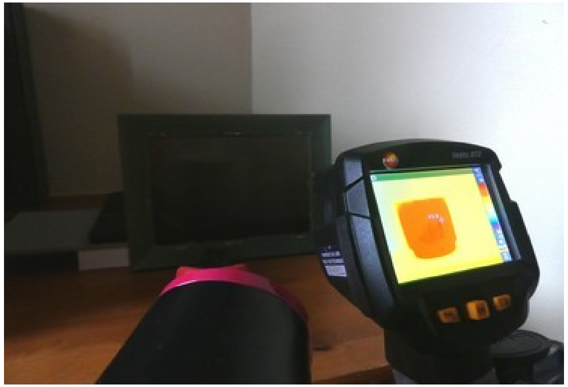
[Maron et al., 2025]

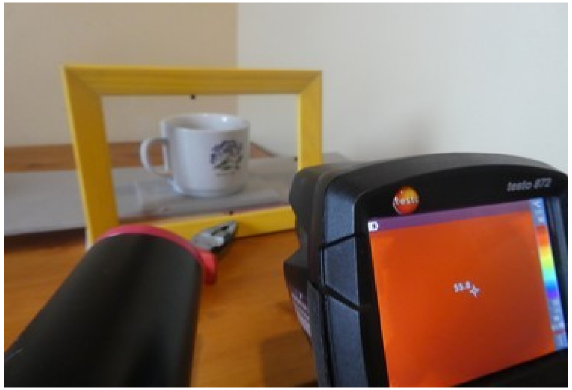
Observing with an infrared camera

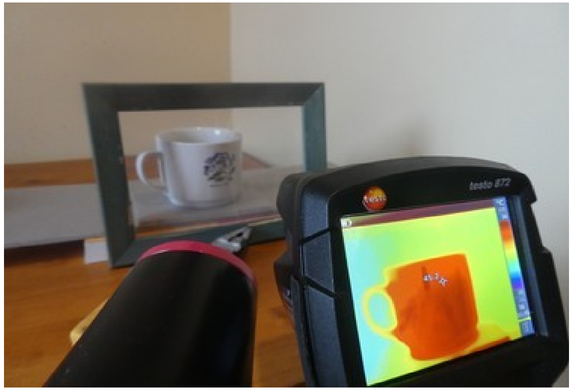
A material can be transparent or opaque, and these properties depend on wavelength, can be different for visible and infrared radiation.

Observing with an infrared camera









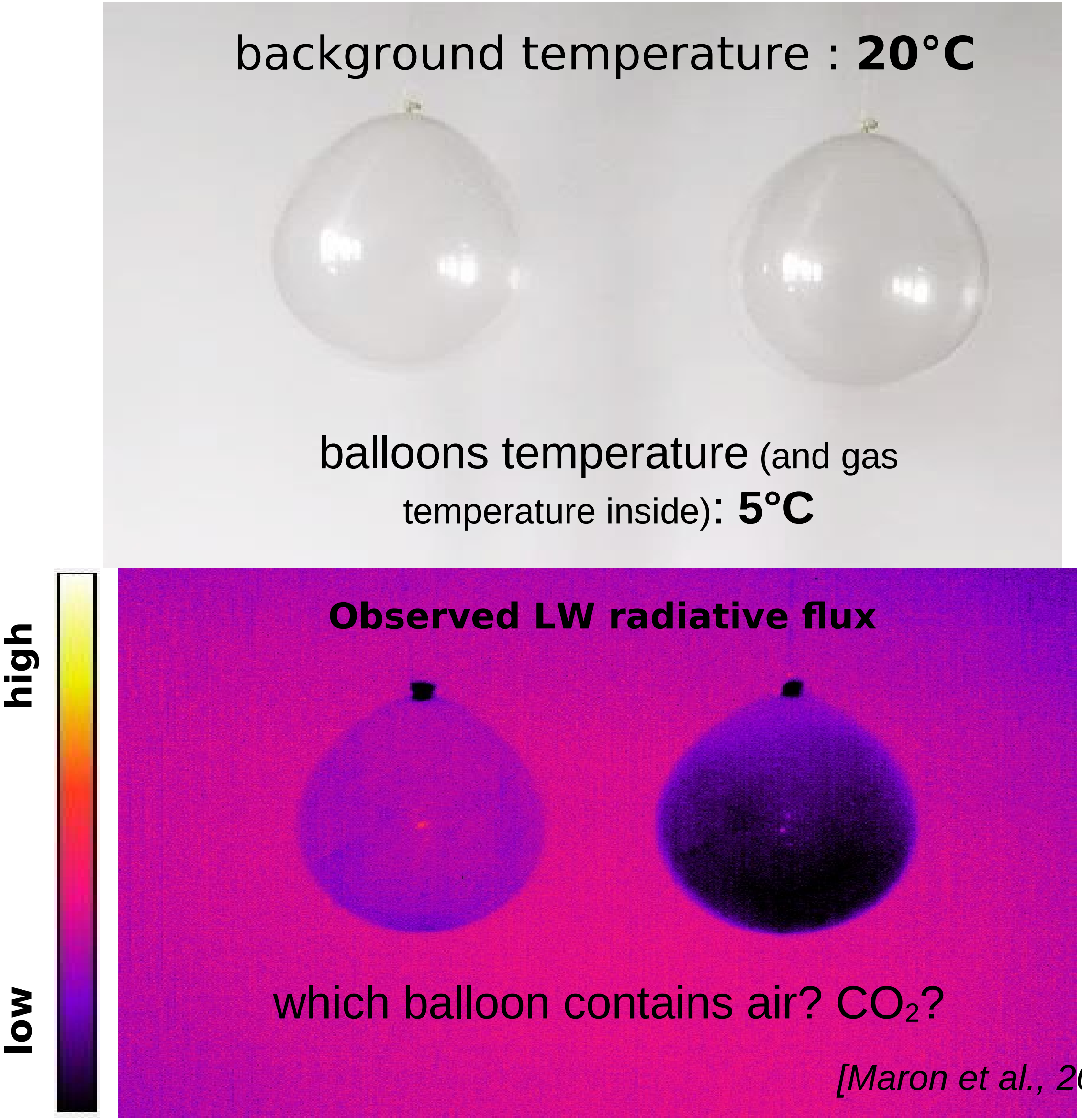
If the plates are heated, the wood and glass emit more radiation, while the plastics emit less.

A material that is a good absorber of infrared radiation is also a good emitter.

Kirchhoff law: absorptivity = emissivity ; $\boldsymbol{\alpha_\lambda = \varepsilon_\lambda}$

Observing with an infrared camera

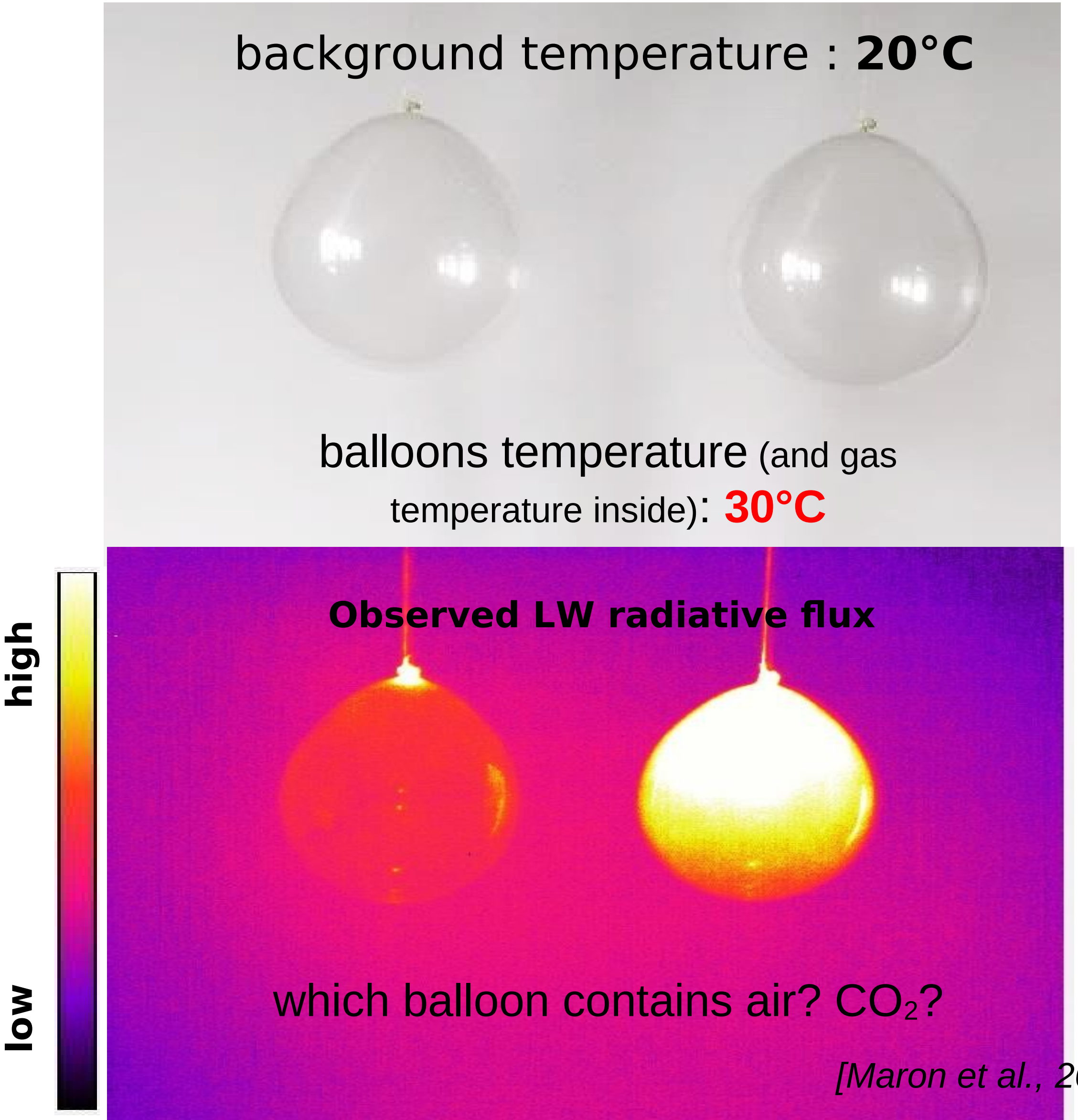
Infrared "CO_2" camera



[Maron et al., 2025]

Observing with an infrared camera

Infrared “CO_2“ camera



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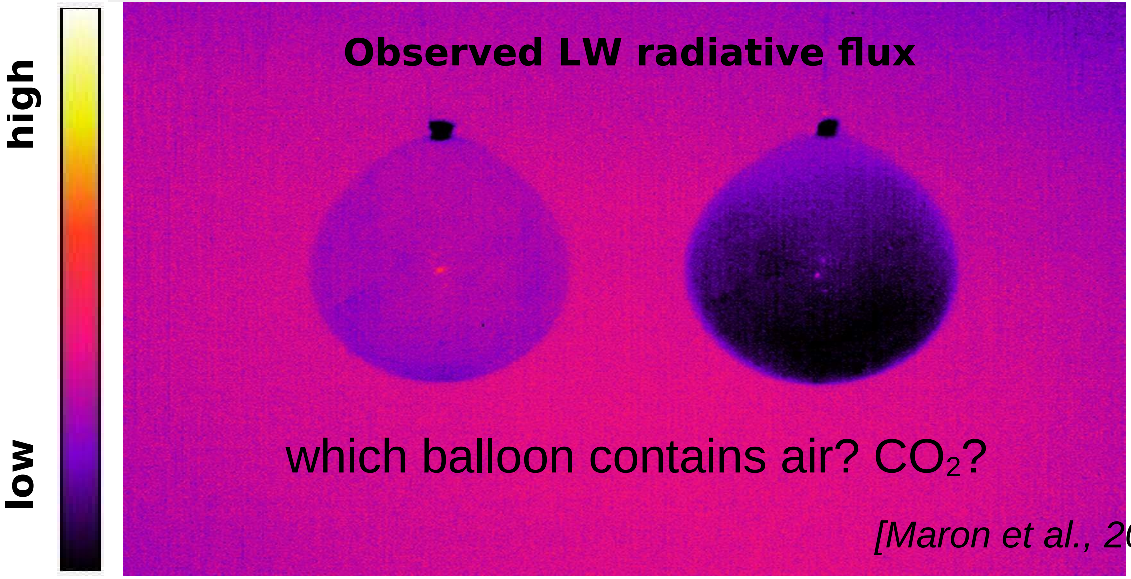

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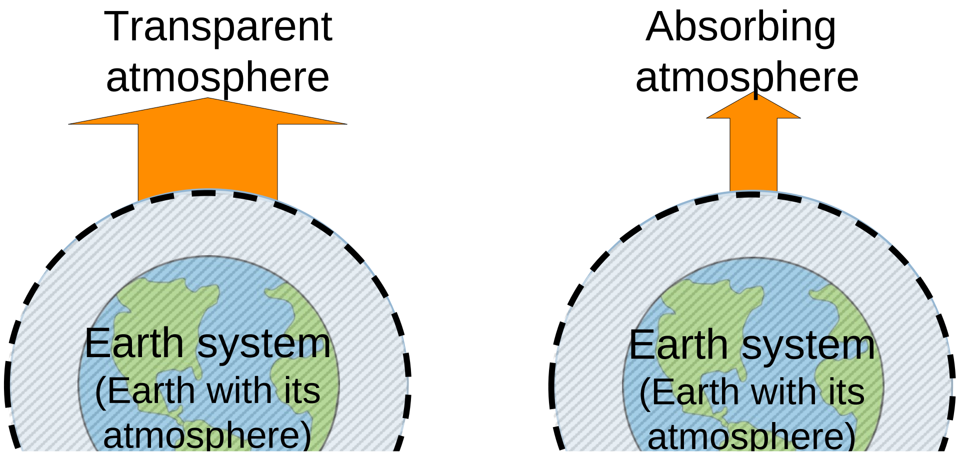
The greenhouse effect



Same
Warm surface
Cool atmosphere

Measure of greenhouse effect:

$$\boxed{G = F_s - F_e} = \underbrace{[B(T_s) - B(T_e)]}\ \underbrace{A(0,\infty)}$$

The greenhouse effect depends on:

difference between surface temperature and atmosphere emission temperature via the Planck function

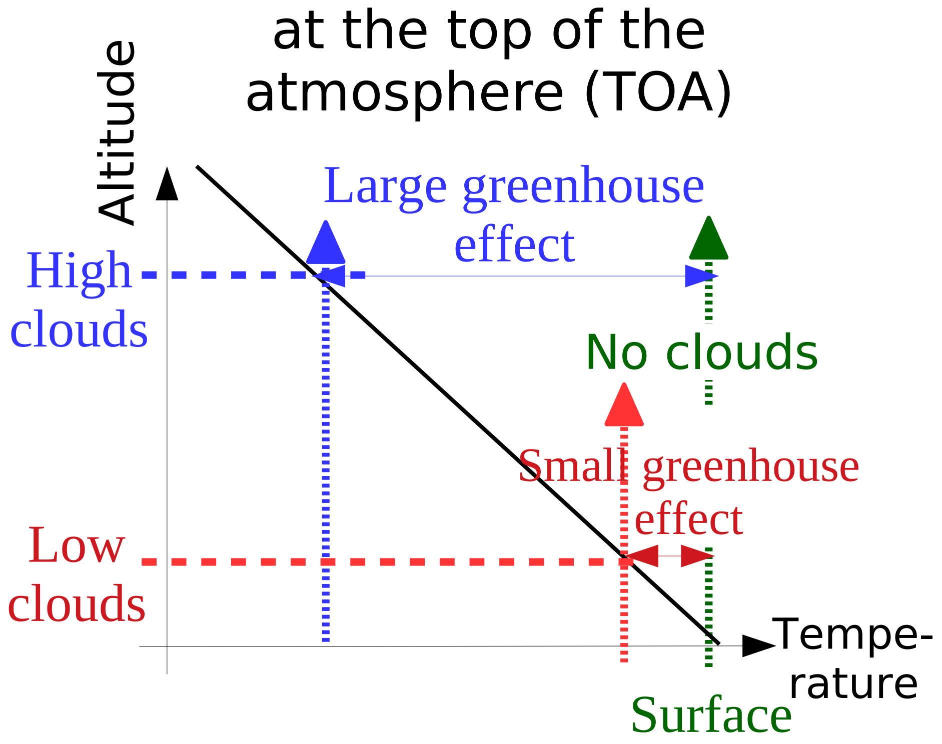
absorptivity of the whole atmosphere

The greenhouse effect is all the more important when:

- absorptivity of the atmosphere in the infrared range is high
- difference between atmosphere emission temperature and surface temperature is large.

The greenhouse effect

Clouds ≈ blackbody in the LW



Magnitude of the greenhouse effect

$G = F_s - F_e$

F_s : flux emitted by the surface

F_e : flux emitted by the Earth toward space

The flux emitted by a medium is an **increasing function of temperature** (Planck law)

- High level clouds have a large greenhouse effect because their temperature is much lower than that of surface

When computing G, both flux F_s anf F_e need to be positive

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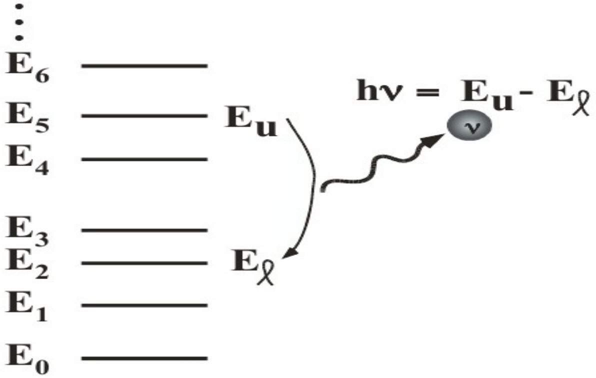
Absorption by gases



- **Line emission and absorption** by transition between states of different energy
- In the infra-red: level of energy correspond to change in vibration and vibration-rotation of molecules
- Complex molecules are better absorbing

Absorption coefficient for an absorption line ***i*** at frequence *ν*:

$$k_{\nu,i} = n \ S_i \ f_{\nu,i}$$

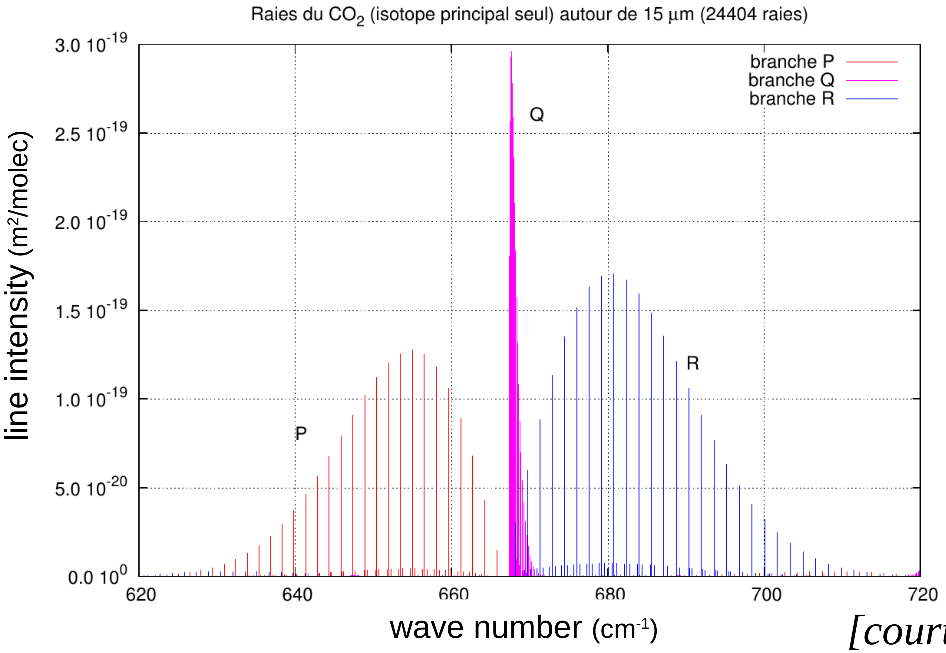
with:

n **: molecular density** (mol/kg)

