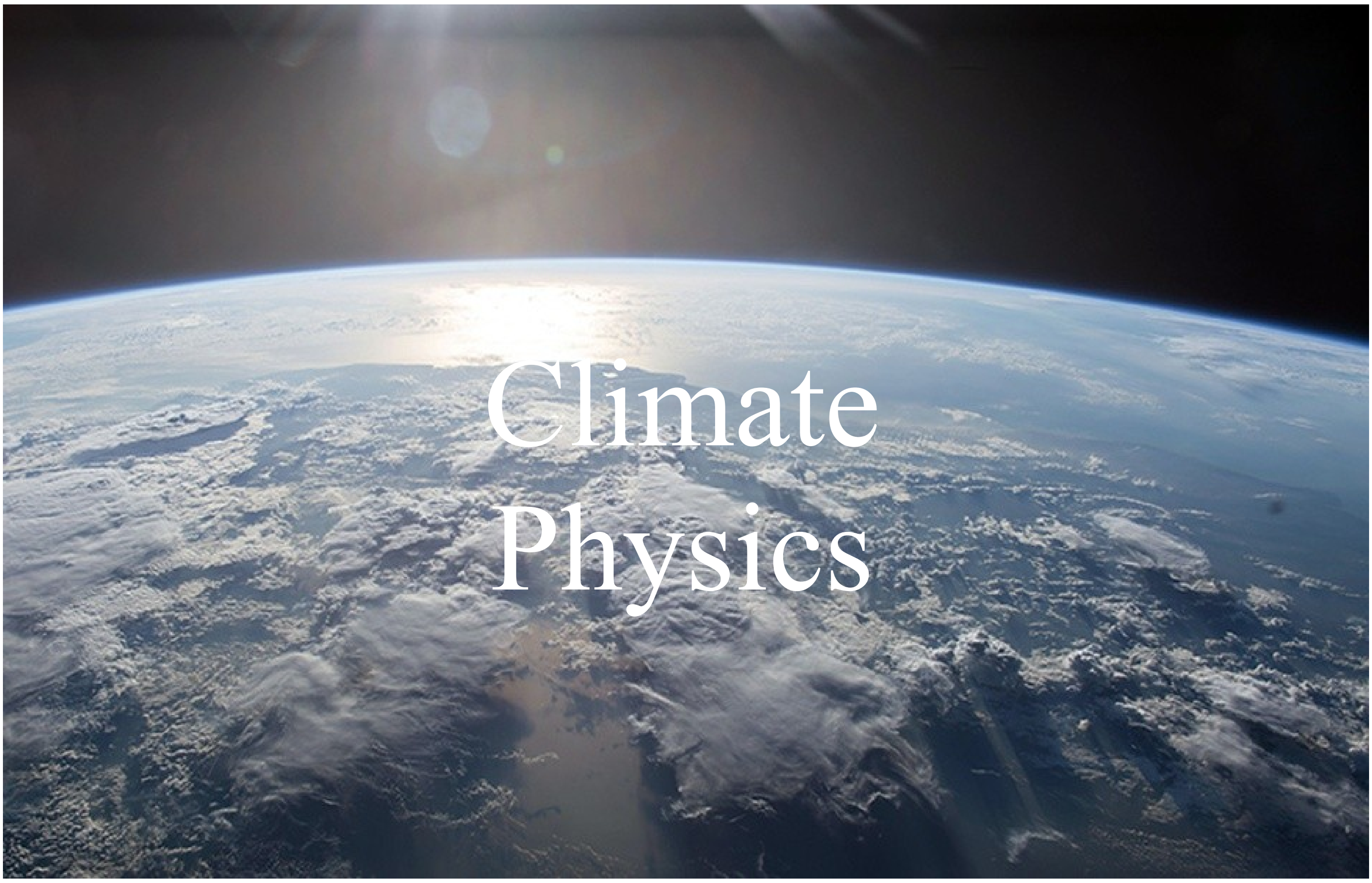
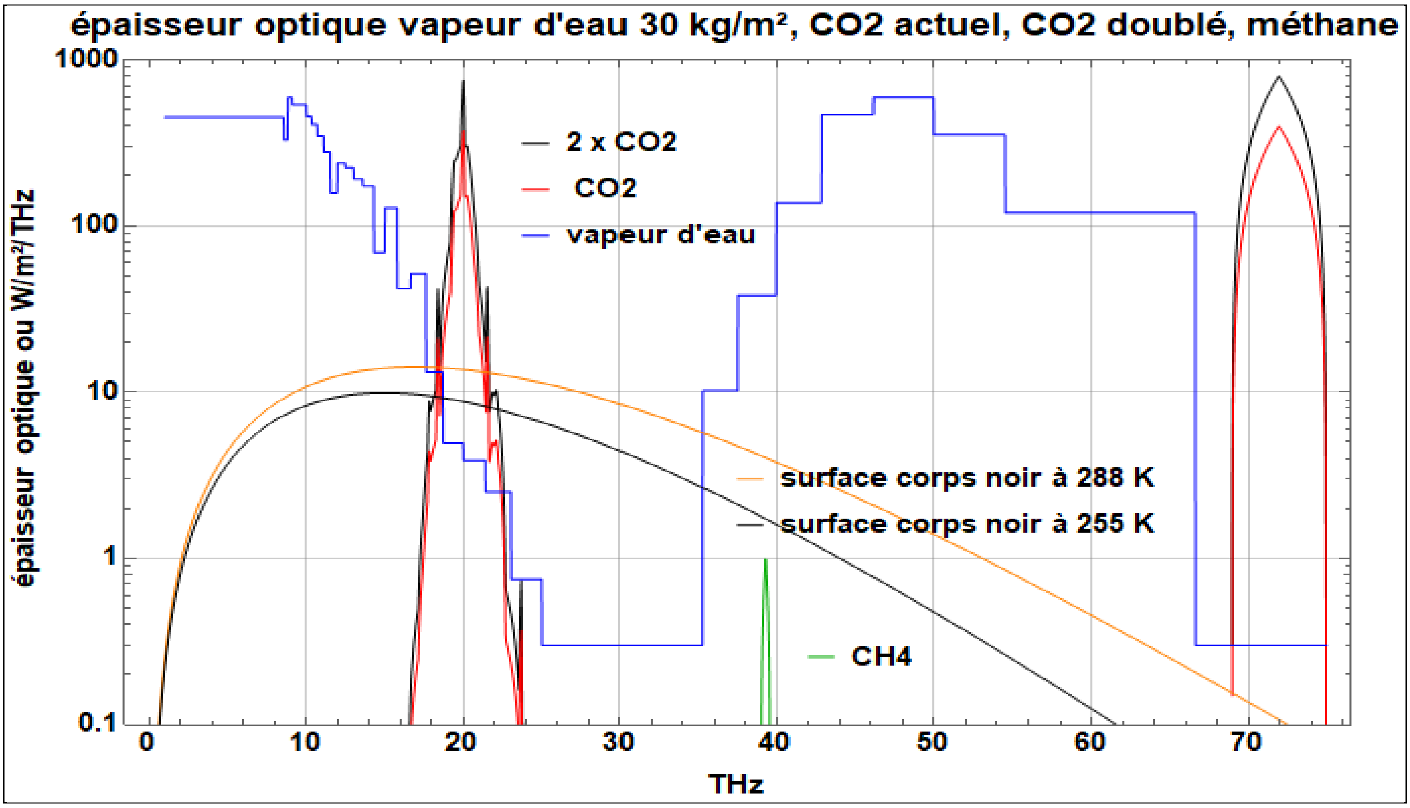