$\boldsymbol{S_i}$ **: line instensity** (m^2/mol)

$\boldsymbol{f_{\nu,i}}$ **: line profile** (-)

Lines intensity for 667cm^{-1} CO_2 band



[courtesy J. Lefrère]

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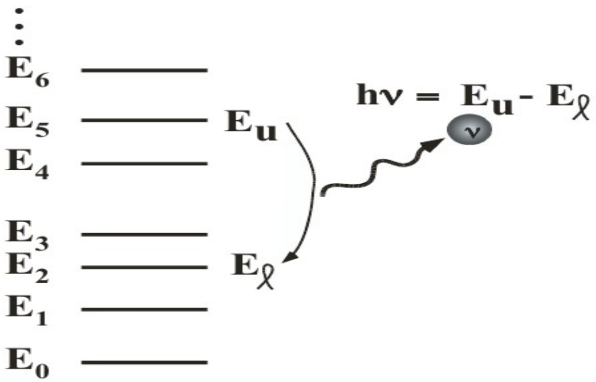

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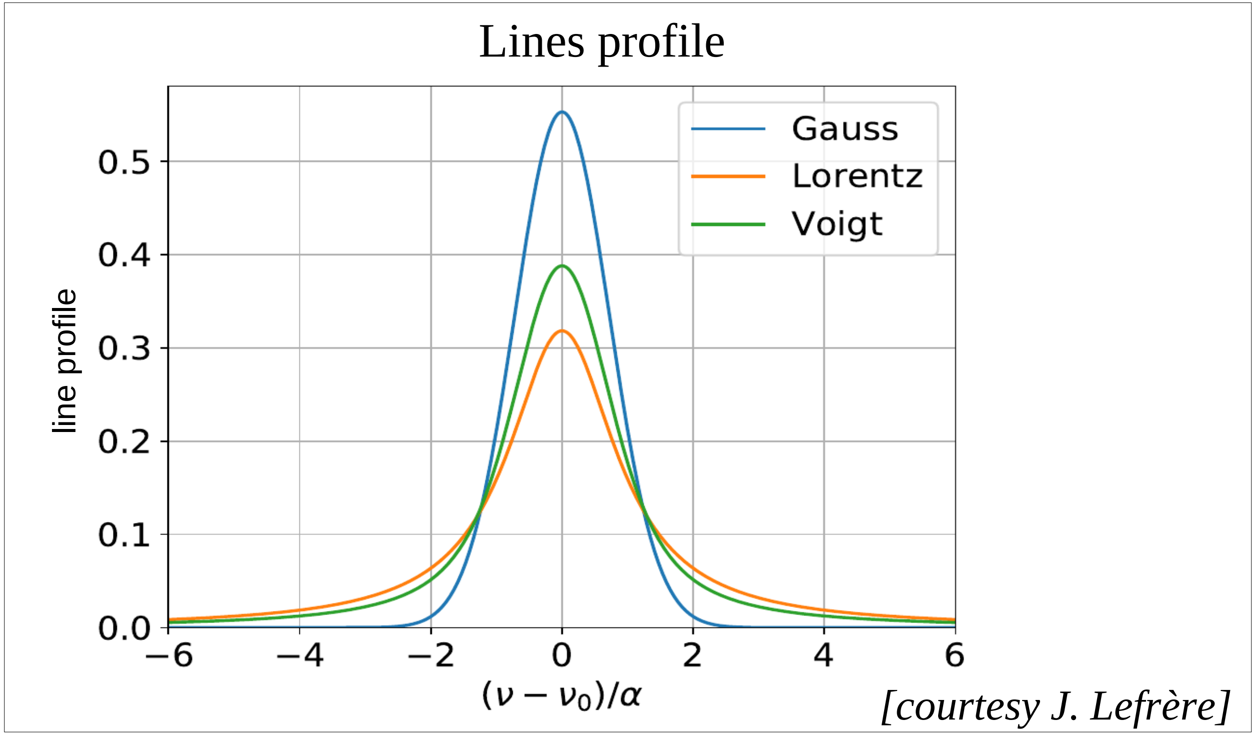
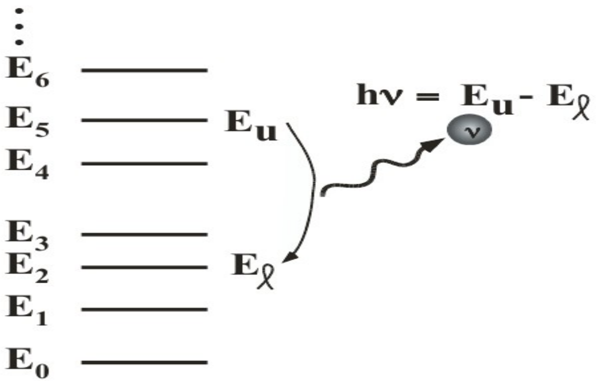


[courtesy J. Lefrère]

Absorption by gases



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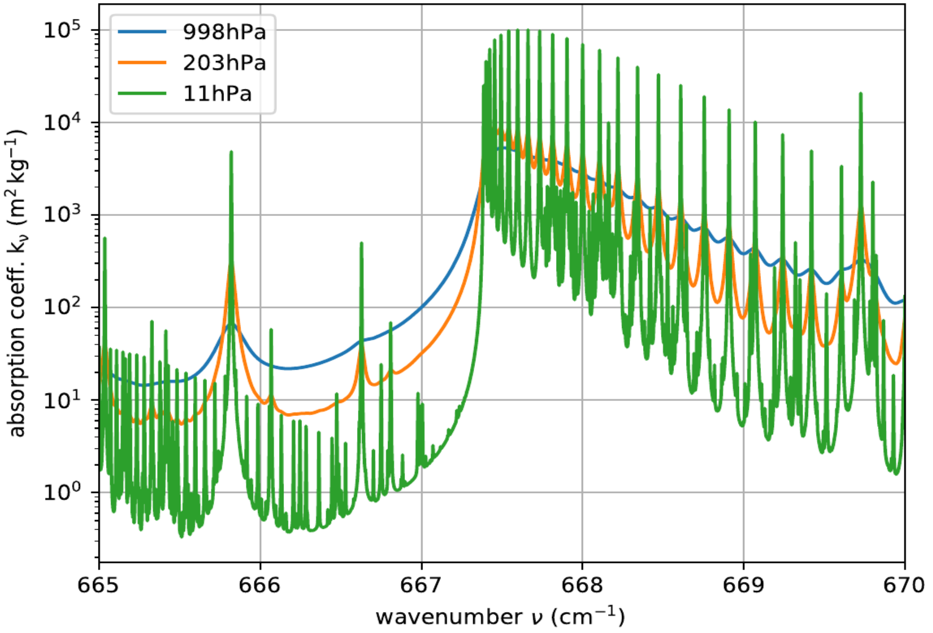
CO_2 absorption coefficient near 667cm^{-1}



Typical radiative properties of the Earth atmosphere

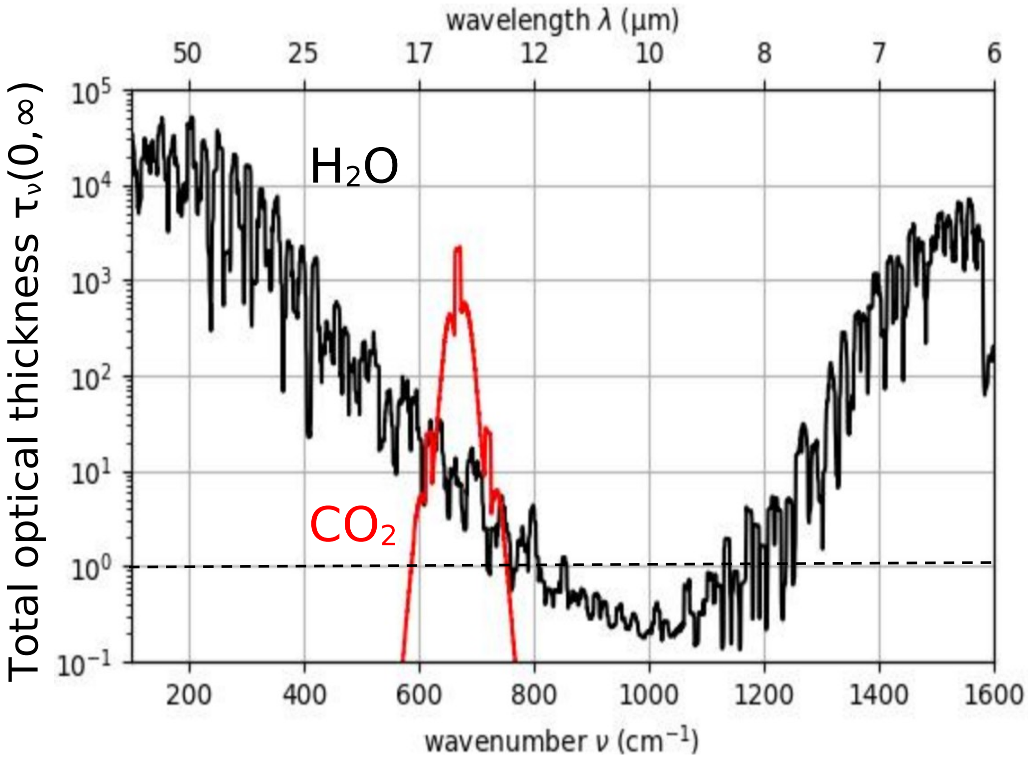
Optical thickness: $\tau_\nu(\infty,0)=\int_\infty^0 k_\nu(z)\rho(z)\,dz$

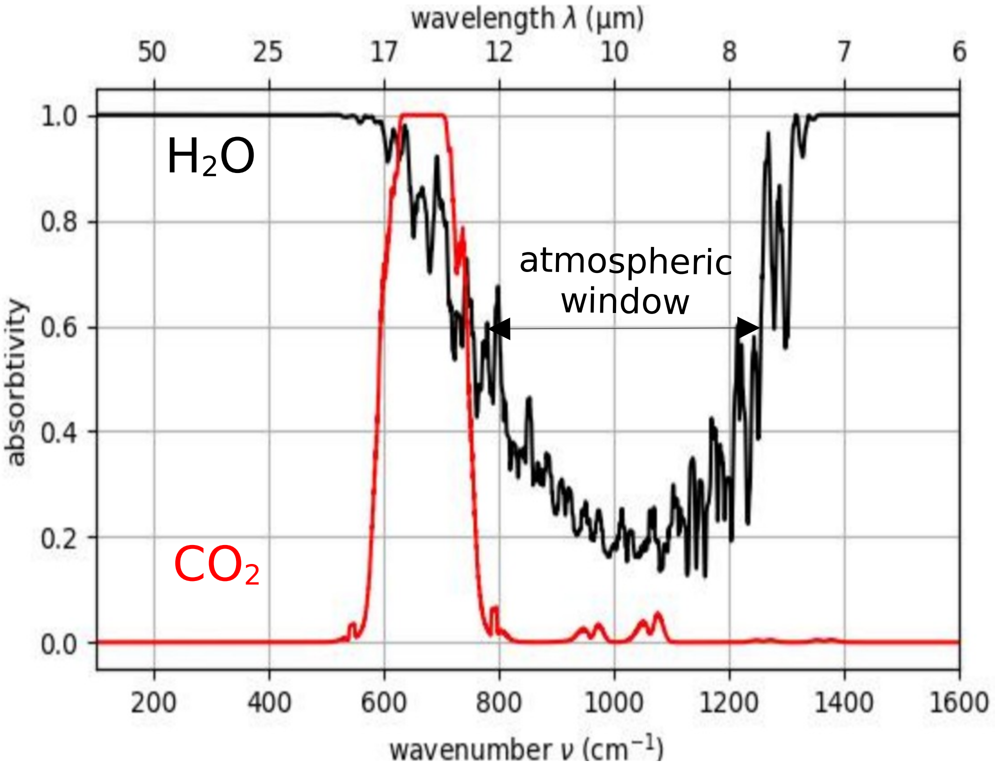
With k_ν extinction coef. (m^2/kg) and ρ volume mass of absorbing gas (kg/m^3)

Transmissivity: $T_\nu(\infty,0)=e^{-\tau_\nu(\infty,0)}$

Absorptivity: $A_\nu(\infty,0)=1-T_\nu(\infty,0)$

Assuming no scattering

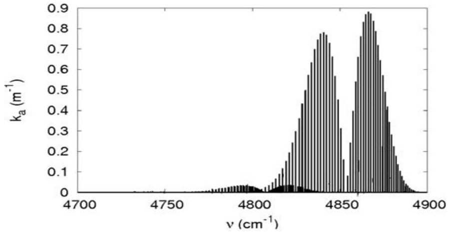




- *Very wide range* of optical thickness, of absorption intensity

Line-by-line radiative transfer model

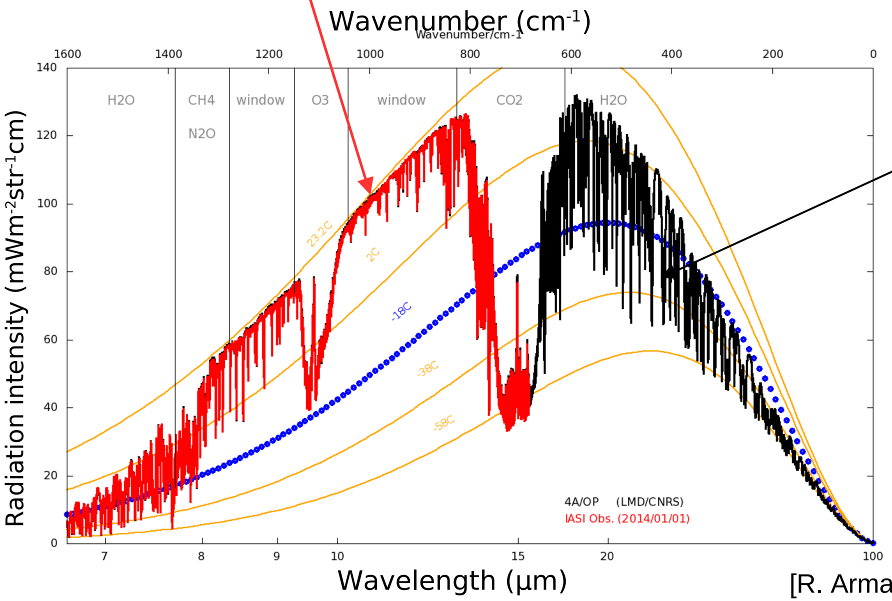
IASI instrument



Gas radiative properties

Atmospheric characteristics

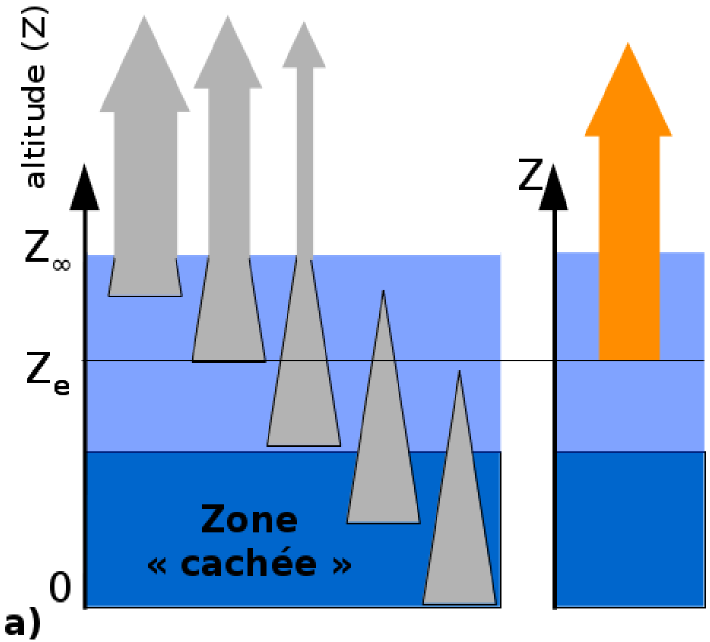
4A line-by-line model



Very good accuracy of current reference radiative transfer models

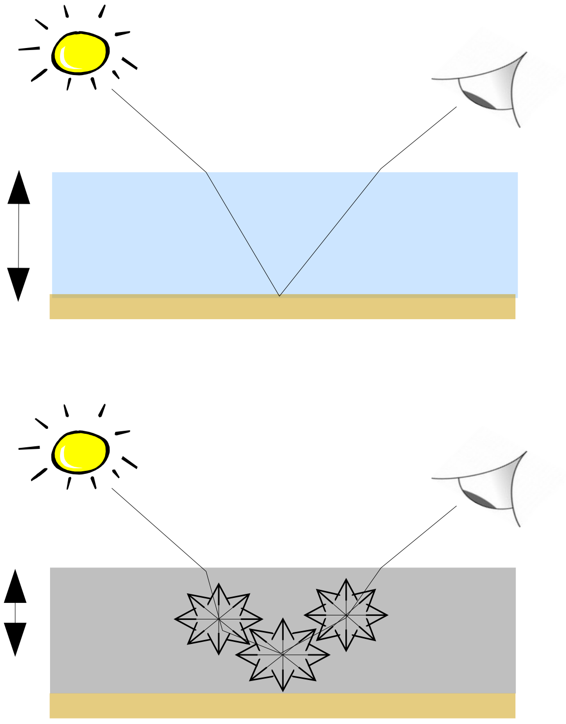
[R. Armante, LMD, 2019]

The concept of emission height



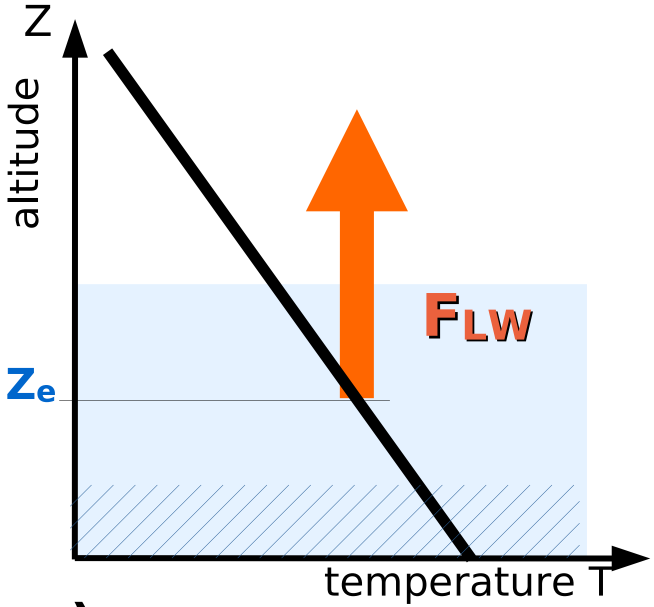
[Dufresne et Treiner, 2011]

Analogy with the visibility distance



Greenhouse effect in a ***stratified*** atmosphere

dT/dz constrained by convection



a)

Reference value of GHGs concentration

F_{LW} : outgoing infrared (LW) radiation

Ze: emission height

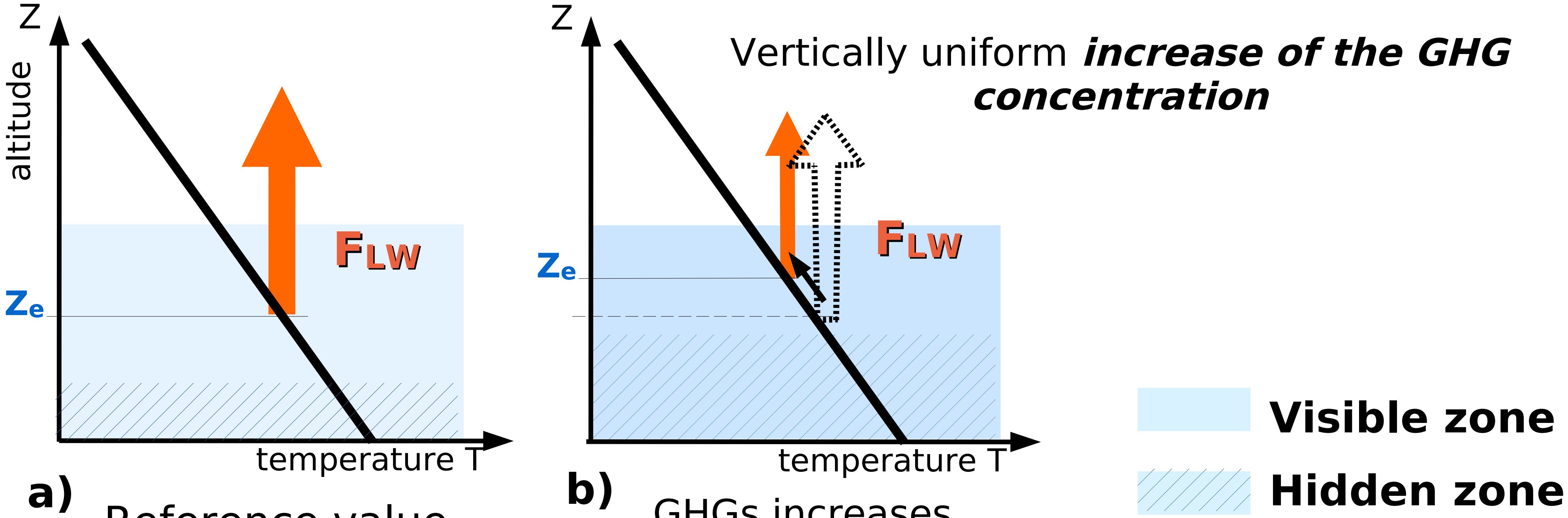
Visible zone (photons emitted upwards reach the space)

Hidden zone (photons emitted upwards are absorbed and do not reach the space)

[Dufresne, Treiner, 2011]

Greenhouse effect in a ***stratified*** atmosphere

dT/dz constrained by convection

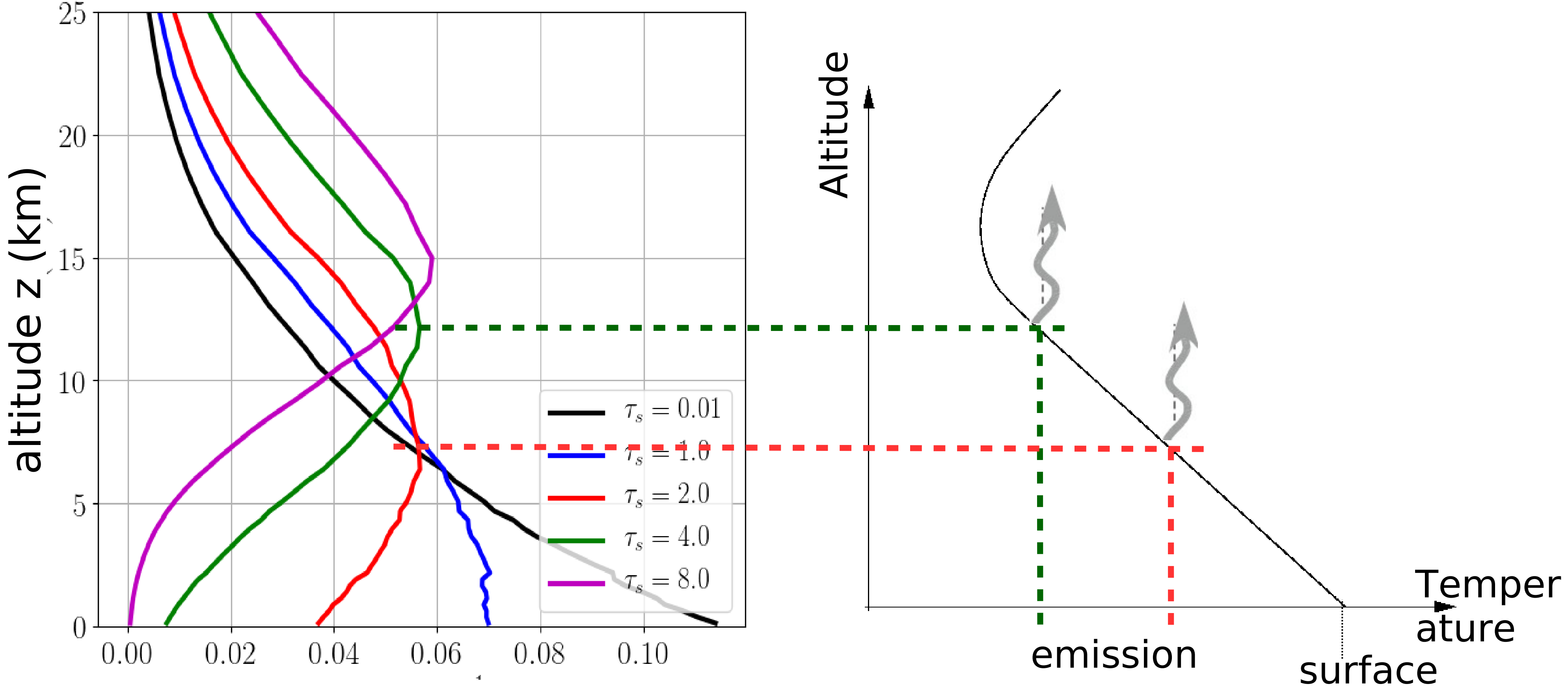


a) Reference value of GHGs concentration

b) GHGs increases, Z_e increases, T_e decreases, **Fir** decreases => increase of the greenhouse effect

[Dufresne, Treiner, 2011]

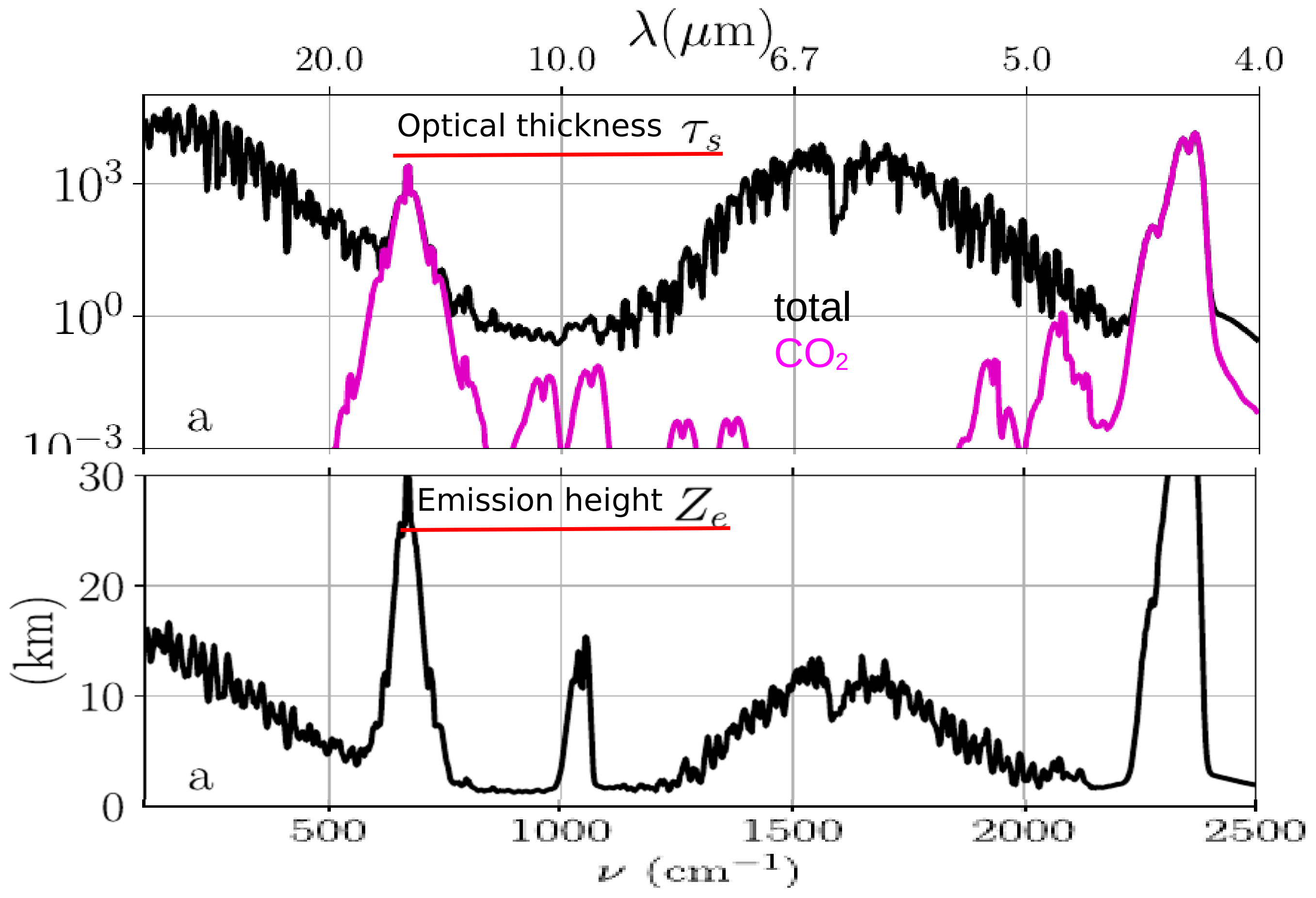
The concept of emission height

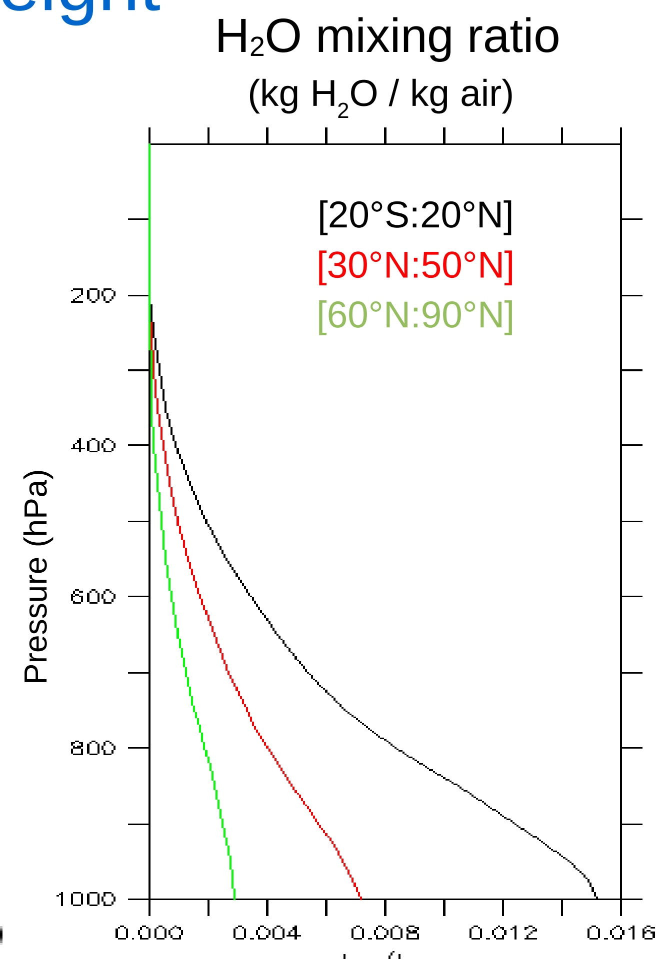


Probability density function (km^{-1}) that a photon reaching space has been emitted at altitude z for different optical thicknesses of the atmosphere

[Dufresne et al., 2020]

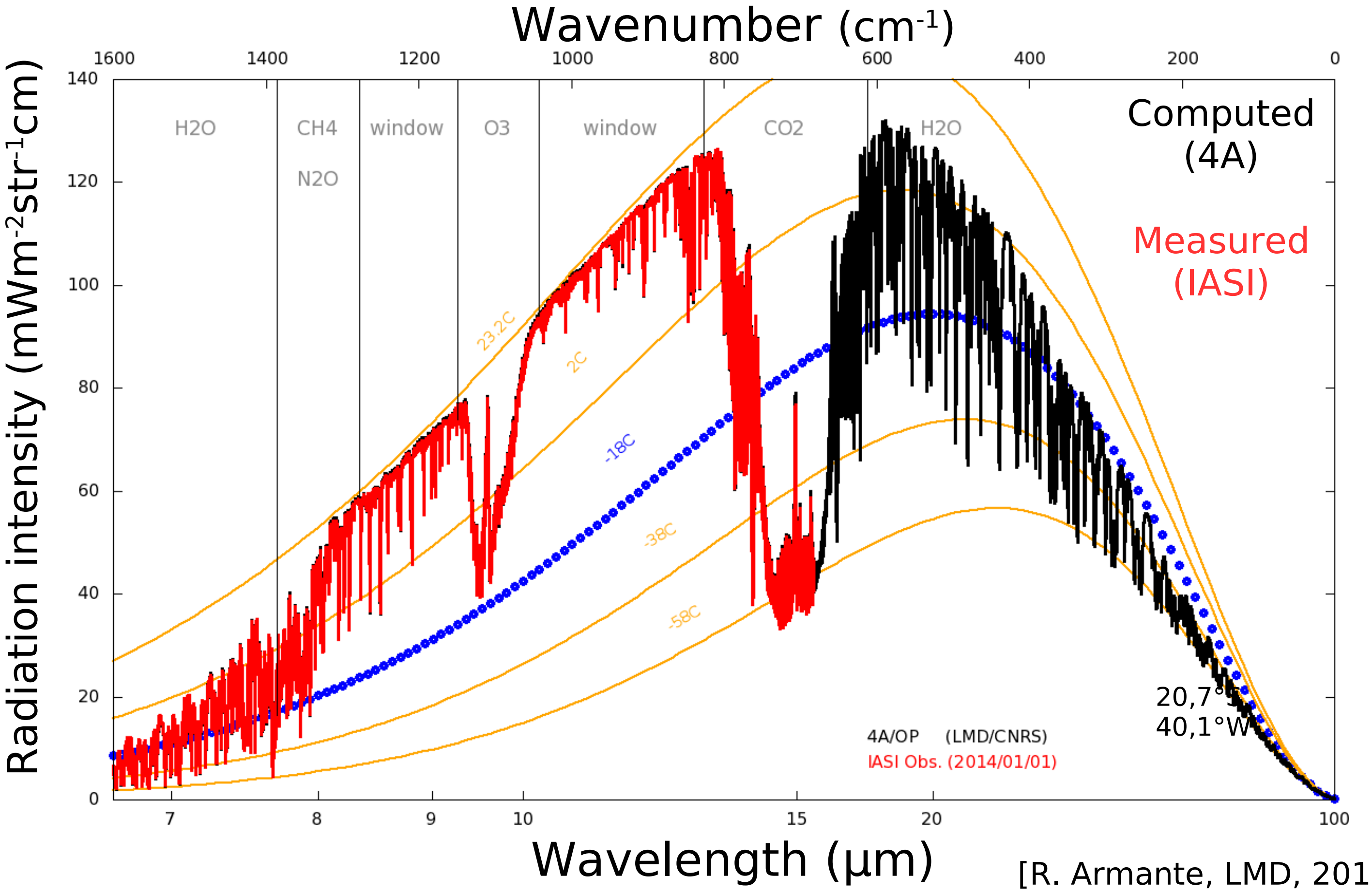
The concept of emission height

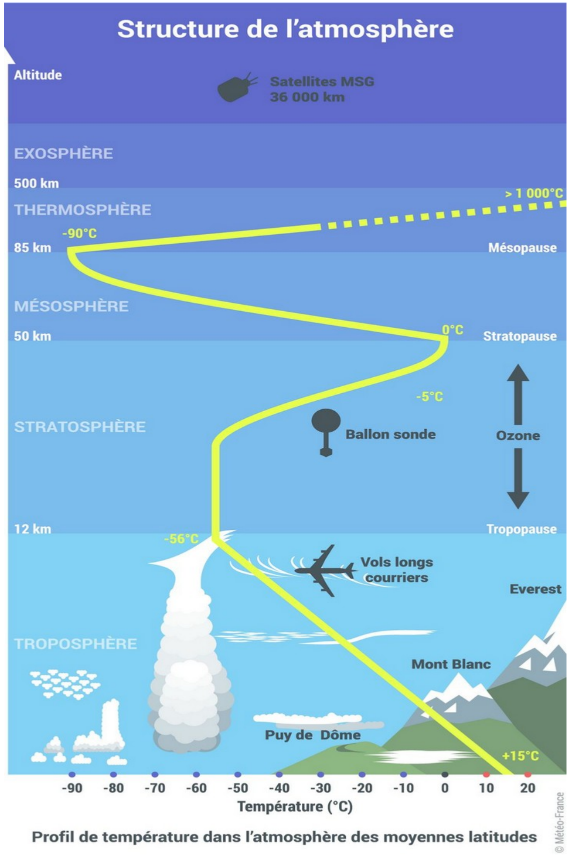




[Dufresne et al., 2020]

Spectrum of the radiation emitted by the Earth as measured by satellites



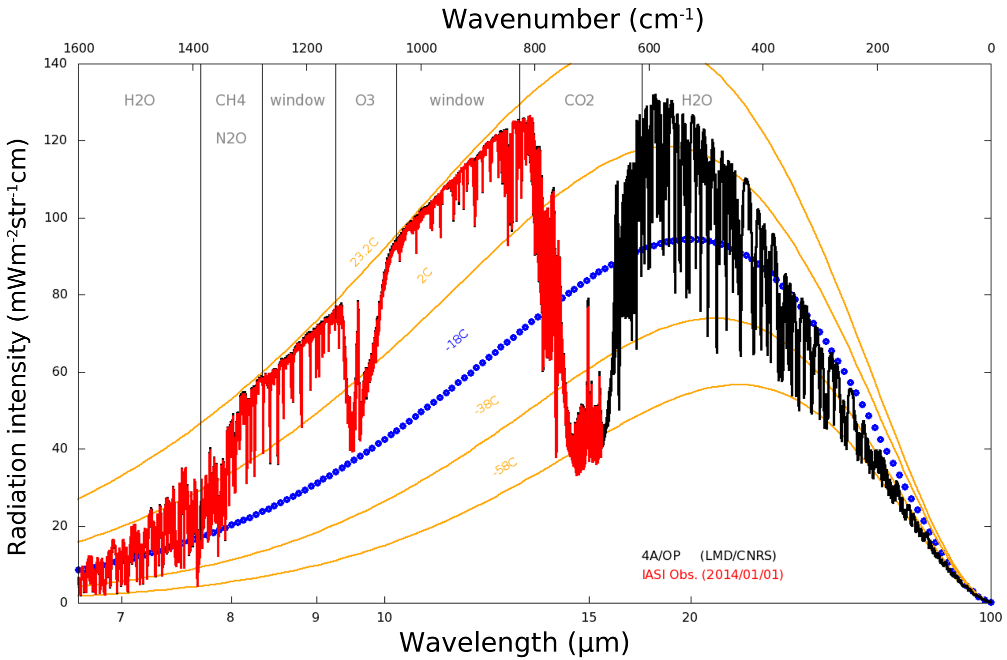


[R. Armante, LMD, 2019]

The greenhouse effect

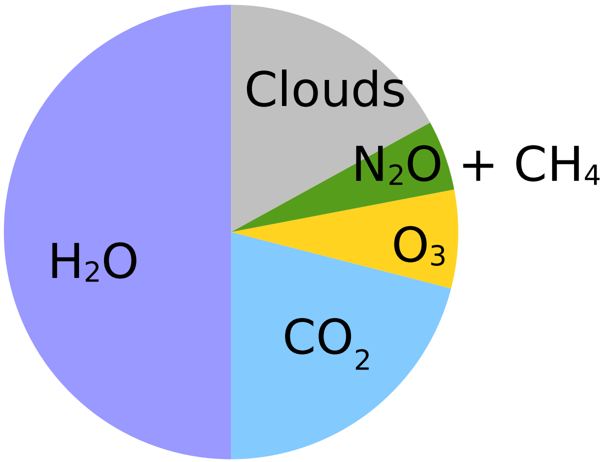
Measure of the **greenhouse effect** : ***difference*** between the radiative ***flux emitted by the surface*** and the radiative ***flux emitted by the planet*** (i.e. the outgoing flux at the top of atmosphere (TOA)

$$\boxed{G=F_s-F_{TOA}}=\int_\nu [F_{\nu,s}-F_{\nu,TOA}]\,d\nu$$ both flux F being positive



Contributions to the greenhouse effect

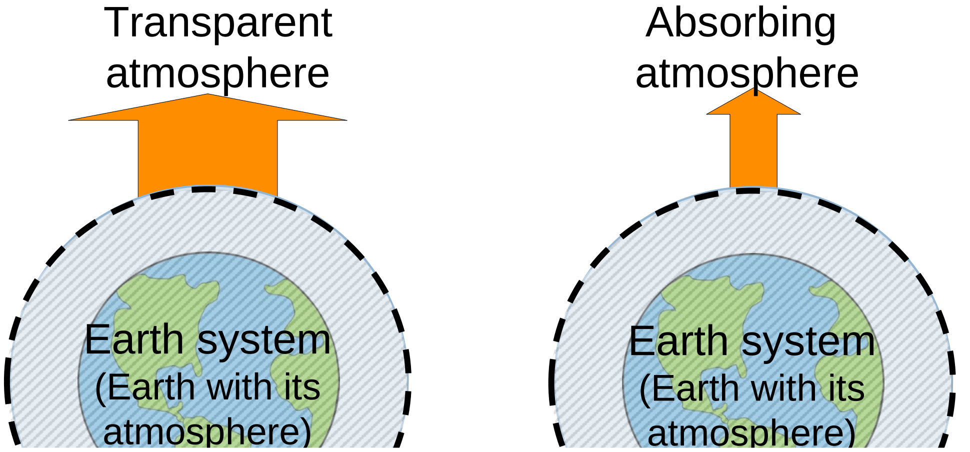
H_2O	50%
CO_2	21%
Clouds	17%
Ozone	7%
N_2O+CH_4	5%



[Kiehl, Trenberth, 1997]

The greenhouse effect

Same
Warm surface
Cool atmosphere



Measure of greenhouse effect: $$\boxed{G = F_s - F_e} = \int_\nu [B_\nu(T_s) - B_\nu(T_e)]\, A_\nu(0,\infty)\, d\nu$$

depends on the difference between surface temperature and atmosphere emission temperature via the Planck function

depends on the absorptivity of the whole atmosphere

The greenhouse effect is all the more important when:

- absorptivity of the atmosphere in the infrared range is high, over a wide spectral domain
- difference between atmosphere emission temperature and surface temperature is large.