Forget the "Greenhouse Effect"
and return to the Fundamentals



Jacques-Marie Moranne

Révisions

0 30/11/2019 Diffusion pour relecture

Sommaire

Foreword by François Gervais

At the basis of the so-called atmospheric greenhouse effect, the absorption and emission of thermal radiation by the vibrations of a gas molecule are essential. In a quantum description, we will talk about the absorption and emission of a photon. These phenomena are related to Physics. Air molecules with at least two different atoms, e. g. oxygen and hydrogen in the case of the water vapour molecule, carbon and oxygen in the case of the carbon dioxide molecule CO_2, carbon and hydrogen in the case of methane, are thus the seat of atomic vibrations capable of absorbing and emitting thermal radiation. These vibrations are observed in the infrared range of the electromagnetic spectrum. This book describes in detail these mechanisms, which are essential for understanding the physics of the atmosphere and its implications for climate. Conversely, and strangely enough, there is no trace of an infrared spectrum of the atmosphere in the 1500 pages of the last IPCC AR5 report... From this point of view, this book fills a serious gap.

Should climatology remain reserved for climatologists, as insinuated by some media, which too often tend to make it a priority in a debate that is no longer scientific but highly politicized ? The keyword "climatology" is one of the 55 that define the scope of teaching and research within the framework of section 23 "Physical, human, economic and regional geography" of the French National Council of Universities. Just as universities know how to define the skills of a mathematician, a physicist, a chemist, a biologist, a geographer in order to eventually recruit them, so does climatology appear in its true place, a sub-discipline of Geography among 54 others. How many authors of the IPCC reports, the Intergovernmental Panel on Climate Change, justify a thesis in climatology ? In any case, neither its current President nor the previous one. IPCC authors have generally made their thesis in other disciplines and have taken the climate train, which has become highly politicized, promising credits, budgets, contracts, travel, honours and promotions. Arrhenius, winner of the Nobel Prize in Chemistry in 1903, to whom the paternity of the atmospheric greenhouse effect is generally attributed, was he a "climatologist"?

Camille Veyres' footprint can be seen in some parts of this text and in some figures. I met Camille in 2014 to realize that, without consulting each other, both had developed parallel research with fairly similar conclusions. This meeting in a café near the Palais Brongniart at the invitation of the HEC Alumni Geostrategies Group will pave the way for the formation of the "Grogniarts du CO_2" group, which has now been considerably enlarged and become the "Association des Climato-Realistes". I published these findings in the International Journal of Modern Physics and then in Earth Science Reviews.

This book, more detailed and educational than the sometimes somewhat abstruse nature of scientific articles in English, is therefore welcome. It should interest those who know how to read a curve, a graph, an equation, so still many people, and fortunately. In this sense, let us hope that it will contribute to combating a growing and damaging disaffection for scientific culture.

The spring bloom is a delight. In our hemisphere, during the spring and summer seasons, it is accompanied by a drop of some 55 billion tonnes of CO_2 in the atmosphere, feeding a growing vegetation. It is the seasonal Keeling oscillation, precisely measured by infrared spectrometry. The amplitude of this fall is increasing faster in La Jolla, California than the rate of CO_2 in the air, indicating that vegetation is still undernourished. As essential to vegetation as it is irreplaceable, CO_2 is the opposite of a pollutant, it is a fertilizer.

Ignoring or concealing this benefit, merchants of fear live at the expense of the anxious people who listen to them. A media hype that has become unbearable amplifies this insidiously maintained concern. How can we resist such propaganda ? How can we protect ourselves against a fear that has become an instrument of power ? An excellent remedy is to learn about Climate Physics through this book.

His tour de force is to always remain accessible without falling into the trap of an oversimplified popularization, to the point that it could become misleading. We can only encourage the reader to engage in *the little intellectual gymnastics of immersing himself in this presentation and then, if we hope he has benefited as much as he would like, to make it known and spread it.*

François Gervais

Professor Emeritus at the University of Tours (France)
Former CNRS Research Director at the Centre de Recherche sur la Physique des Hautes Températures, Orléans
Former Director of the UMR CNRS 6157
Expert Reviewer of the IPCC AR5 report

March 28, 2019

Executive Summary

Once the albedo and withdrawings at different levels of the atmosphere have been deducted, the Earth receives very little radiation from the sun (in accordance with Stefan Boltzmann's Law) to justify its average temperature of 15°C. (The Moon, at the same distance from the sun as the Earth, has an average temperature of about - 80°C).

This average temperature of 15°C is due to the Lapse Rate which, due to the compression of air by gravity (under its own weight), increases the temperature from the tropopause to the ground level as the pressure increases as the altitude decreases (according to Laplace's Law : PV^{γ} = Cte) : 6.5°C / km on average, from the tropopause.

In the other direction, to maintain its energy and thermal balance, the Earth must return to the cosmos the energy it permanently receives from the Sun ; and it can only exchange with the cosmos by radiation.

The surface of the earth's ground radiates in a range of waves (infra-red known as "distant" or "thermal") where the air, up to several thousand meters above sea level, is almost completely opaque through the absorption bands of CO_2 and especially water vapour ; the evacuation of this heat then takes several paths :

- a narrow window between these absorption bands, called the "Atmospheric Window", still allows a small part of them to be evacuated by direct radiation from the surface of the earth and the oceans to the cosmos.
- a significant portion of the earth's warm air is moved up by natural convection to a level where water vapour is sufficiently rare to no longer prevent its heat from being dissipated by radiation.
- most of it is carried away by the evaporation of the oceans and the evapo-transpiration of plants and soils, which, as by means of a heat pipe that would bypass the water vapour absorption bands, transfers, by convection, considerable energy (latent heat of vaporization/condensation) from the ground surface to the top of the clouds where it is recovered by condensation, and then evacuated by radiation (water vapour, rarefied, no longer impeding it). The warmer the weather, the more this heat pipe flows : it is the main regulator of the climate.
- the balance of the radiation in the CO_2 absorption band is released mainly into the stratosphere, where CO_2 is rare enough to no longer impede it.