Towards a more correct and relevant explanation of the greenhouse effect

I. Conceptual framework

II. Principle of the greenhouse effect

III. Gaz absorption, emission height and the greenhouse effect

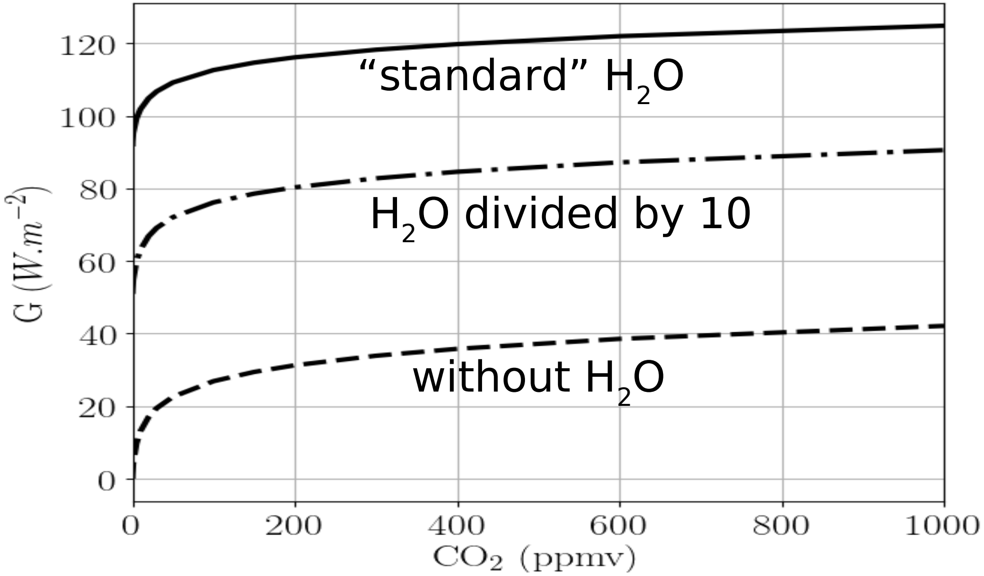
IV. Focus on the CO_2 greenhouse effect

V. From radiative forcing to surface temperature change

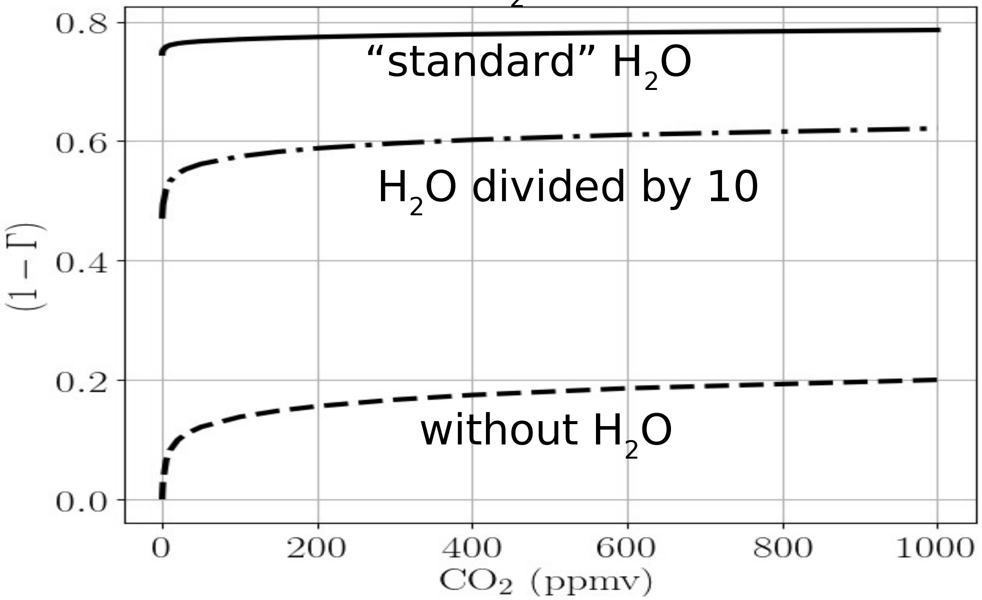
The CO_2 saturation paradox

$$G = F_s - F_e = \int_\nu [B_\nu(T_s) - B_\nu(T_e)]\ A_\nu(0,\infty)\, d\nu$$

Greenhouse effect as a function of **CO_2 concentration** for different H_2O concentrations



Total absorptivity $A_\nu(0,\infty)$ of the atmosphere as a function of **CO_2 concentration** for different H_2O concentrations

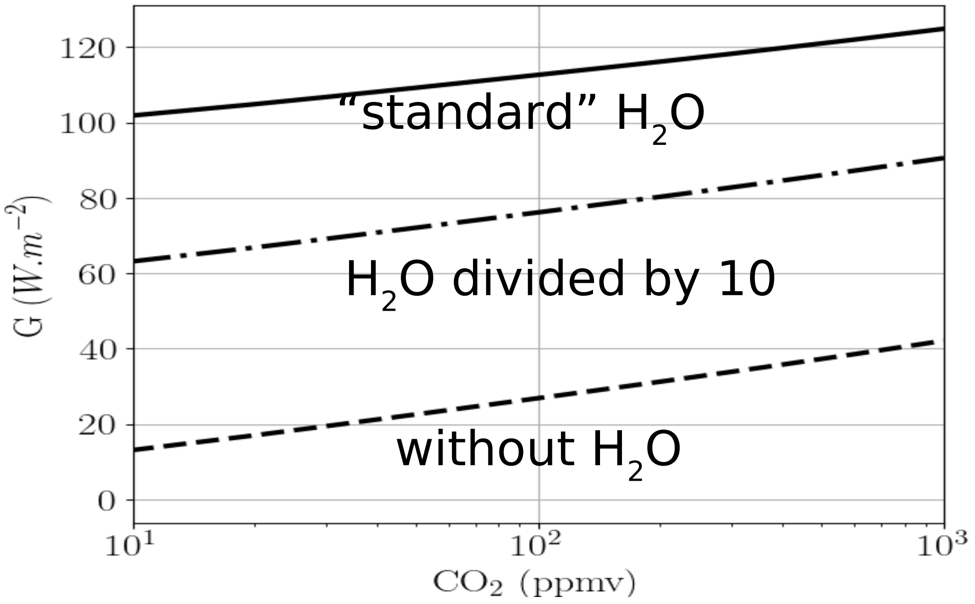


Why does the greenhouse effect increase with CO_2 while absorptivity does not when there is some H_2O?

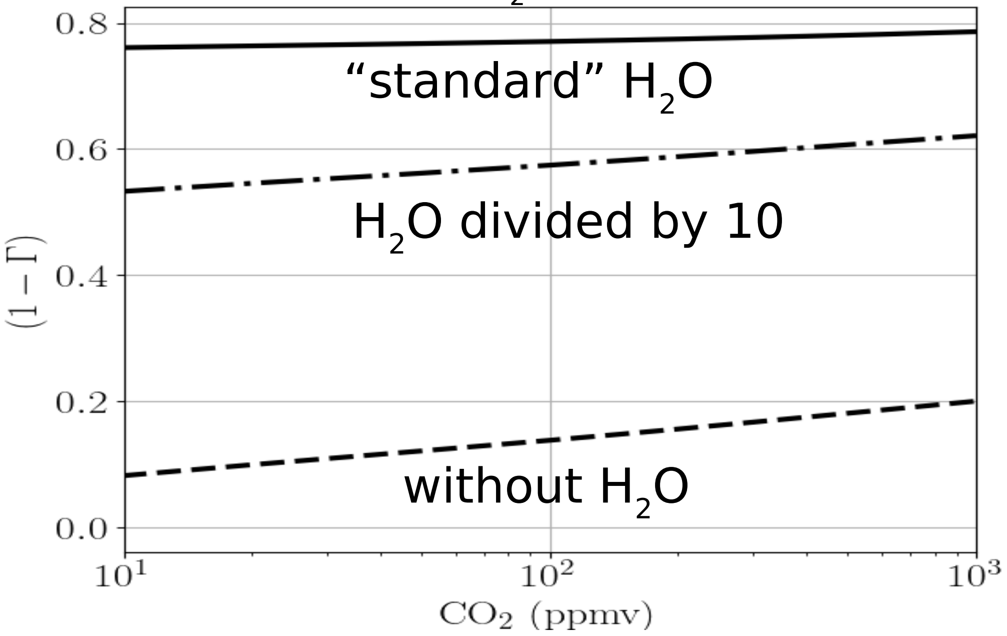
The CO_2 saturation paradox

$$G = F_s - F_e = \int_\nu [B_\nu(T_s) - B_\nu(T_e)]\ A_\nu(0,\infty)\, d\nu$$

Greenhouse effect as a function of **CO_2 concentration** for different H_2O concentrations



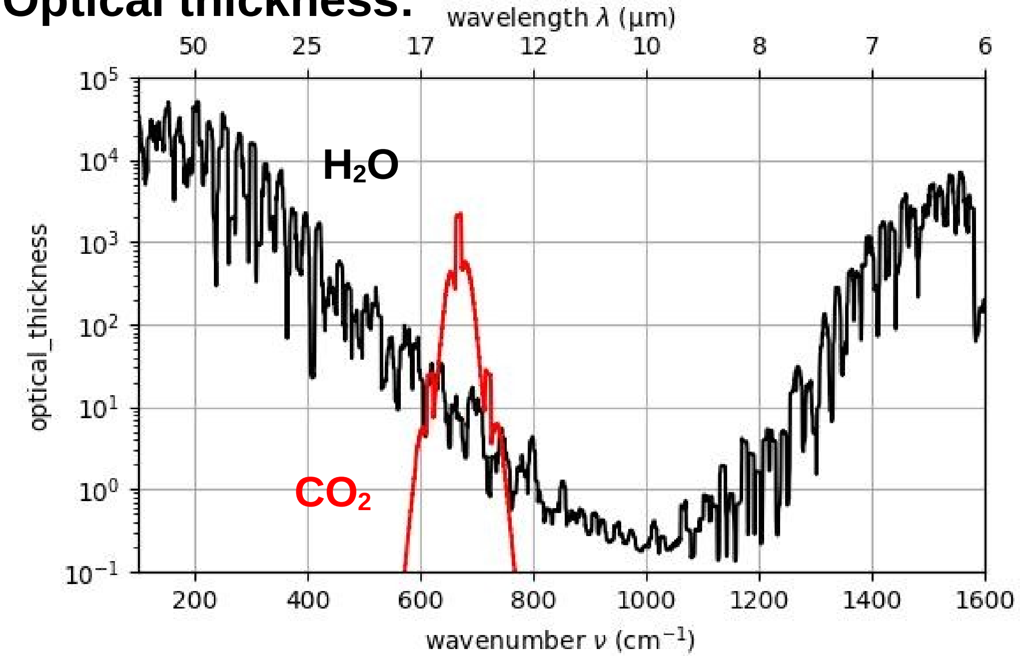
Total absorptivity ε_a of the atmosphere as a function of **CO_2 concentration** for different H_2O concentrations



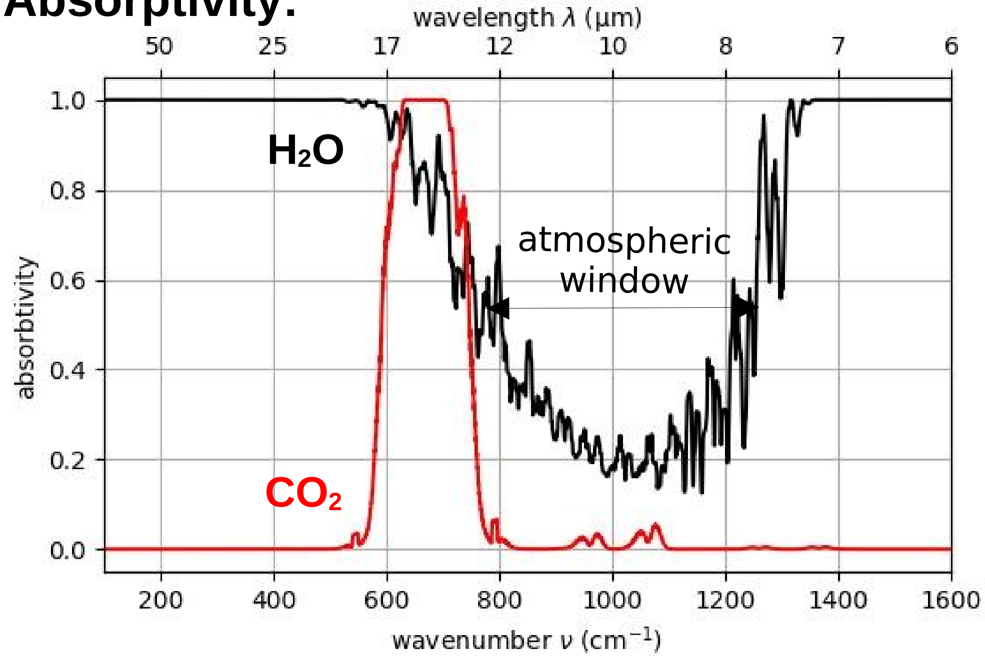
Why does the greenhouse effect increase with CO_2 while absorptivity does not when there is some H_2O?

The CO_2 saturation paradox

Optical thickness:



Absorptivity:



The water vapor masks the CO_2 absorption by does not "mask" the radiative effect of CO_2 because:

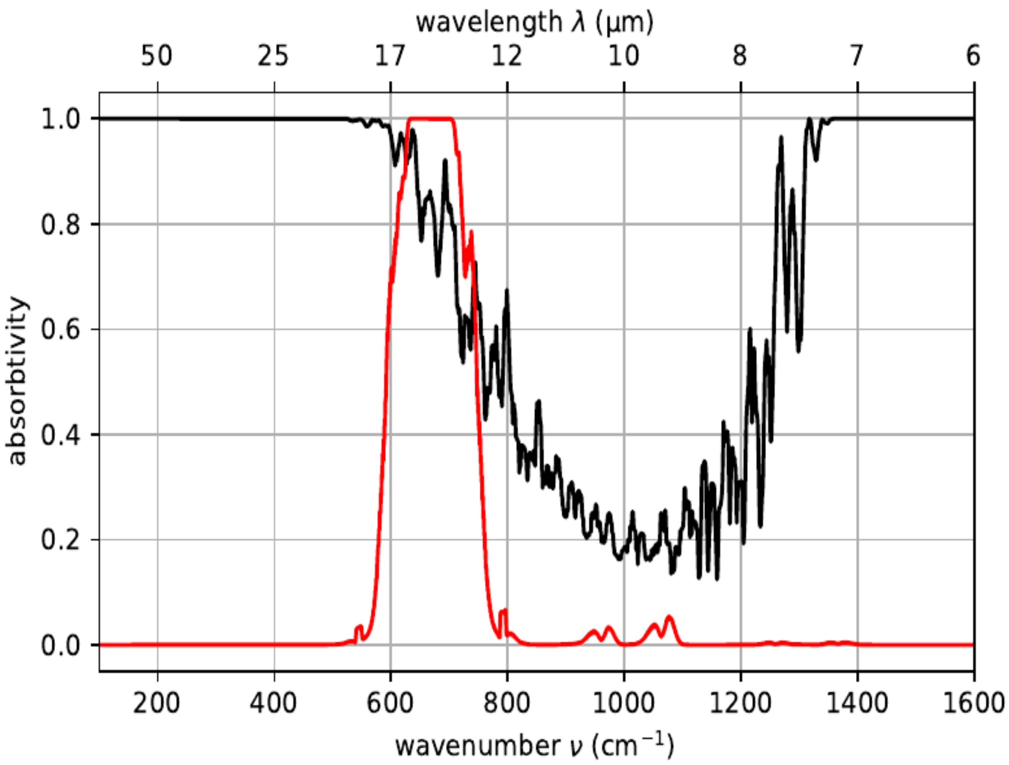
1) Over a wide spectral range, the optical thickness of CO_2 is larger than that of H_2O => There, the emission temperature depends only on CO_2

2) This effect is amplified as most of the water vapor is close to the surface

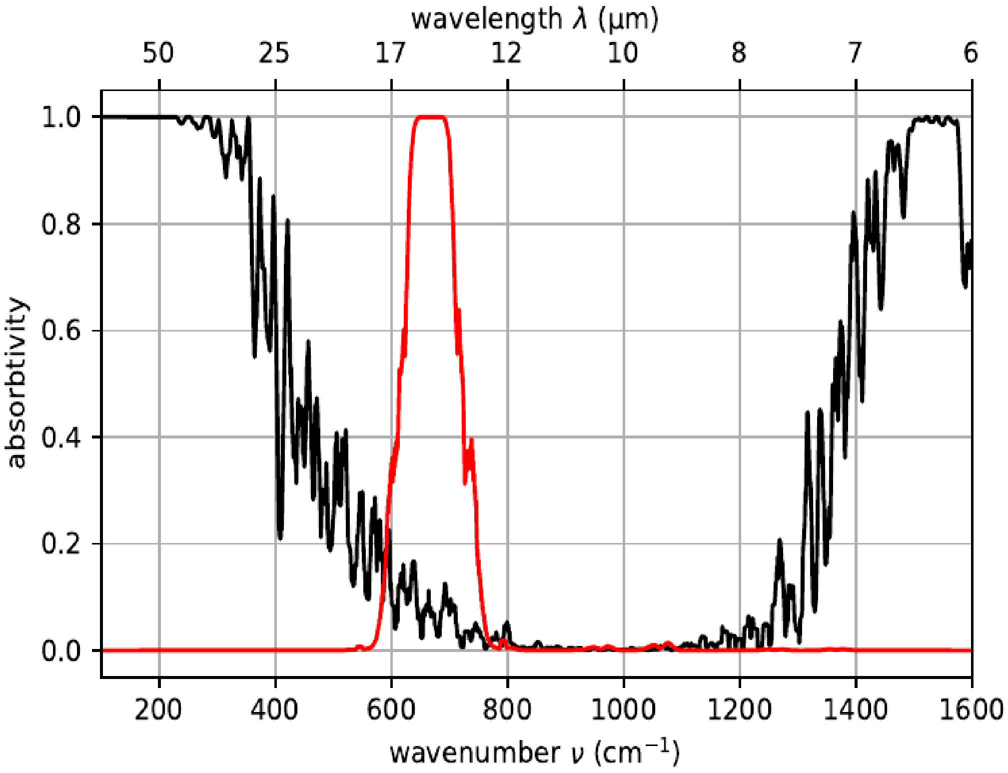
The CO_2 saturation paradox

Absorptivity of the atmosphere between the TOA and

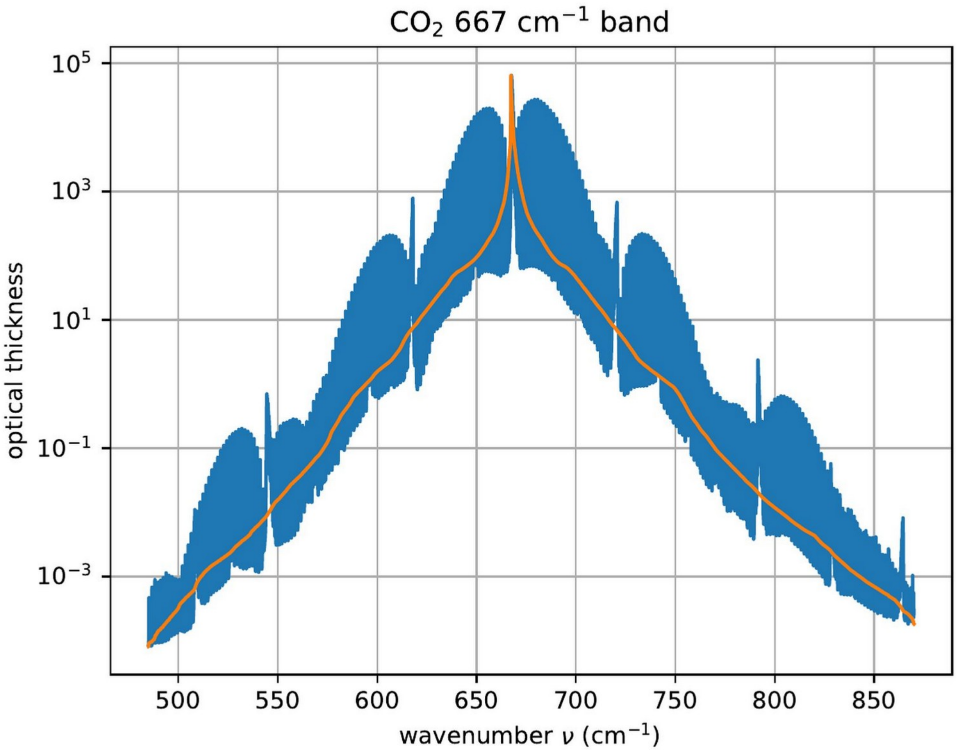
surface

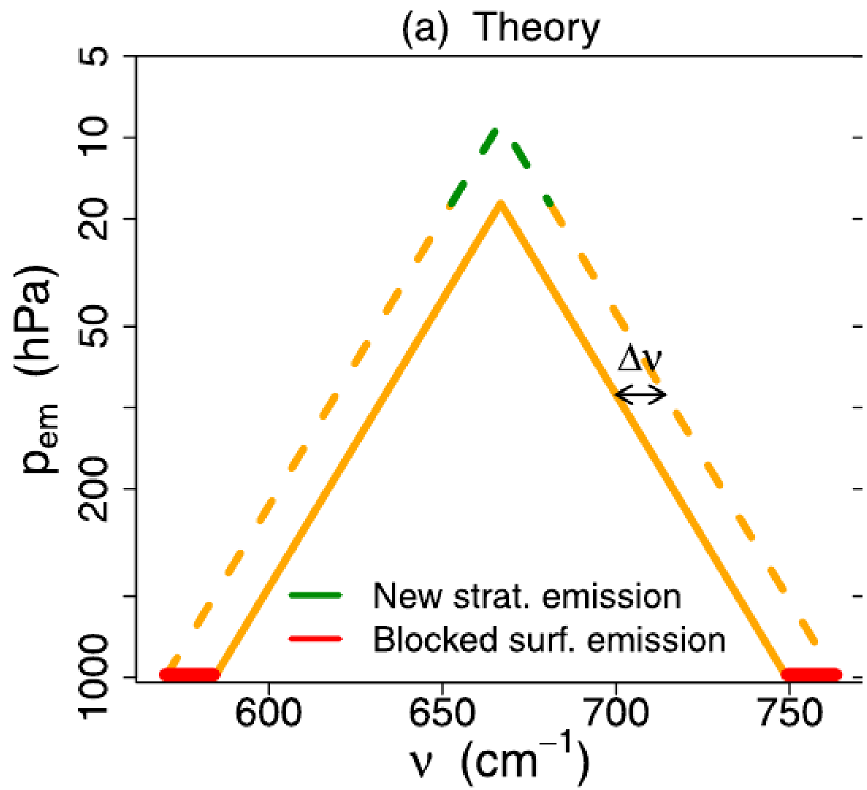


an altitude of **5km**



Why CO_2 radiative forcing is a logaritmic in CO_2 concentration?





[Jeevanjee &Seenley, 2021]

forcing proportional to $\frac{\partial \log \tau}{\partial \nu} \log CO_2$

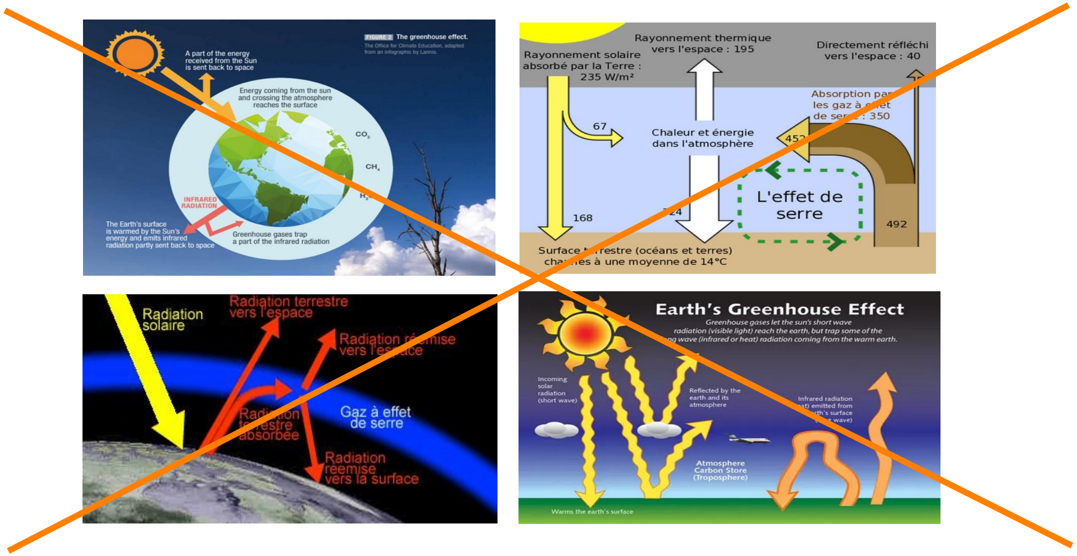
The greenhouse effect due to CO_2

Absorption by CO_2 is not saturated when CO_2 is the only absorbing gas

H_2O does not mask the greenhouse effect of CO_2 because the emission height of CO_2 is greater than that of H_2O in the spectral range where both absorb

When increasing CO_2 concentration, the increase in the greenhouse effect is due to

- an increase in spectral absorptivity (when below 1)
- an increase in emission altitude and therefore a decrease in emission temperature in the troposphere



Presenting the greenhouse effect as an atmosphere that warms the surface by emitting infrared radiation towards the surface:

- Is inconsistent (false) with the definition of its measure: $G = F_s - F_e$
- Logically leads one to question the role of CO_2 in the greenhouse effect (saturation effect, masking of CO_2 by H_2O), to fail to understand why high clouds have a greater greenhouse effect than low clouds, etc.
- Doesn't allow for an answer to these legitimate questions.

Towards a more correct and relevant explanation of the greenhouse effect

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From radiative forcing to temperature change

We analyze how the flux emitted by the Earth towards space depends on greenhouse gaz concentration **all other conditions being equal**. What about the Earth's surface temperature response ?
Answering this question requires considering **the whole physics of climate, i.e. global climate models**

Radiative forcing and feedback framework

In response to an external forcing, the response ΔN of the net flux at the TOA, may be expressed as:

Change in net flux at the TOA

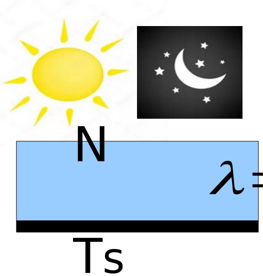
$$\boxed{\Delta N \approx \Delta Q + \lambda\, \Delta T_s}$$

Change in global mean **surface** temperature

radiative forcing "climate feedback parameter"

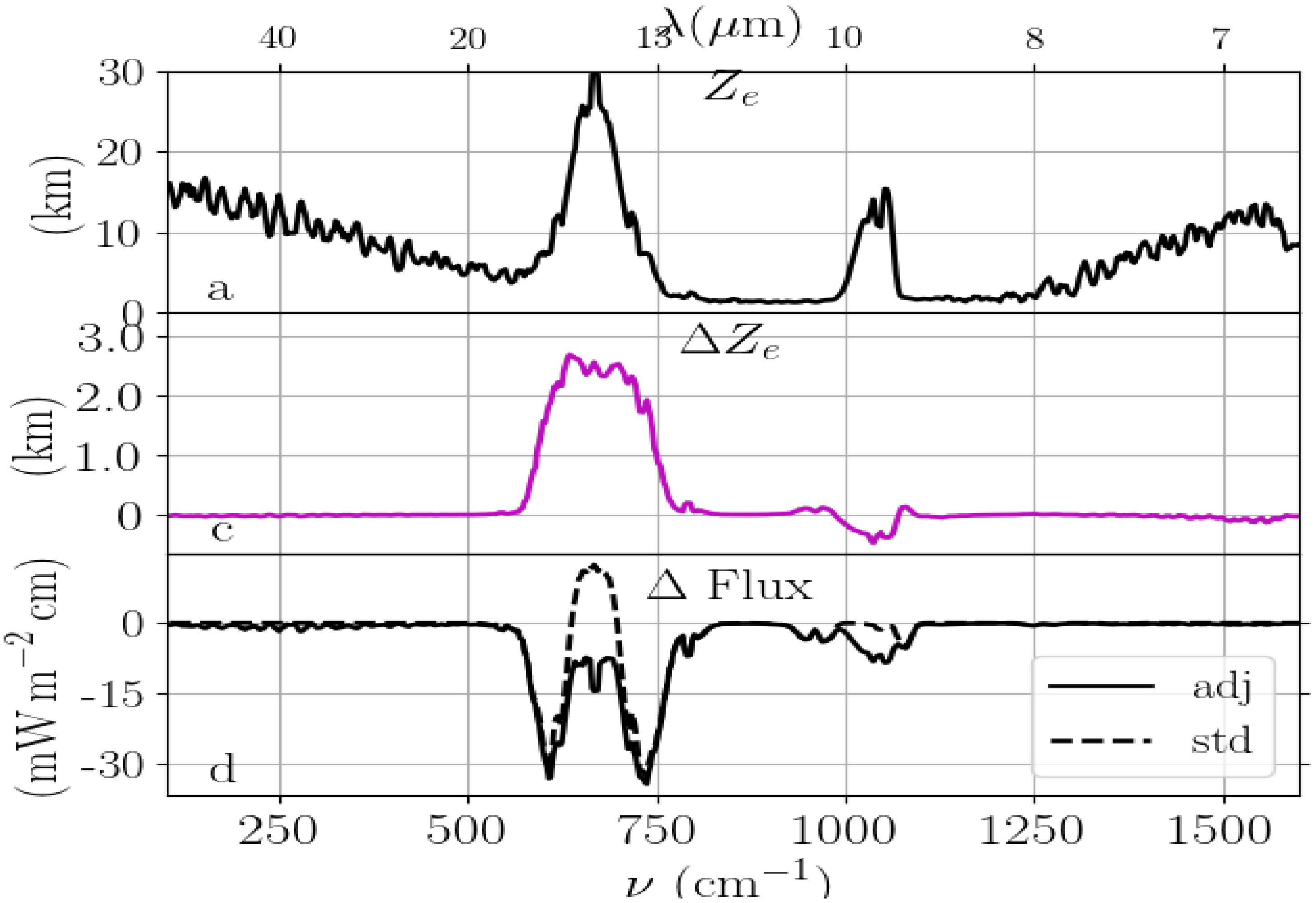
The ***radiative forcing ΔQ*** is the **change in the net radiative flux N** (W.m^{-2}) at the top of atmosphere due to the external forcing **without the surface temperature T_s adjusting** to this perturbation. The radiative forcing aims to compare the magnitude of different perturbations that impact climate.

The ***climate feedback parameter λ*** (W m^{-2} K^{-1}) is the **sensitivity of the net radiative flux N** at the top of atmosphere due to a change in the **surface temperature T_s**



$$\lambda = \frac{dN}{dT_s}$$

CO_2 forcing with stratospheric adjustment



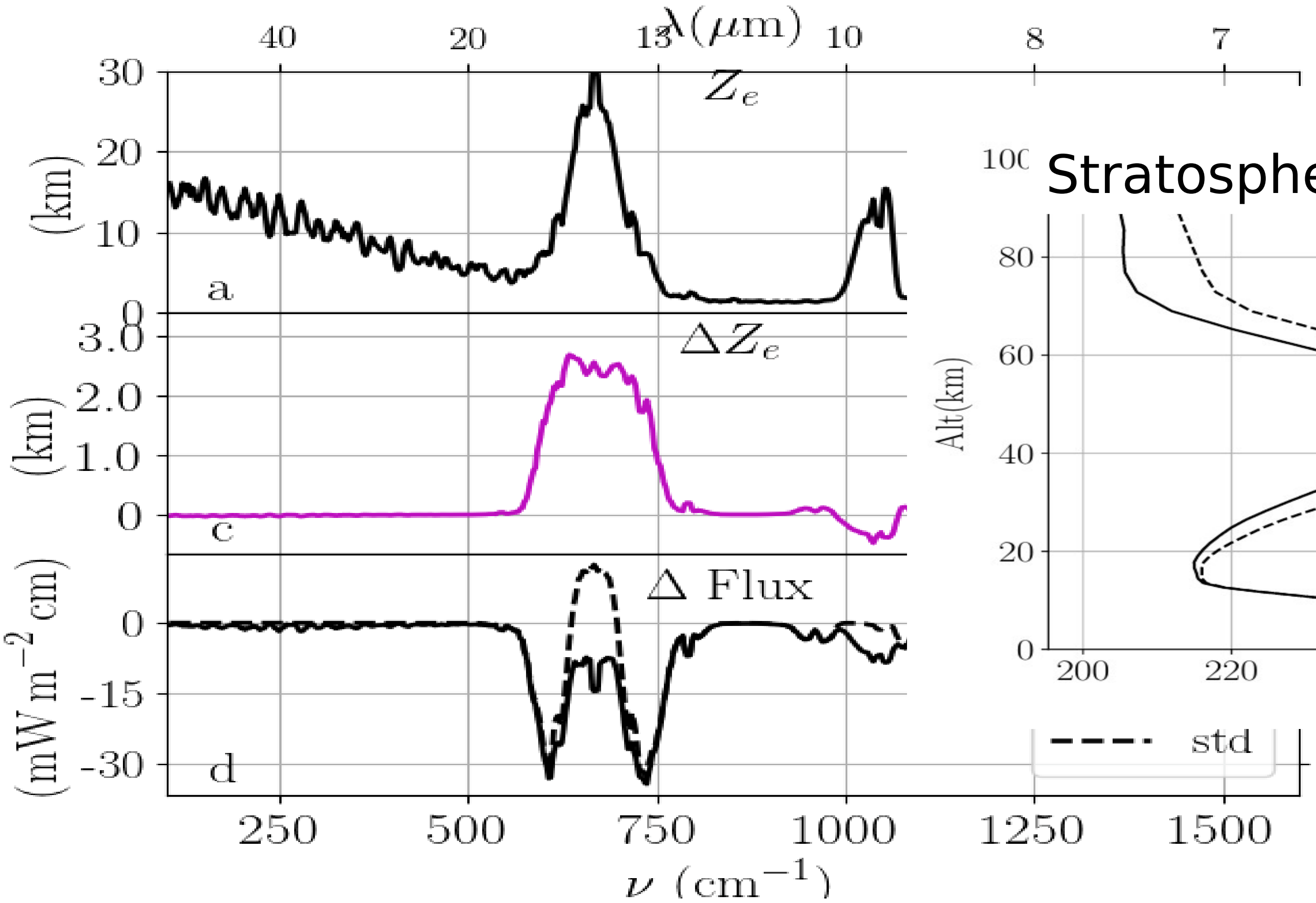
Emission height

Change in emission height for a doubling of CO_2 concentration

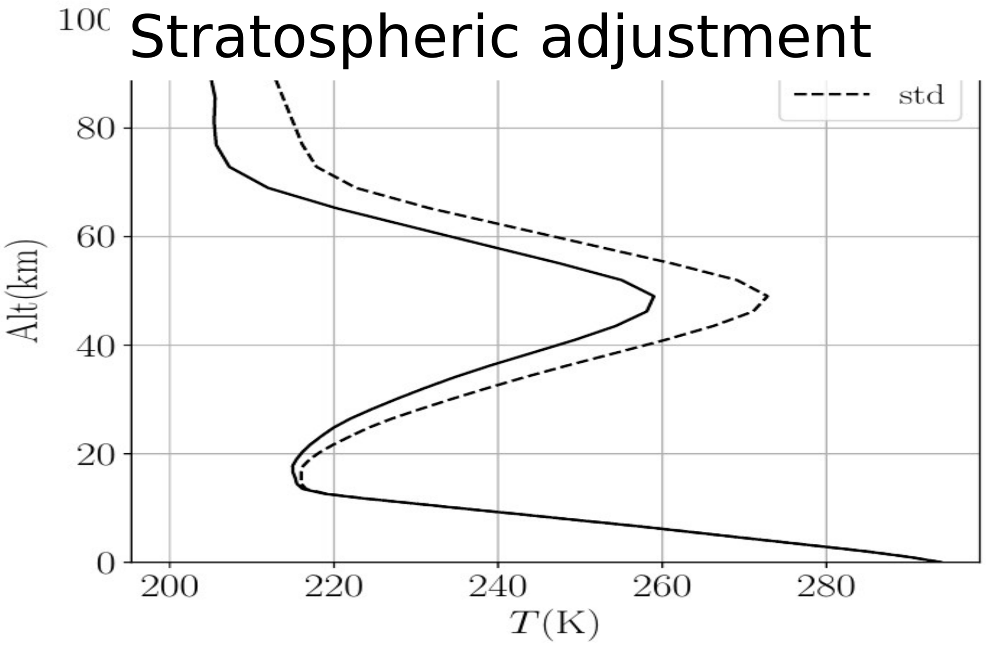
Change in radiative flux at the top of the atmosphere

[Dufresne et al., 2020]