Equilibrium factors with oceans and vegetation make it unlikely that the atmospheric CO_2 concentration will double ; but if such a doubling were to occur, it would have a minor impact on the CO_2 absorption band, and on the temperature increase it could cause ; and this impact would be largely offset by an increase in the flow rate of the water vapour heat pipe : in total, the temperature increase would not exceed 0.5°C.

We must therefore look elsewhere for the causes of the current global warming, especially since the latest observations seem to blame sunstroke, probably through a decrease in albedo, the reasons for which are not known with certainty.

In addition, the climate follows cycles, which are themselves quite poorly known, but whose amplitude may be greater than the increase we are experiencing.

Finally, it should not be forgotten that the climate is chaotic, and that accurate climate simulations at a particular location in 50 years or more are a matter of wet finger.

1. Presentation

1.1. Why this Book ?

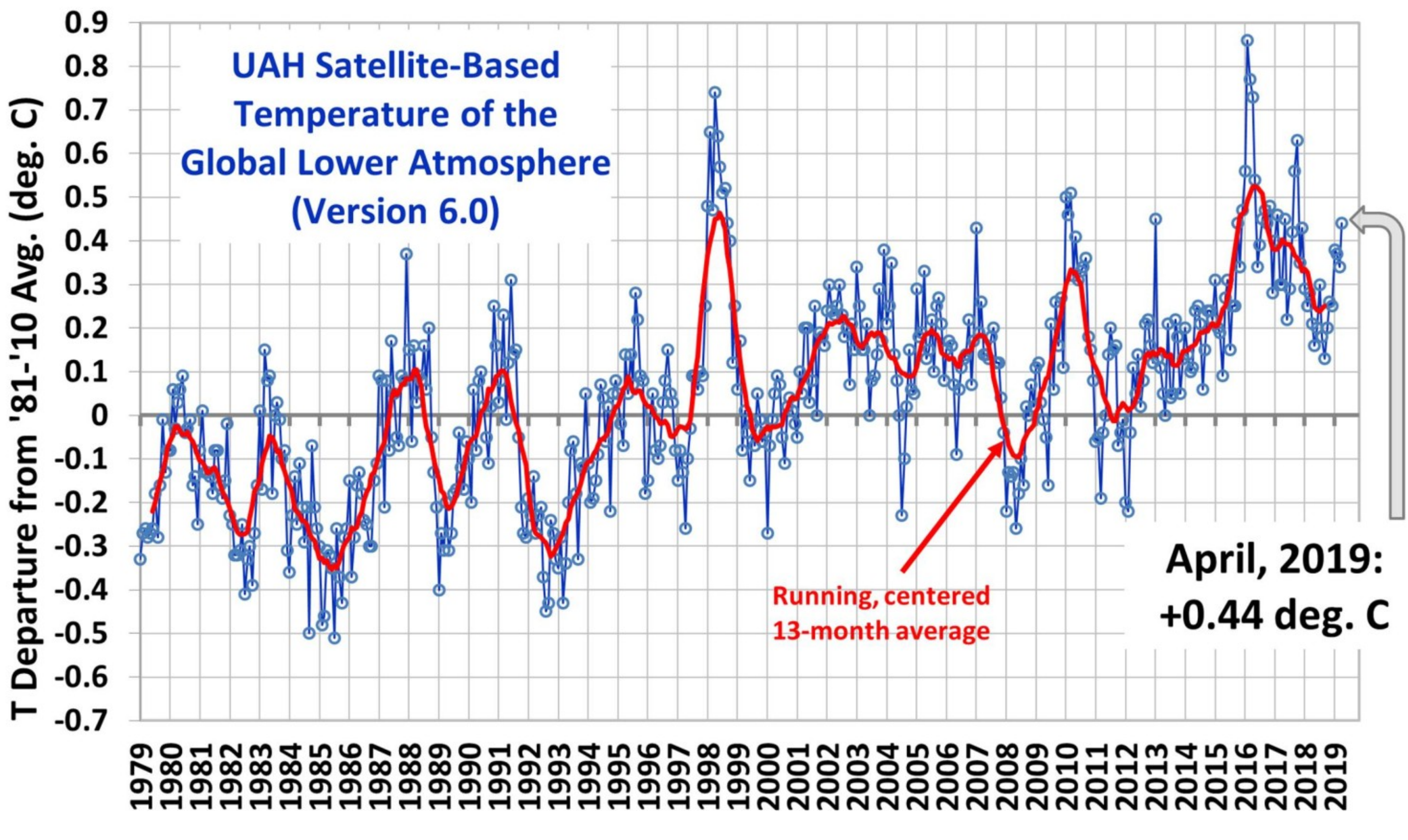
When the Swedish Svante Arrhenius (Nobel Prize in Chemistry 1903) theorized about the Atmospheric Greenhouse Effect in an article entitled "On the influence of carbonic acid in the air on ground temperature", published in 1896, it was still believed that electromagnetic waves propagated in a "solid ether".

It should be noted that Arrhenius saw only positive effects, as warm periods have always been prosperous periods, and CO_2 can only be beneficial to agriculture (whereas we see only negative effects, to the point of considering CO_2 as a "pollutant" : times are changing).

At the time, he estimated that a doubling of the CO_2 rate would cause a warming of about 5°C (slightly more than the 2-4.5°C forecasts made by the IPCC more than a hundred years later, in 2007, based on the same theory). But the water vapour and carbon dioxide absorption spectra used by Arrhenius were extremely erroneous, at thermal infrared wavelengths ; with the correct spectra known since the 1920s, Arrhenius calculations give +0.2°C (plus two tenths of a degree Celsius) for a doubling of carbon dioxide levels in the air.

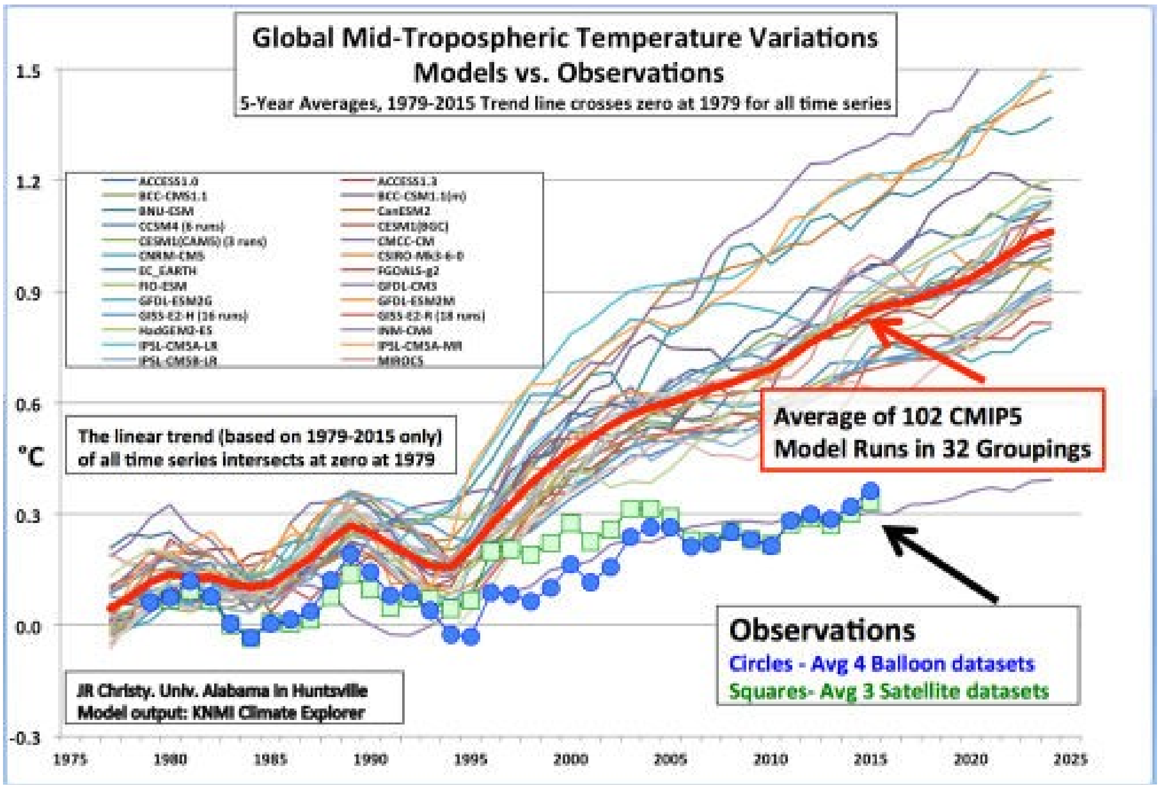
Paradoxically, a century later, we no longer believe in "solid ether", of course, but we have never questioned the foundations of this theory of atmospheric greenhouse effect, which is at the root of the current explanation of human-induced global warming.

Of course, no one can deny that the temperature has risen over the past 50 years (previously, in the 1970s, it was thought more like a cooling or even a new glaciation) :



Global average of monthly averages of temperatures measured in the lower troposphere between the surface and 2 km since 1978 by devices observing the infrared radiation of oxygen molecules, devices on board various satellites ; this average is expressed as a deviation, month by month, of the average temperature of the month compared to the average of the same month calculated over 1980-2010.
Source : http ://www.drroyspencer.com/

... However, not as fast as computer models of climate calculation predicted :



Source : http ://www.globalwarming.org/2016/02/05/satellites-and-global-warming-dr-christy-sets-the-record-straight/

When reality deviates significantly from the models, two attitudes are possible :

- consider that, since science is "settled", the gap is transitory (or even false), and that reality will catch up with models (in other words, give more faith to models than to reality) : this is the political-media and quasi-religious attitude of some countries such as France ;
- consider, as any scientist would do, that this gap requires at least an explanation, and therefore a possible questioning of the physics underlying these models, especially since the climate has shown in the past that it was subject to significant variations (Medieval Optimum around the year 1000, Little Ice Age 1300 to 1850).

In fact, no one knows exactly how climate modelling computer programs are made : some claim that they are extrapolations of weather modelling programs, but the latter, designed to predict local weather over a few days, are not qualified to incorporate annual variations in CO_2 concentration, considered the main actor in global warming, nor climate cycles, also multiannual, nor urban heat islands which are formed over several decades.

And so, it seemed important to us to rethink things : our goal is to explain how the Climate works (and not the weather), using common sense, and starting from the basic physical and chemical laws of Thermodynamics, which we learned in high school and which are based on theories validated by experience, and from which climatology cannot derogate.

Moreover, even if we devote a paragraph to it, we will deliberately avoid talking about "greenhouse effect", "feedback", "forcing", terms that are more akin to slogans, and that may suggest the existence of a particular climate theory that would allow us to ignore the fundamental physics of climate : if there is a "Greenhouse Effect", it necessarily relies on physical foundations, without the need to name it ; moreover, a conventional greenhouse operates essentially by blocking convection and evaporation, which goes against the functioning of the atmosphere : the analogy is very unwelcome.

Similarly, we will avoid talking about "greenhouse gases", to describe gases that have the property of absorbing all or part of the thermal Infra-red emitted by bodies at earth temperatures : these gases act very differently from each other, and classifying them in the same category makes no sense.

Finally, we will see that the laws of physics call into question a certain number of preconceived ideas, and even well anchored, ... which is not surprising : Climatology is at the origin a purely descriptive activity, which essentially concerns the Natural Sciences and Geography, and not Physics.

1.2. Approach

This book is intended for as wide an audience as possible : it requires basic knowledge of thermodynamics, but it is a popularization book that should interest those who are interested in the mechanisms, who will find explanations expressed in a language that we have wished simple and understandable.

It is nevertheless backed by more detailed technical appendixes where the informed and less hurried reader will find additions, making it possible to dig deeper into physical and mathematical demonstrations, and to address the "quantitative" aspects.

1.3. Outreach, Evolutions, and Comments

Unlike many "scientists", we do not consider Science to be settled : the subject is made complex by the number of scientific disciplines it encompasses, and by the very complexity of the Earth, its atmosphere, and its oceans ; and therefore :

1. This book is intended to be widely distributed and therefore free of charge : the authors wrote it out of simple scientific conviction, and do not expect any remuneration from it : and therefore it is free of rights (it is ultimately only a question of physics). Make it known and spread it as widely as possible around you : it will be our greatest reward.
2. We are open to criticism, as it enriches the scientific debate ; and its publication on the Internet (https ://laphysiqueduclimat.fr) is open to (albeit moderate) comments.
3. Depending on this, the book is likely to evolve : it will have a revision index that will identify and qualify these changes.
4. For this reason, it is only available in electronic format (pdf).