CO_2 forcing with stratospheric adjustment



Stratospheric adjustment

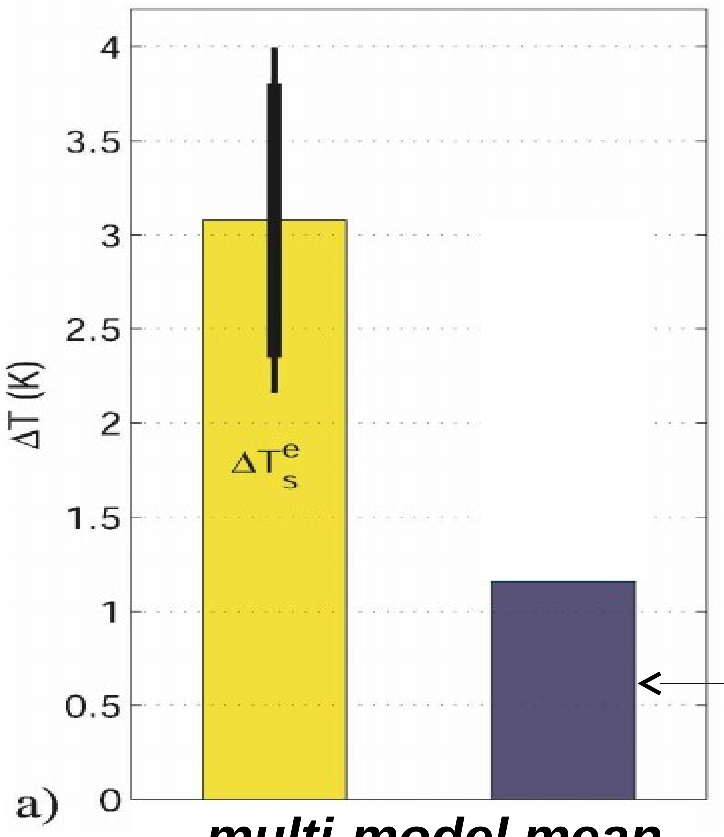


[Dufresne et al., 2020]

Temperature response to a CO_2 doubling forcing

$$\boxed{\Delta N = \Delta Q + \lambda \, \Delta T_s}$$

$$\Delta N = 0 \quad \Rightarrow \Delta T_s = -\frac{\Delta Q}{\lambda} \qquad \lambda = \lambda_P$$



multi-model mean

Planck response, or direct response to forcing

$$\lambda_P = \frac{\partial N}{\partial B(T)} \frac{\partial B(T)}{\partial T_s}$$

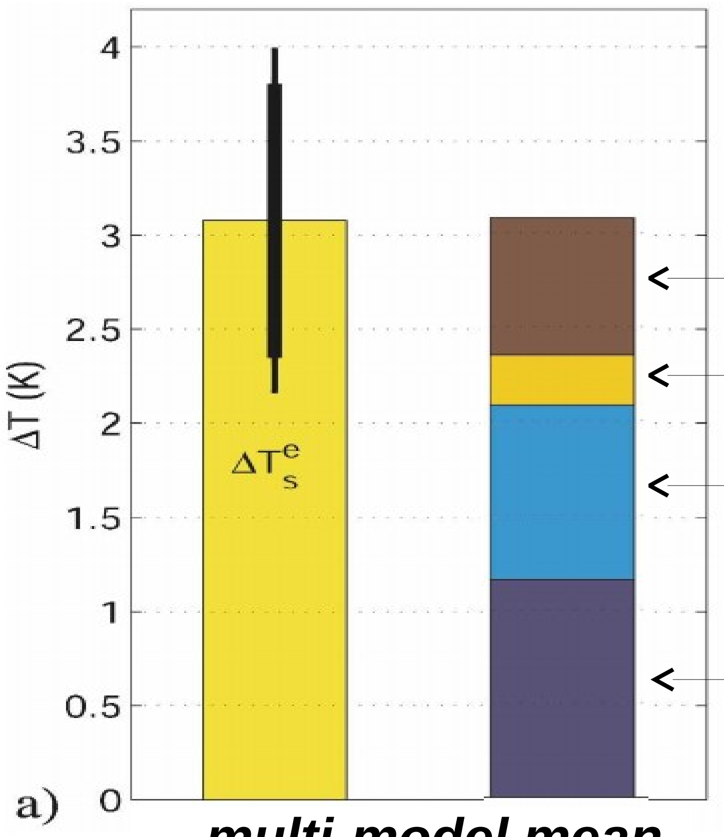
(Dufresne & Bony, 2008)

Temperature response to a CO_2 doubling forcing

$$\boxed{\Delta N = \Delta Q + \lambda\, \Delta T_s}$$

$$\Delta N = 0 \;\Rightarrow\; \Delta T_s = -\frac{\Delta Q}{\lambda}$$

$$\lambda = \lambda_P + \lambda_w + \lambda_A + \lambda_C$$



multi-model mean

Climate feedbacks: response to forcing due to changes of climate variables

clouds $\quad \lambda_{Cl} = \frac{\partial N}{\partial Cl}\frac{\partial Cl}{\partial T_s}$

surface albedo $\quad \lambda_A = \frac{\partial N}{\partial A}\frac{\partial A}{\partial T_s}$

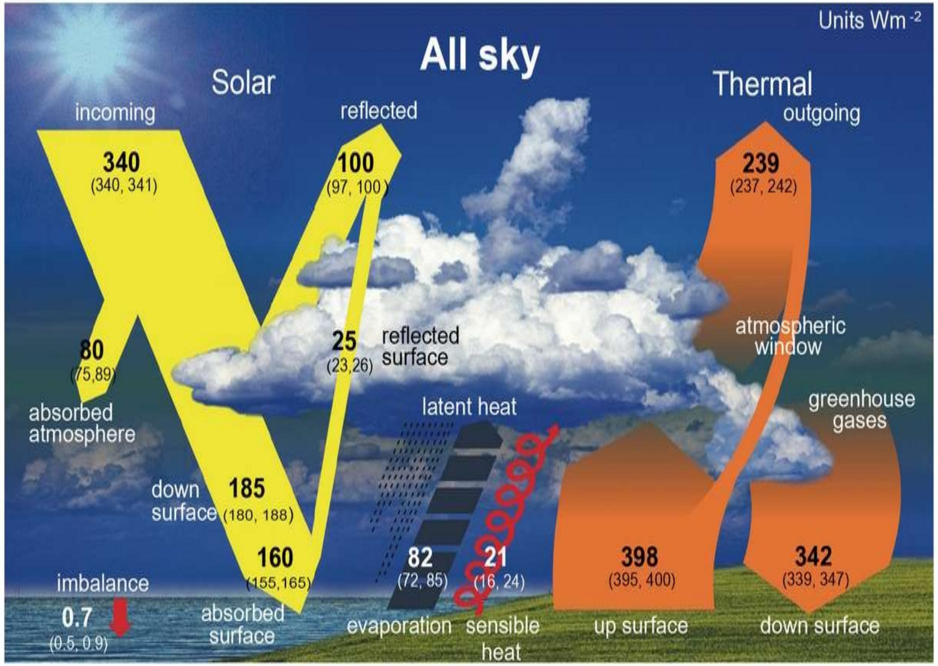
water vapor $\quad \lambda_w = \frac{\partial N}{\partial H_2O}\frac{\partial H_2O}{\partial T_s}$

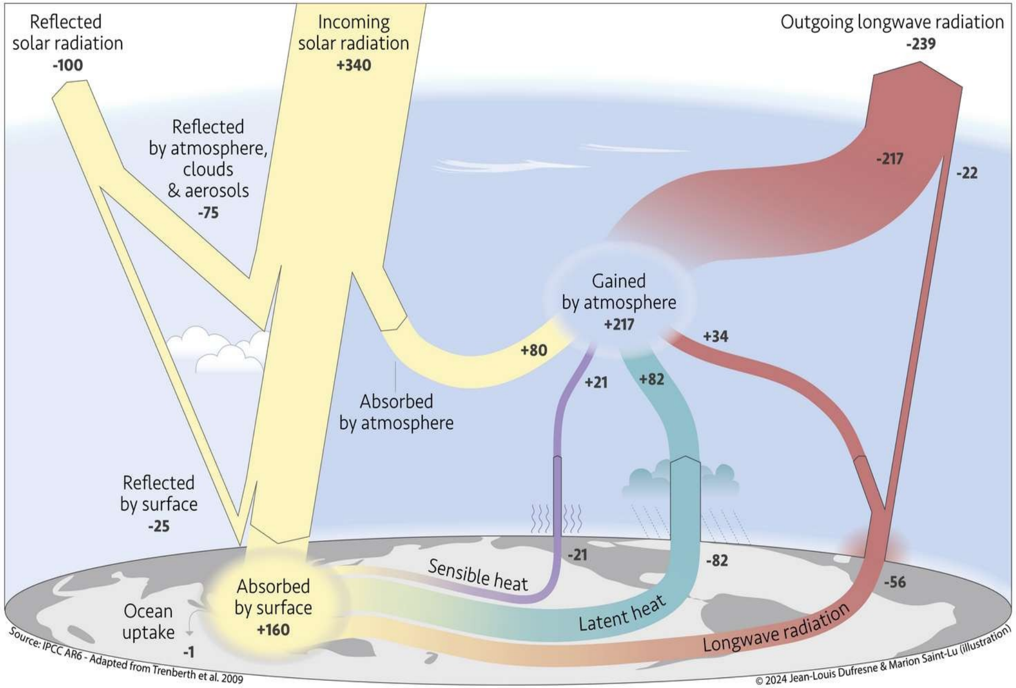
Planck response, or direct response to forcing

$$\lambda_P = \frac{\partial N}{\partial B(T)}\frac{\partial B(T)}{\partial T_s}$$

(Dufresne & Bony, 2008)

Energy flows in the Earth atmosphere





[IPCC AR6, ch7, 2021; Trenberth & Fasullo, 2012]

Same, redesigned by Saint-Lu & Dufresne
Also in Peixoto and Oort, 1992

After an increase in CO_2, the power of the infrared radiation emitted by the atmosphere towards the surface increases mainly because of the increase in temperature and water vapour, not because of the increase in CO_2.

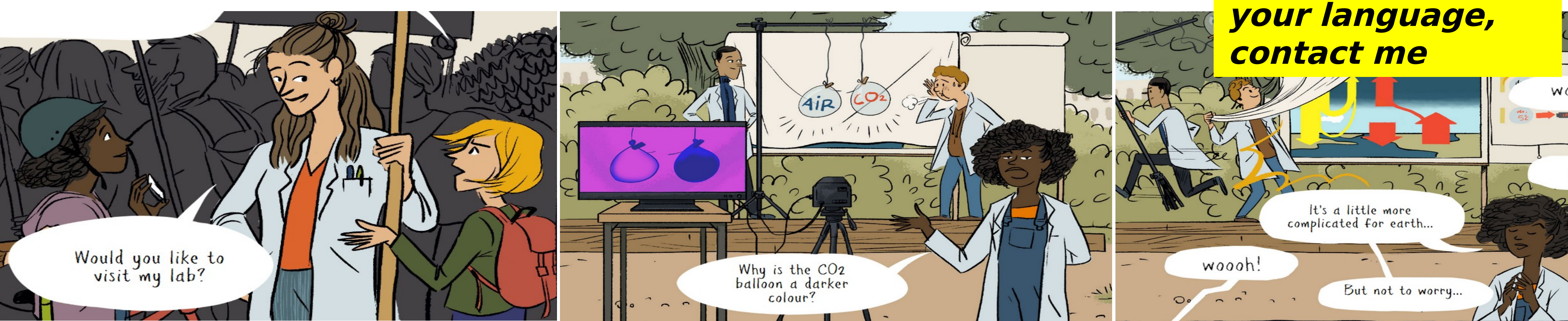
Any feedback very welcome !

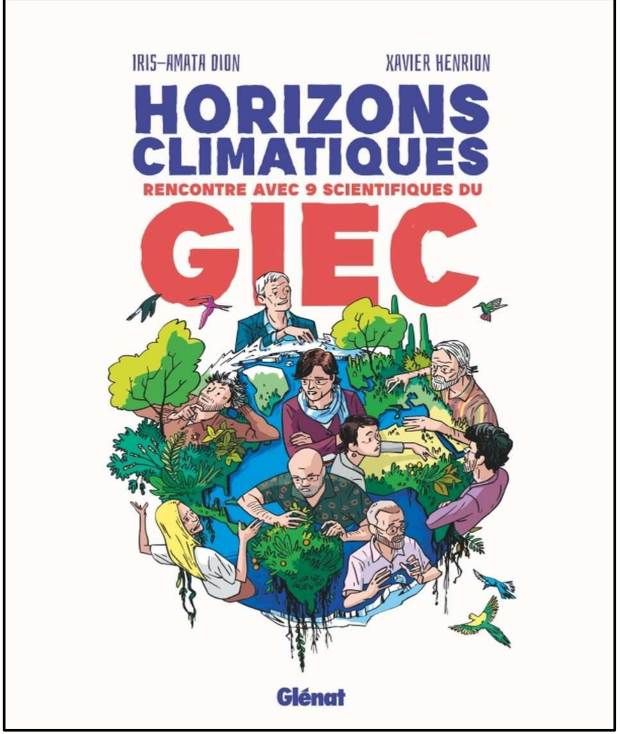
valentin.maron@univ-tlse2.fr

https://www.grandiloquents.fr/en/climat

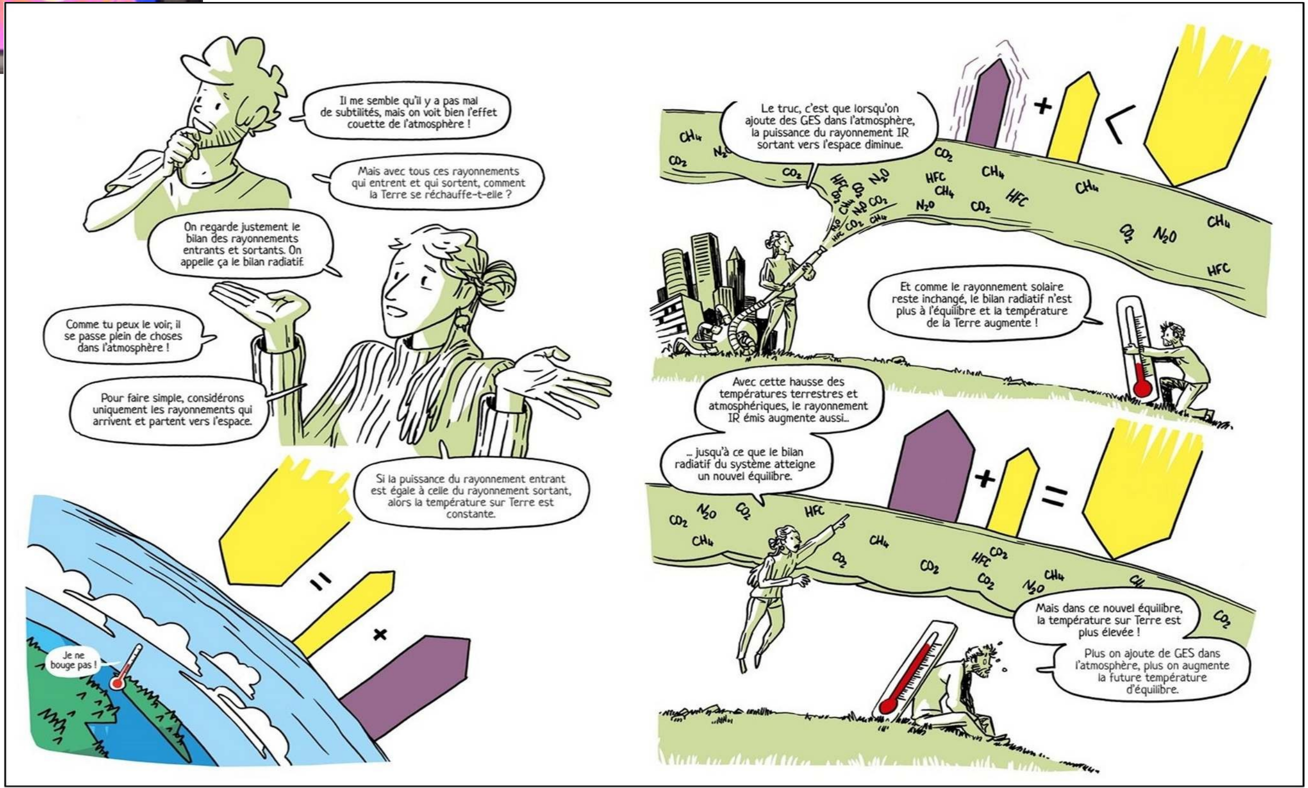
(pedagogical content to use it in class

If you are interested for a translation in your language, contact me





IRIS-AMATA DION



Further readings

Greenhouse effect:

• V Maron, JL Dufresne, LP Pelissier, A Rabier, M. Cochepin, “Quelles expériences et quelles représentations pour construire le lien entre CO_2 et réchauffement climatique avec des non spécialistes ?”, 2025, https://hal.science/hal-04744461v1

• Dufresne J.-L., V. Eymet, C. Crevoisier, J-Y Grandeix; Greenhouse effect: the relative contributions of emission height and total absorption, J. of Climate, 33(9), 3827-3844, https://doi.org/10.1175/JCLI-D-19-0193.1

• Dufresne J.-L., J. Treiner (2011), L'effet de serre atmosphérique: plus subtil qu'on ne le croit!, La Météorologie, No. 72, pp. 31-41, http://dx.doi.org/10.4267/2042/39839

• Pierrehumbert R.T.; Infrared radiation and planetary temperature. Physics Today 1 January 2011; 64 (1): 33–38. https://doi.org/10.1063/1.3541943

• Benestad, R. E. (2017). "A mental picture of the greenhouse effect". Theor Appl Climatol. 128 (3–4): 679–688. doi:10.1007/s00704-016-1732-y

IPCC AR6 Technical Summary. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V. et al. (eds.)]. Cambridge University Press, pp. 33−144. doi:10.1017/9781009157896.002

Vidéo:

• **Science Etonnate: SATURATION de l'EFFET DE SERRE : Le réchauffement a-t-il atteint sa limite ? , par David Louapre:** https://scienceetonnante.com/2023/10/06/la-saturation-de-leffet-de-serre/

• **Sabine Hossenfelder: I Misunderstood the Greenhouse Effect. Here's How It Works.** https://www.youtube.com/watch?v=oqu5DjzOBF8