1.4. The Author

This book is the result of teamwork ; it was written by Jacques-Marie Moranne.

Jacques-Marie Moranne is an engineer from the Ecole Centrale de Lille (1969).

He has practiced most of engineering professions, from engineering (chemical engineering), to the creation and management of a computer company, including maintenance, organization and methods, CAD, associated databases, both in large companies (Air Liquide, Elf, Areva, Saint-Gobain) and small ones.

Jacques-Marie Moranne was initially, and until the Copenhagen COP, a climate-alarmist, but the contradictions, both factual and physical, awakened his critical mind, and gradually led him to doubt and then to dig into the underlying physics, with the help of undeniable specialists, like Camille Veyres, who provided the essential material for this book, and who is the author of the technical appendixes to which it is attached.

Jacques-Marie Moranne is a member of the Association des Climato-Réalistes.

Jacques-Marie Moranne does not claim to be a climatologist, but Climate Physics is, above all, applied thermodynamics ; and engineering training provides all the necessary foundations.

2. Introduction and Overview

2.1. Radiative Budget and Climate

The Earth, with its atmosphere, is in the interstellar space ; it can only exchange energy (or heat) with the cosmos, and therefore only by radiation, because there is no other possible mode of exchange in the space.

And to maintain its thermal balance, the Earth radiates towards space (on average over the year, because the earth's soils and oceans store heat during the day or in summer and release it at night and in winter) an energy necessarily equal to that it receives from the Sun, otherwise it would warm up without limit.

But what happens at the upper limits of the atmosphere interests us only in a very indirect way : for our part, climate is played out in the "troposphere" (on average between 0 and a dozen km above sea level, at more than 0.2 bar atmospheric pressure), and on the Earth's surface, where this radiation contributes to the thermodynamic functioning of the atmosphere and the oceans, before being returned to space.

The transformation of solar radiation into energy, thermodynamic exchanges within the atmosphere and with the oceans, and the re-transformation of this energy into radiation, form the basis of climatological science, which is therefore directly and exclusively governed by Physical Laws.

Indeed, even if radiation plays an important role (all bodies radiate), and can serve as a guiding principle in understanding the climate (to the point that we will devote an entire chapter to it), other physico-chemical laws are involved in the heat exchanges that impact temperature :

- mixing : convection (vertical circulation) and advection (inter-latitude circulation) of air,
- compression-expansion,
- change in physical state (evaporation-condensation, melting-freezing),
- chemical state change : exo- or endothermic reactions.

Each of these phenomena reflects a specific heat (or energy) <> temperature relationship : for example, evaporation takes place without any change in temperature, but consumes a very large amount of energy (latent heat).

The laws will be recalled in the chapters where they are relevant.

2.2. Simplifications

This book is intended to be accessible to as many people as possible. As a result, it allows itself a certain number of simplifications and approximations, without however freeing itself from the underlying physics :

On Earth :

1. We will neglect heat from the Earth's core (less than 0.07 to 0.08 W/m^2), natural radioactivity, and tide-related deformations, negligible compared to our purpose, stable and not subject to evolution for "anthropogenic" (i.e. man-made) reasons ;
2. The atmosphere will be limited to an altitude where the air is sufficiently rarefied so that the temperature is no longer correlated with molecular agitation, and where radiation passes through it and escapes freely, i.e. at the top of the stratosphere (around 50 km) ;
3. We will also consider that this System is in an established regime, in particular we will ignore any phenomenon

   . temporary, such as a volcanic eruption or an El Niño episode, that disrupts it,

   . or transient (transition from state A to state B) : in this case, the two successive states will be compared at equilibrium.

On the calculations :

1. The physical laws involved are generally not linear (for example, we will see that the temperature of a body isolated in space is proportional to the fourth root of the received radiation energy), and many calculations are too complex to have their place in this document ; we will therefore have to reason on averages, while being aware of the limits and dangers of such reasoning, but which still allow :

- to give orders of magnitude, which can be considered representative,
- to make comparisons,
- to measure the impact of a particular parameter ("anthropogenic" or not) on the climate from a global point of view, which is ultimately our goal.

2. The Earth is spherical, orbits around the sun in an elliptical orbit (of low eccentricity), and on itself around an inclined axis, and its surface constituents (oceans, deserts, forests,...) are themselves of a heterogeneous nature and distribution : this makes some calculations much too complex to be made in detail in this document;
3. Some physical phenomena are chaotic (everyone knows that it is impossible to predict the weather, i.e. the climate at a given place, beyond a few days) : we will say a word about them at the end of the book ;
4. We know that some phenomena are cyclical, with impacts that can be very significant in terms of temperatures : they will be ignored in the body of the book, but some will be cited as examples ;
5. Finally, many of the figures given here are not directly calculable or measurable in a precise way, and are therefore questionable (we can find different values on the Internet, on "serious" sites) : our purpose is not to focus on precise values, but on reasoning, orders of magnitude (say to the nearest 5%), and variations according to criteria.

3. Reminders on Electromagnetic Radiation

3.1. Physical Laws of Thermal Radiation

The temperatures noted T are expressed in K (degrees Kelvin), knowing that :

- 0 K is the absolute zero (nothing can be colder)
- the temperature in K is equal to the temperature in °C + 273.15 (thus, 288.15 K = 15°C ; 0 K = -273.15°C)

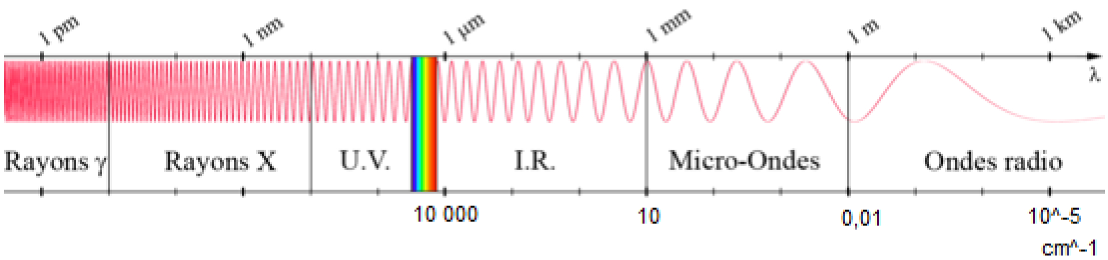
Let's start at the beginning : the Earth, at the edge of the atmosphere, receives all its energy from radiation (from the Sun), and returns it to the cosmos also entirely by radiation.

It is therefore logical to devote an entire chapter to this mode of heat (or energy) exchange, knowing that there are others whose benefits will be understood later on. This chapter does not claim to be exhaustive ; it is essentially a reminder of the basic principles and physical laws that concern our subject.

Radiation is an electromagnetic vibration characterized by :

- the amplitude of its waves (or the power they carry),
- their wavelength λ, often expressed in µm or nm, which extends from metric (radio) waves to gamma rays (10^{-7} to 10^{-9} µm), passing in order through microwaves, infra-red, visible (which occupies only a very narrow wavelength band : 0.4 to 0.7 µm), ultraviolet, and X-rays.

Ultraviolet rays, X-rays and gamma rays are ionizing rays : being more energetic, they have the ability to modify the structure of atoms and molecules (mutations in our DNA for our part, but also in smaller molecules such as ozone molecules : we will discuss this a little later).



(I.R. = infra-red ; U.V. = ultra-violet)

Note : in the wavelength domain that concerns us, instead of wavelength (a quantity more commonly used by opticians), electromagnetic radiation specialists think more in frequency, usually expressed in cm^{-1} (number of waves per cm) (ν_{cm-1} = 10 000 / $\lambda_{µm}$), but also in GHz (Giga-Hertz), or THz (Terahertz). The horizontal scale is then inverted.

Wave length	1 nm	100 nm	1 µm	1 mm	1 m	1 km
Frequency (Hz)	300 000 THz	3000 THz	300 THz	300 GHz	300 MHz	300 kHz
Frequency (cm^{-1})	10^7 cm^{-1}	10^5 cm^{-1}	10 000 cm^{-1}	10 cm^{-1}	0,01 cm^{-1}	10^{-5} cm^{-1}
hν (eV)	1241	12,4	1,24	0,0124	0,000124	

Reasoning in frequency is of interest in the energy domain of interest to us, the energy of a photon being proportional to its radiation frequency :

$$\mathbf{P=h\nu}\text{, with } \mathbf{h} = \text{Planck Constant} = 6{,}626\ 10^{-34} \text{ Joule / Hz, and } \nu \text{ in Hz}$$

If we made an analogy with sound, radio waves would correspond to infrasound, and ultraviolet waves to ultrasound, knowing that man perceives only a part of it (between 20 and 20,000 Hz for sound, about 400 to 790 THz for light : the colours of the rainbow).

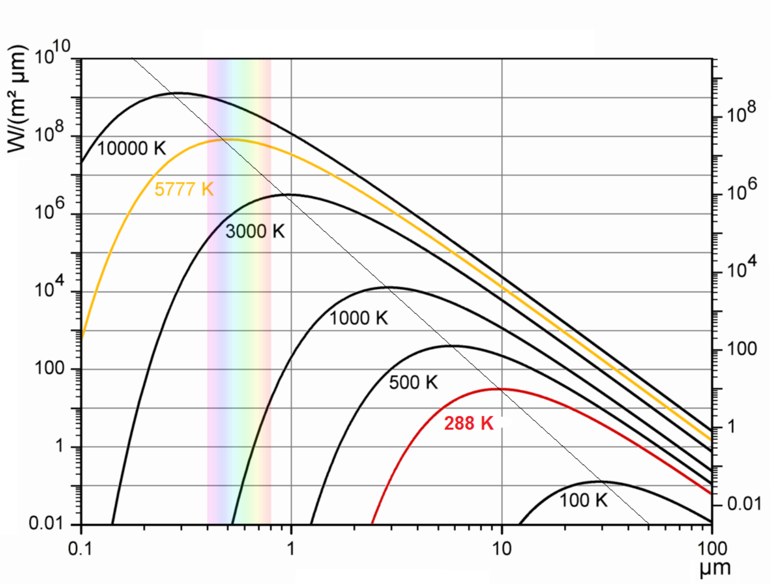
Monochromatic radiation has a single wavelength (or a single "color" if it is in the Visible). In sound, this would correspond to a pure sinusoidal note.

But in nature, all bodies radiate, depending on their temperature, according to a spectrum that covers a whole range of wavelengths. For example :

- iron heated to red, around 750°C, emits in the visible red, but also in the infrared (not visible to the human eye).
- iron heated to white, around 1250°C, emits in a whole range of waves between infrared and purple, and including the whole visible range (the white colour resulting from the mixing of the colours of the rainbow).

In vacuum (i.e. when the body can only exchange its heat by radiation), and for a perfect radiant body ("black" body), the frequency and intensity distribution of the Spectrum **depends only on its temperature** ; it is given by **Planck's Law**[1], which gives, for each wavelength (or frequency), the radiated power per m^2 of surface area and per unit of frequency or wavelength ; it is reflected by the curves below (where the two scales, horizontal and vertical, are logarithmic).

Temperatures are expressed in K (degrees Kelvin) :



Source : https ://en.wikipedia.org/wiki/Planck%27s_law

Again, if the analogy were made with sounds, it would correspond to a noise-emitting body (a mixture of sounds), all the louder and higher, the more powerful the emitting body would be.

The spectra are one under the other and shifted to longer wavelengths according to their temperature (decreasing). **Wien's law** defines the curve of the maxima of these spectra (linear in the figure above in logarithmic scales).

In addition, **Stefan Boltzmann's Law** defines the radiative flux (i.e. the total energy output per m^2 of surface area of the hot source), for an ideal "black body", as being proportional to its absolute skin temperature to the 4^{th} :

$$\boxed{M = \sigma T^4}$$

- M is expressed in Watts/m^2 of surface
- T in Kelvin (K) (add 273 to the temperature in °C),
- σ (sigma) is Stefan Boltzmann Constant = $5{,}67 \times 10^{-8}$. (easy to memorise : continued from figures 5,6,7,8)

In the graph, we will note in particular :

- the sun's spectrum (5777 K : surface temperature of the Sun), the maximum of which is in the visible range (nature is well done !) (we speak of surface temperature, knowing that the temperatures inside the Sun are much higher) ;
- the 288 K curve, corresponding to a body at 15°C, i.e. the average radiation of the earth's surface at 15°C : it should be noted that this spectrum is entirely included under the Sun's spectrum, but very shifted on the infrared side (the logarithmic scale of the graph overwrites this shift, but it is from 1 to 162 000 in intensity :

---

[1] Planck's law for a surface radiating towards a half-space is written: $(0.04632\, f^3) / (e^{(48\, f\, /\, T)} - 1)$
where f is the frequency in THz and T is the temperature in Kelvin; example: at f = 20 THz and T = 288 K the radiation emitted by the "blackbody" surface over a band of 1 THz is 13.7 W/m²/THz.