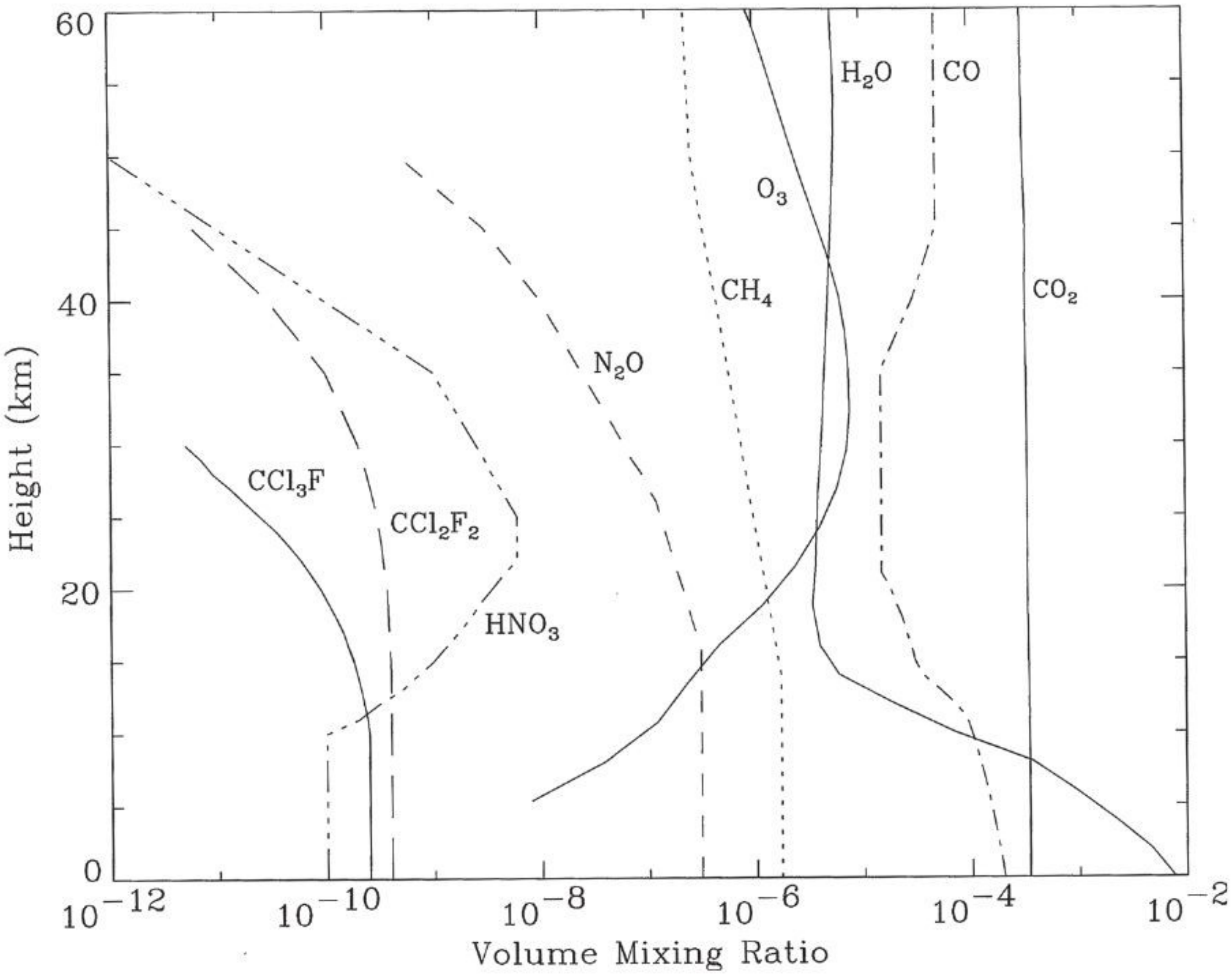
[NASA]

Solar radiation dominates Earth energy inputs

Rayonnement électromagnétique reçu du Soleil (principalement visible et IR)	$1{,}7\ 10^{17}$ W
Géothermie (radioactivités à période longue : ^{238}U, ^{235}U, ^{232}Th, ^{40}K)	~ $4{,}4\ 10^{13}$ W
Civilisation en 2010 (~10^9 humains consommant 10 t de pétrole/an)	$1{,}6\ 10^{13}$ W
Énergie rotative dissipée par les marées	$2{,}8\ 10^{12}$ W
Vent solaire (pour « cible magnétosphérique » de 25 R_{Terre} ~ 10^{14} W)	~ $2\ 10^{11}$ W
Rayonnement du fond cosmologique (corps noir* à 2,7 K)	$1{,}6\ 10^9$ W
Rayonnement électromagnétique reçu des étoiles (visible, IR)	~ $1{,}3\ 10^9$ W
Rayonnement cosmique (protons, alphas…)	$9\ 10^8$ W
Météorites (~ 30 000 tonnes par an, supposant $v_{impact} \approx 20$ km/s)	~ $2\ 10^8$ W

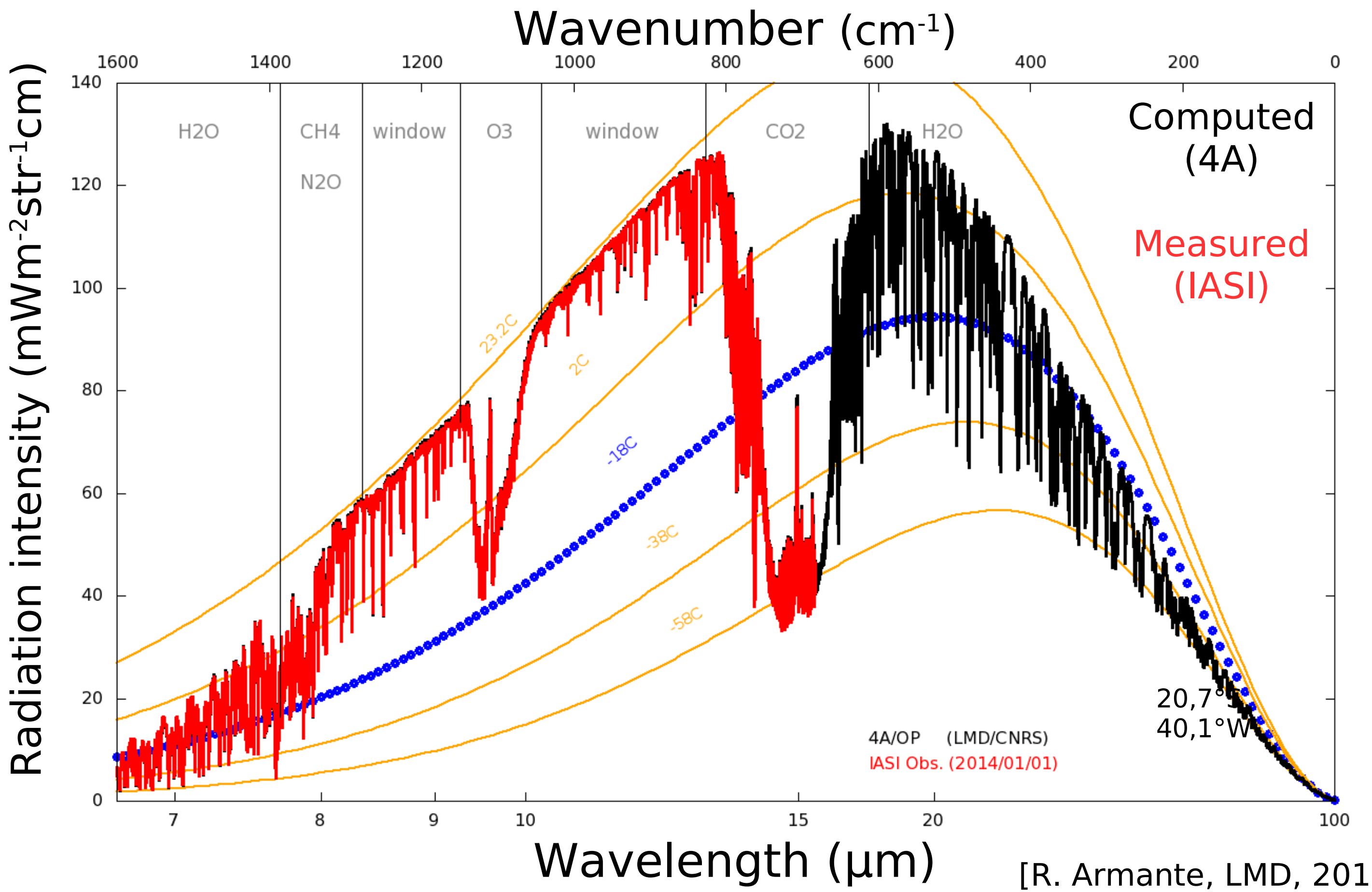
Surface of the Earth: 510 10^{12} m^2
1 PW = 10^{15}W

Source : P. von Balmoos in Le Climat à Découvert, CNRS éditions, 2011

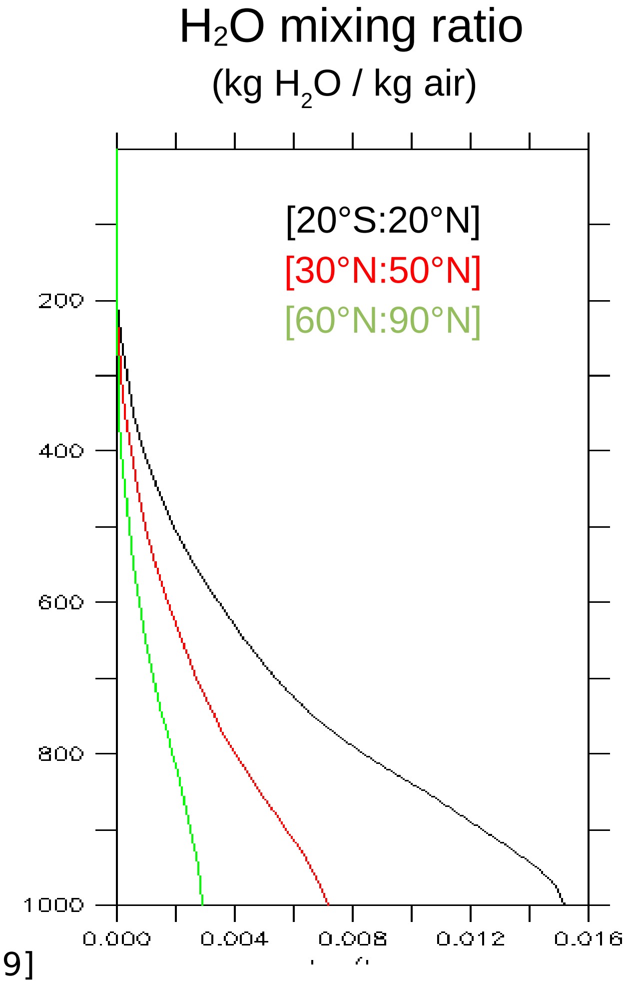


[Stamnes, 2008]

Spectrum of the radiation emitted by the Earth as measured by satellites

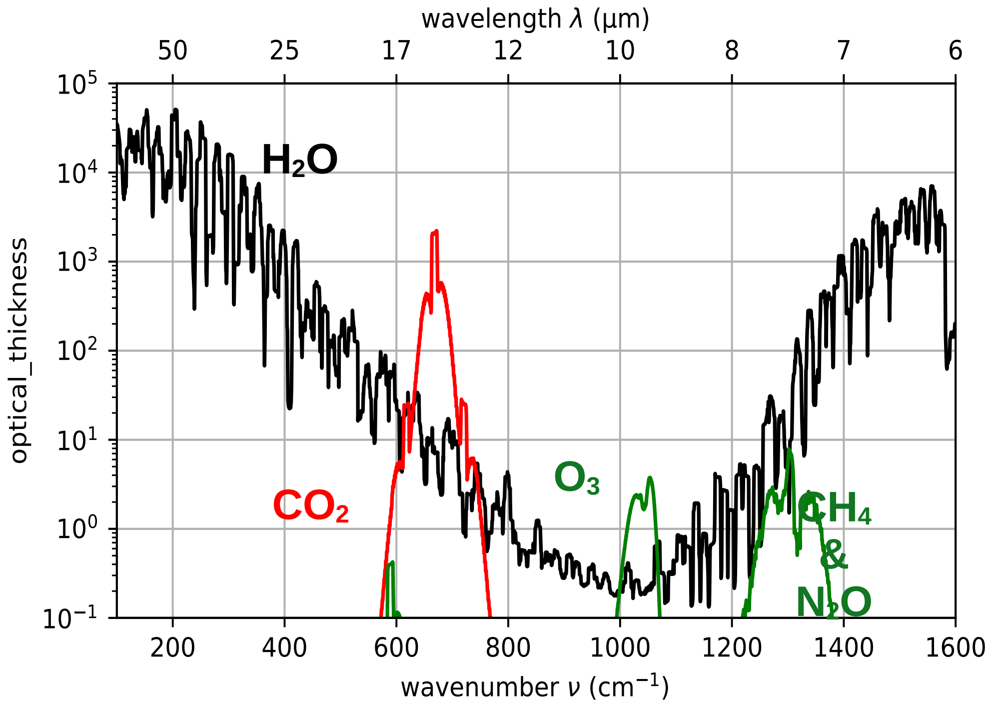


[R. Armante, LMD, 2019]

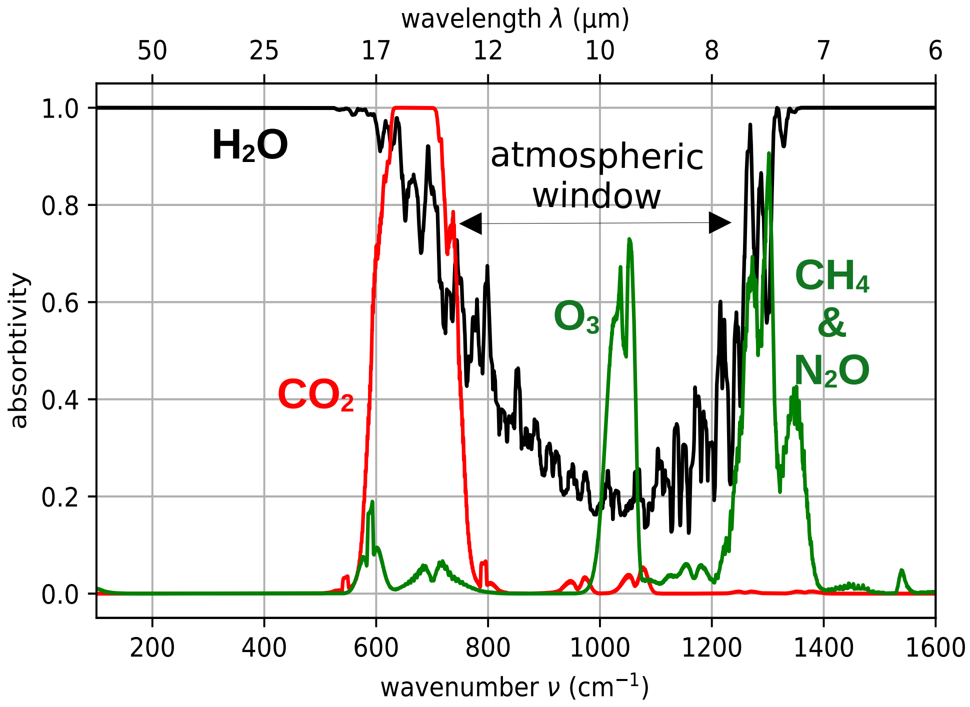


Gaz absorption in the atmosphere

Optical thickness:

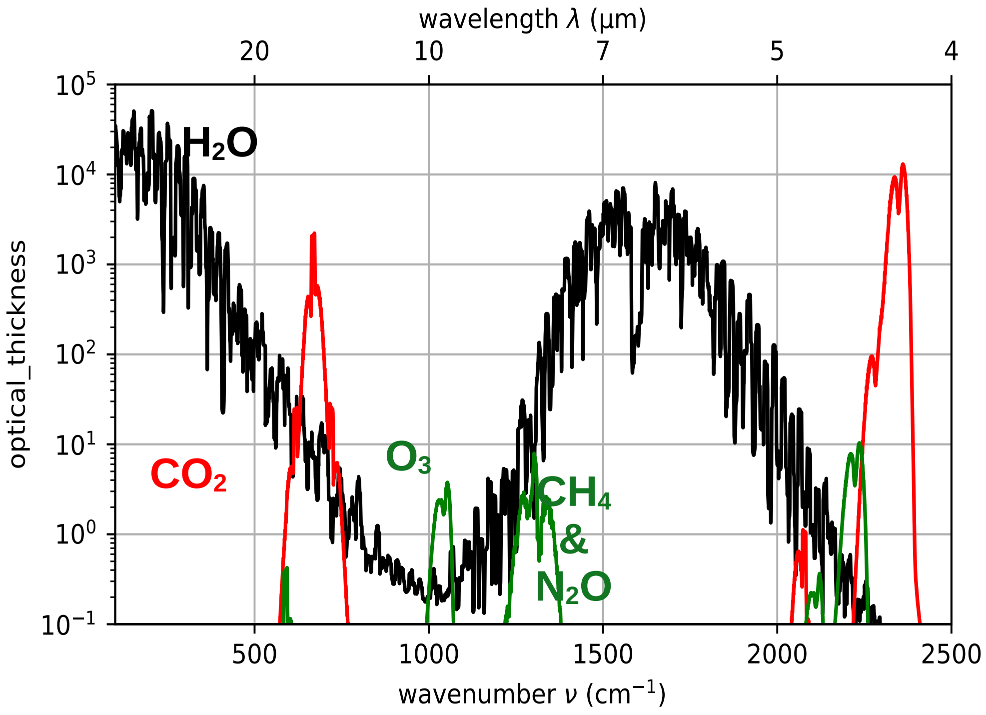


Absorptivity:

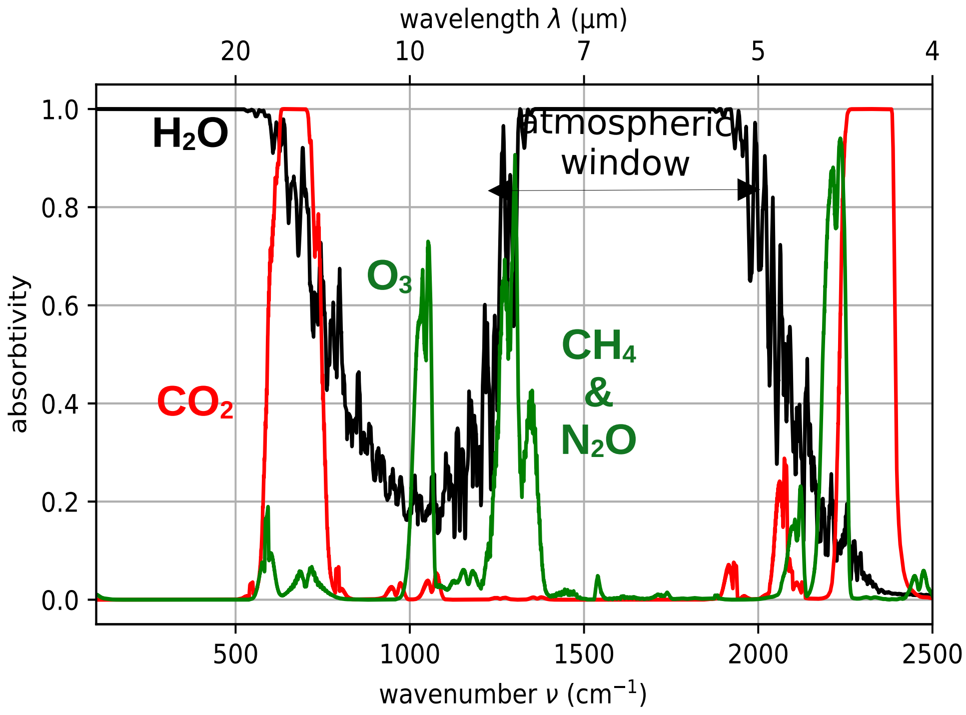


Gaz absorption in the atmosphere

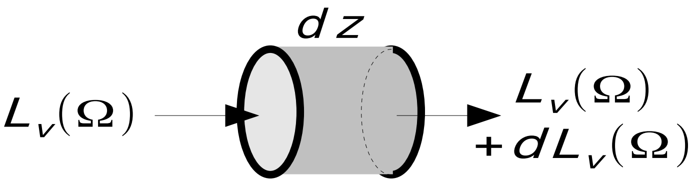
Optical thickness:



Absorptivity:



LW flux at the TOA



Radiative transfer equation in a non-scattering media

$$\boxed{\frac{dL_\nu}{dz} = k_\nu \rho (B_\nu(T) - L_\nu)}$$

L_ν	spectral radiance
z	distance
k_ν	**absorption coefficient** per unit of mass
$B_\nu(T)$	black-body emission (Planck function)
ρ	volumic mass of absorbing gaz

$$\frac{dL_\nu}{d\tau} = (B_\nu(T) - L_\nu) \quad \text{with} \quad d\tau = k_\nu \rho \, dz$$

τ, optical thickness

Optical thickness between z_1 and z_2: $\tau_\nu(z_1, z_2) = \left| \int_{z_1}^{z_2} k_\nu(z) \rho(z) \, dz \right|$