$5777^4/288^4$) : we will speak of "thermal" or "distant" infra-red, invisible to the naked eye, as opposed to "solar" infra-red, which is generally very close to the visible.

The spectrum emitted by each star thus makes it possible to know its surface temperature (e. g. 3000 °C for Betelgeuse, 11 000 °C for Sirius).

Compared to Planck's Law, Stefan Boltzmann's Law expresses the area under the Planck curve (integral over frequency or wavelength).

This law is fundamental for our subject, since it translates into temperature the energy received (or emitted) by radiation. It is remarkable because it works both ways :

- a "black body" surface (in vacuum) that receives and absorbs energy M stabilizes at temperature T (so it does not heat up indefinitely).
- a "black body" surface (in vacuum) at temperature T emits (radiates) an energy equal to M.
- T is an equilibrium temperature.

All bodies (solid, liquid, or gaseous) radiate at their own temperature.

Also note : it takes more than 5 W/m2 to raise the temperature of a body from 15 to 16°C

3.2. Emissivity, Absorptivity

In reality, no body is a perfect "black body", and the frequency and intensity distribution of the Spectrum follows a disturbed curve : see below the example of the different land surfaces (Source : Daniel Feldman PNAS 2014).

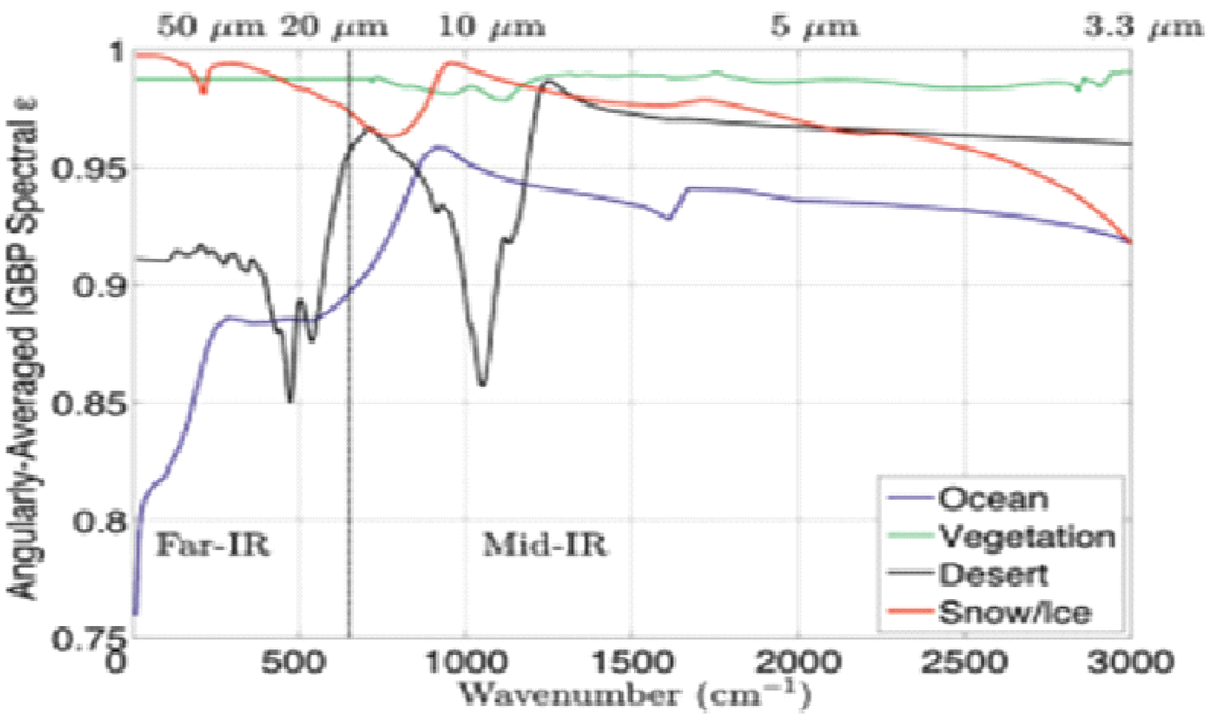


Fig. 3. Angularly averaged, spectrally resolved far-IR surface emissivity for four IGBP land types (ocean, vegetation, desert, and snow) based on 3D radiative transfer calculations and published indices of refraction.

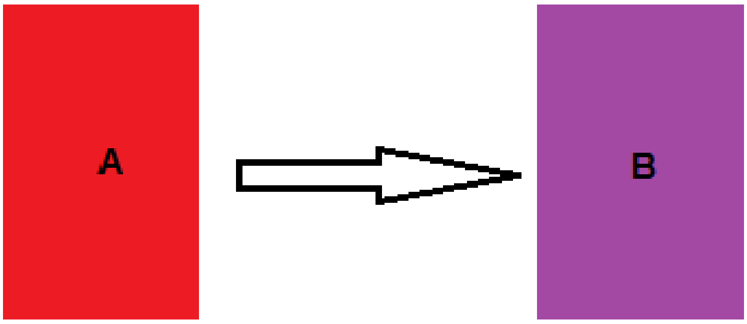
Our purpose is not to give a specific course on radiation, so we will not go into detail here.

But, to simplify, the radiative flux is corrected by a factor **ε** (epsilon) (**emissivity**) (between 0 and 1), depending both on the nature of the surface of the transmitter, and on the wavelength (we speak of **absorptivity** in the other direction for a receiving body, knowing that, for the same body, Emissivity = Absorptivity : Kirchhoff's Law).

$\boxed{M = \varepsilon\, \sigma\, T^4}$ (assuming ε constant across the entire spectrum)

Only the "black bodies" have an emissivity equal to 1 ; we will assume that the Earth has an emissivity of about 0.9.

3.3. Exchanges of Energy (Heat) by Radiation in Vacuum



When 2 bodies are at different temperatures, the hottest (here A) radiates to the coldest (here B) ; but, of course, B also radiates, depending on its own temperature.

If A is hotter than B, the heat transfer from A to B is equal to the difference :

$$M_A - M_B = \varepsilon^2\, \sigma\, (T_A^4 - T_B^4)$$ (assuming the same emissivity for both bodies)[2]

In fact, everything happens as if A radiates, not according to its own surface temperature, but according to its difference in T^4 (temperature to the 4th) with the medium receiving its radiation : 0 K if it is the cosmos (2.7 K strictly speaking).

The radiative heat transfer is, as between two bank accounts, the net balance of an exchange : what B actually receives from A minus what A actually receives from B.