$z = \infty$: top of atmosphere

$z = 0$: surface

Upward LW radiation at altitude z for an atmosphere at uniform temperature T_a with a black surface at temperature T_s:

$$L_\nu(z) = B_\nu(T_s) e^{-\tau_\nu(0,z)} + B_\nu(T_a)(1 - e^{-\tau_\nu(0,z)})$$

$$\boxed{L_\nu(z) = B_\nu(T_s) \underbrace{[1 - A_\nu(0,z)]}_{\textbf{transmittivity}} + B_\nu(T_a) \underbrace{A_\nu(0,z)}_{\textbf{absorptivity}}}$$

= 1-absorptivity

LW flux at the TOA and emission height

Upward LW spectral flux at the top of the atmosphere (TOA) ***for an isothermal atmosphere*** at uniform temperature T_a with a black surface at temperature T_s:

$$F_\nu(\infty)=B_\nu(T_s)\underbrace{[1-A_\nu(0,\infty)]}_{\text{transmittivity}} + B_\nu(T_a)\underbrace{A_\nu(0,\infty)}_{\text{absorptivity}}$$

$$A_\nu(0,\infty)=1-e^{-\tau_\nu(0,\infty)}$$

***For a non isothermal atmosphere*:**

$$F_\nu(\infty)=\underbrace{B_\nu(T_s)[1-A_\nu(0,\infty)]}_{\text{Radiation emitted by the surface toward space}} + \underbrace{\int_\infty^0 B_\nu(T)\frac{\partial A_\nu(z,\infty)}{\partial z}dz}_{\text{Radiation emitted by the atmosphere toward space}}$$

$$A_\nu(z,\infty)=1-e^{-\tau_\nu(z,\infty)}$$

Which we rewrite as:

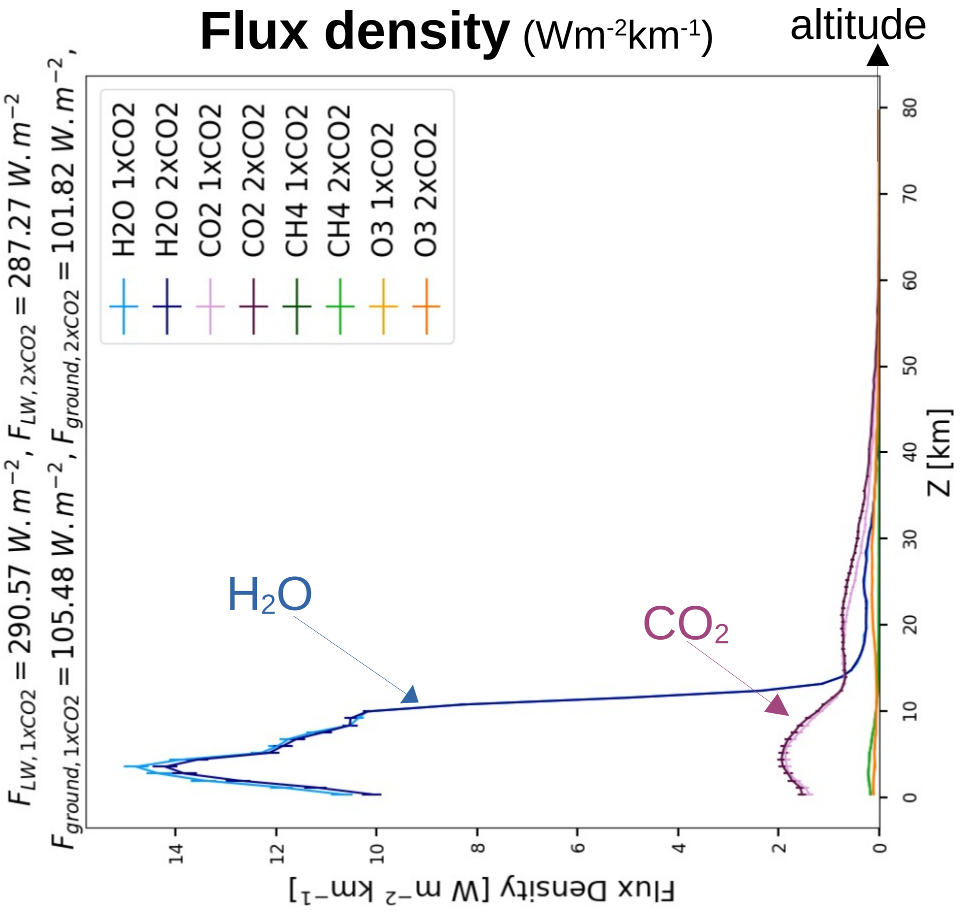
$$\boxed{F_\nu(\infty)=B_\nu(T_s)[1-A_\nu(0,\infty)] + B_\nu(T_e)A_\nu(0,\infty)}$$

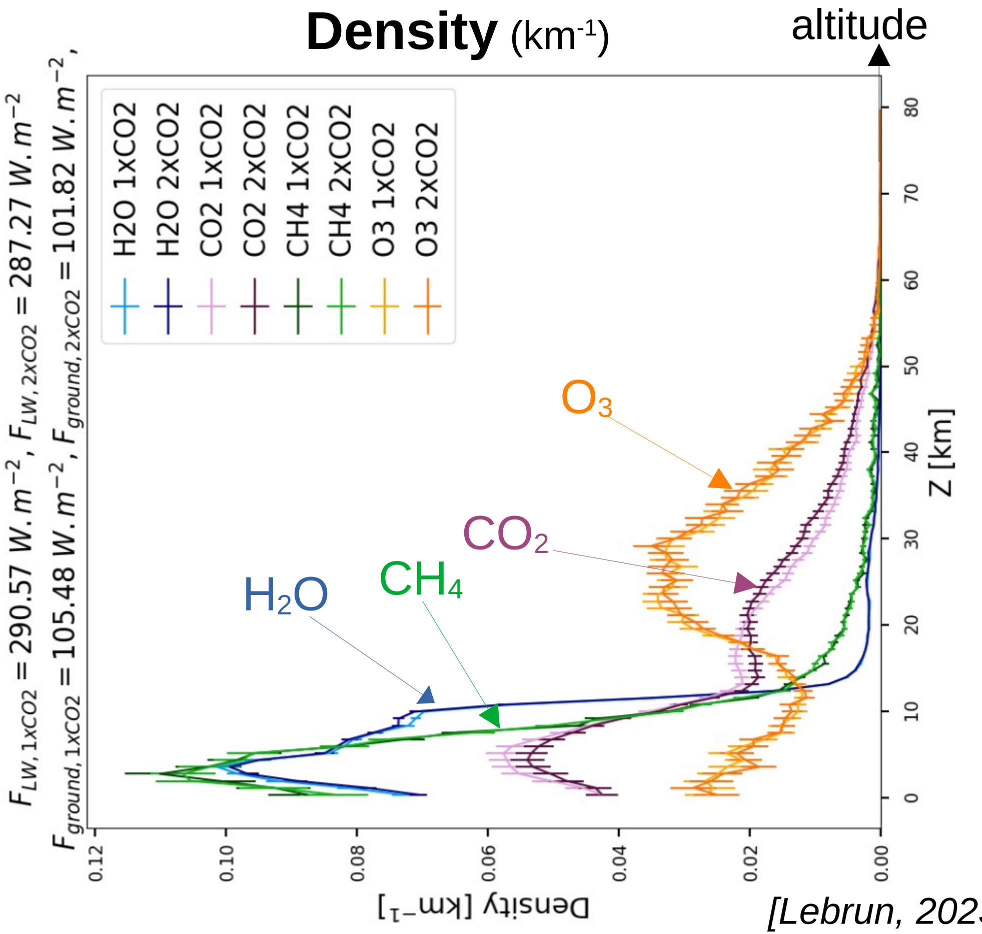
with: $$B_\nu(T_e)=\frac{1}{A_\nu(0,\infty)}\int_\infty^0 B_\nu(T)\frac{\partial A_\nu(z,\infty)}{\partial z}dz$$

T_e: emission temperature of the atmosphere

A common approximation is: $T_e \approx T(z_e)$ where Z_e (emission height) is defined as $\tau(Z_e,\infty)=1$

Vertical profiles of gas contribution





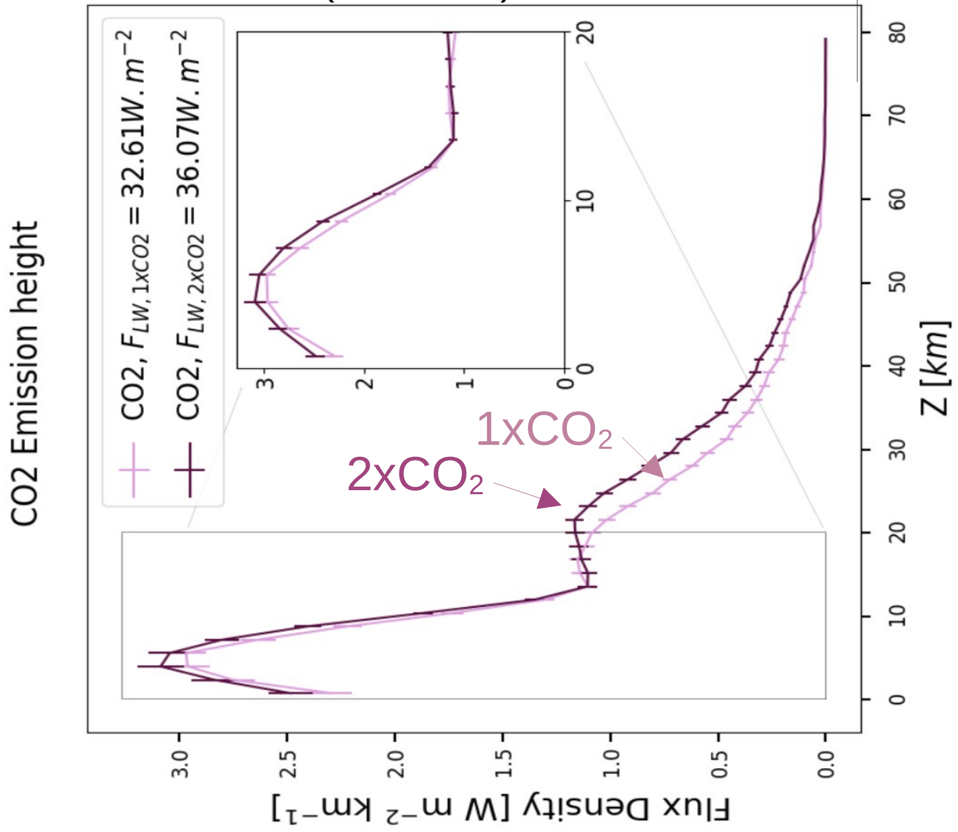
[Lebrun, 2023]

Vertical profiles of gas contribution

CO_2 emission, flux density

(Wm^{-2}km^{-1})

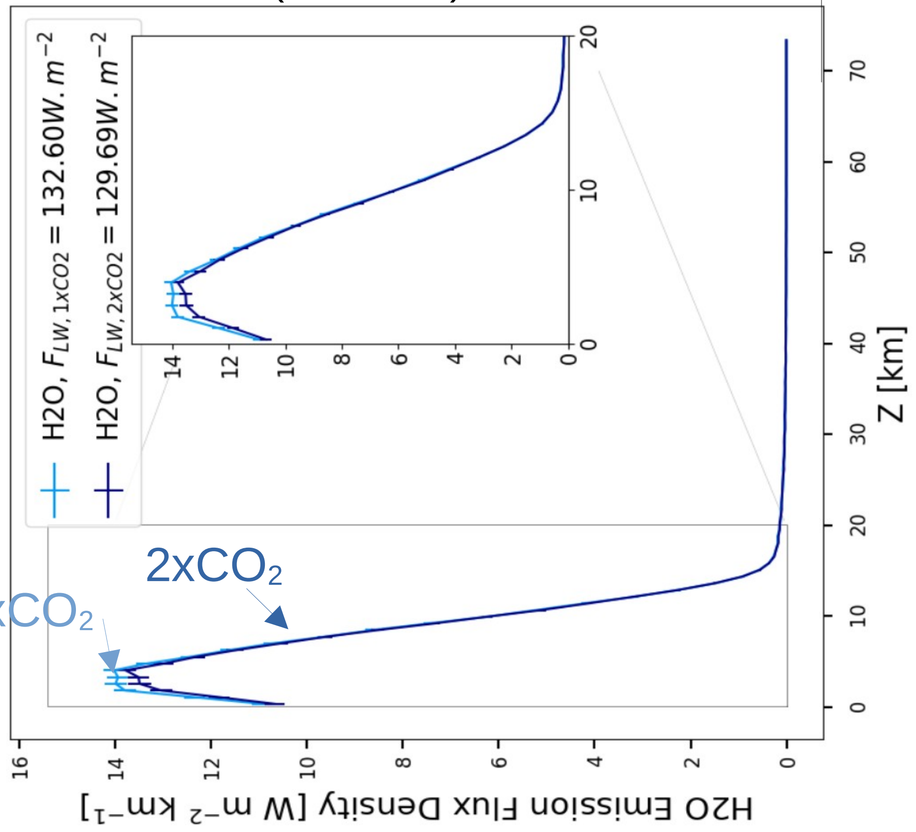
altitude



H_2O emission, flux density

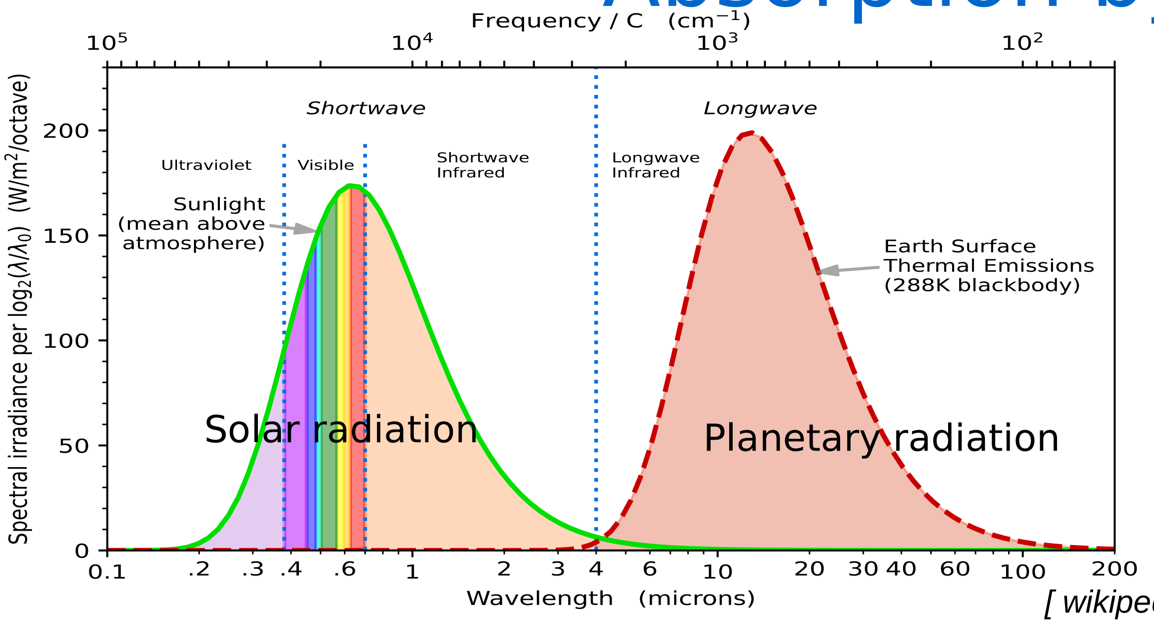
(Wm^{-2}km^{-1})

altitude



[Lebrun, 2023]

Absorption by gases



[wikipedia]

Extinction = absorption + scattering

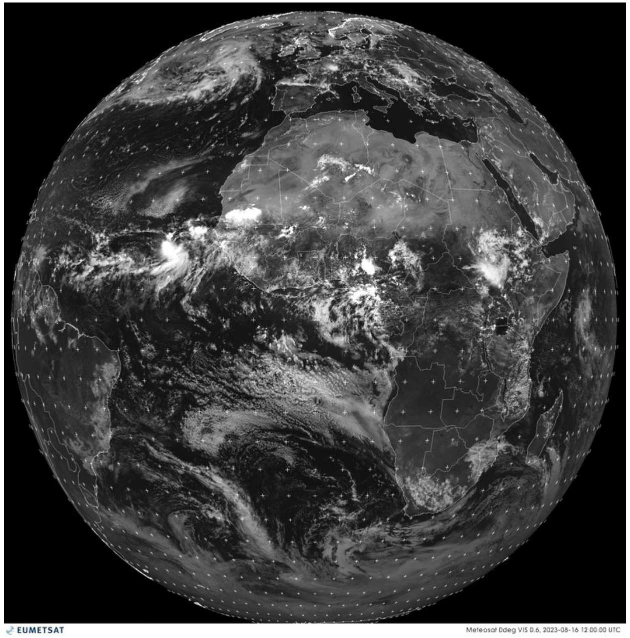
Transmissivity + Absorptivity + Reflectivity = 1

	solar	far IR
absorption	UV: O_2, O_3 Visible: no Near IR: H_2O (gas)	H_2O (gas), CO_2, CH_4, O_3, etc.
scattering	UV: gases (Rayleigh) [+ clouds, aerosols]	Negligible for gases [small for clouds and aerosols]

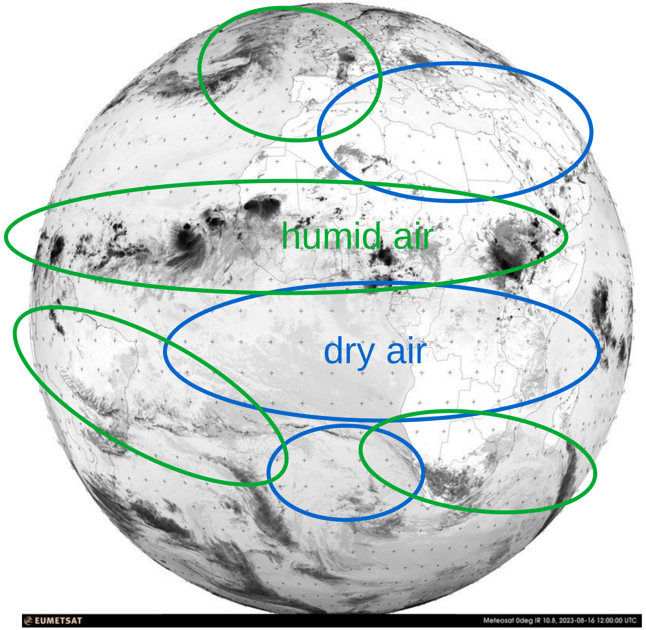
Observation from Meteosat satellite

Meteosat 0° observation on 2023-08-16

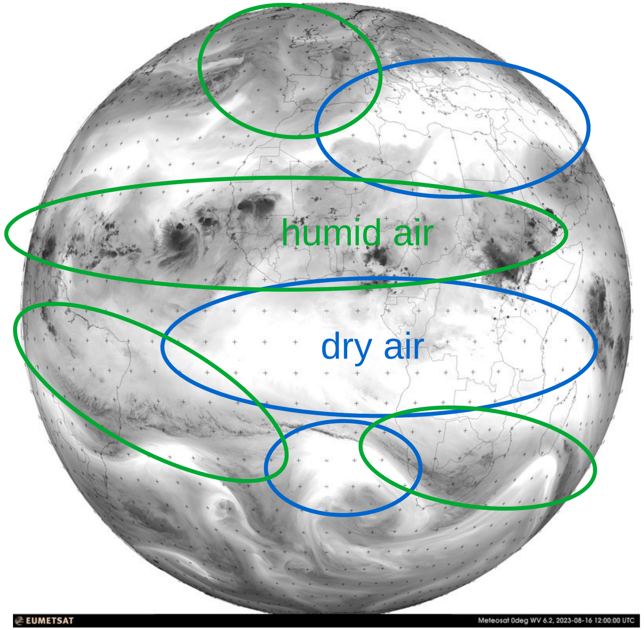
Visible
(0.5-0.9µm)



Atmospheric window
(10.5-12.5µm)



Water vapor chanel
(5.7-7.1µm)



Brightness temperature: White: warm. Black: cold

http://www.meteo-spatiale.fr/src/autres_sources.php