If A and B are at the same temperature, there is no heat (and therefore no energy) transfer between the two by radiative means. This is the case, for example, between the ground surface and the very low atmosphere in contact with it, which are (statistically) (almost) at the same temperature.

When B is exposed to the radiation of A, if A is warmer than B, B absorbs its radiation and heats up, but because of its own radiation related to its temperature, B will reach an equilibrium temperature itself, and then radiate in a spectrum that is below that of A, and shifted to lower frequencies (or longer wavelengths) than that of A (according to the Planck and Wien laws exposed above).

This is what happens to the Sun and the Earth : typically, radiation from the Sun warms the Earth (which is at a lower temperature) by radiation.

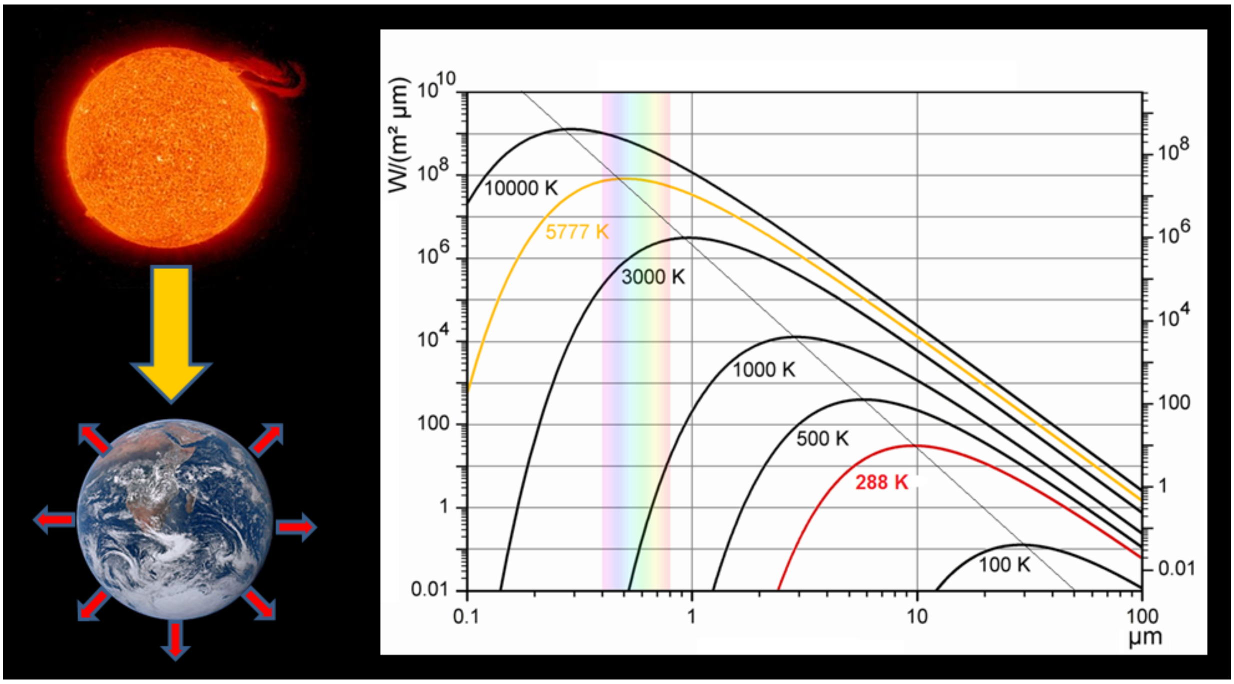
But it is also necessary for the Earth to evacuate the energy it receives (otherwise it would heat up to the temperature of the Sun) : since it is in vacuum, it can also only do so by radiation towards the cosmos (at 2.7 K), also following the same laws according to its own temperature.

---

[2] More rigorously, if A has an absorptivity ε_A et B an absorptivity ε_B, the total power radiated by the surface A to the surface B is $\varepsilon_A\, \sigma T_A^4$ et B absorbs ε_B of it, thus $\boldsymbol{\varepsilon_B}\, \varepsilon_A\, \sigma T_A^4$ reemits the rest oof it : $(1-\varepsilon_B)\, \varepsilon_A$ to A, which reemits $(1-\varepsilon_B)\, \varepsilon_A\, (1-\varepsilon_A)$, the ε_B fraction will be absorbed, and the rest reemitted … the net transfer by surface unit will finally be :

$$\varepsilon_{réduit}\, 5{,}67\, ((T_A/100)^4 - (T_B/100)^4) \text{ with } 1/\varepsilon_{réduit} = 1/\varepsilon_A + 1/\varepsilon_B - 1 .$$

Numerical application : $\varepsilon_A = 0{,}9 = \varepsilon_B$, $T_A = 290$ K, $T_B = 287$ K, $\varepsilon_{réduit} = 1/(2/0{,}9 - 1) = 0{,}818$ and $0{,}818 \times 5{,}67 \times (2{,}9^4 - 2{,}87^4) = 13{,}4$ W/m²



Thus, because of its lower temperature than that of the Sun, its reemission spectrum is below that of the Sun, and is shifted towards "thermal" infra-red (red curve corresponding to 288 K or 15 °C in the graph), compared to the one it receives from the Sun.

In fact, things are a little more complicated : as we will see later, because of the other physical laws involved, and the opacity of certain atmospheric gases, the radiation from the Earth to the cosmos is released at different altitudes, whose temperatures (and therefore emission curves) are generally even lower and more offset.

3.4. Radiation Heat Exchanges in a Medium

In vacuum, where Radiation is the only possible mode of heat exchange, things are simple, but as soon as it encounters an obstacle or enters an environment, the radiation is altered.

3.4.1. Transparency, Absorption, Opacity

A medium is said to be **transparent** when radiation passes through it in a totally free manner (without modification of its wavelength or intensity), as in vacuum.

On the other hand, a so-called "black" body **absorbs** all the radiation it receives. Absorption results in an **opacity** of the medium.

But in nature, no medium is perfectly transparent or completely opaque.

In particular, the same medium can be transparent at some wavelengths, and opaque at others :

- this is the case, for example, of conventional glass, transparent in the visible range, but opaque in the thermal infrared (IR) range ;
- it is also, as we will see below, the case of CO_2 (carbon dioxide), which has an absorption band between 17.5 and 23 THz (584 to 767 cm^{-1}), where it is opaque, and water vapour, which is opaque in almost all thermal infrared (radiation emitted by the Earth) ;
- similarly, the human body is opaque in the visible and infrared, but transparent to X-rays (radiology).

Note : This is a real problem, because a body that receives radiation in a transparent domain may not be able to re-emit it because its re-emission spectrum, colder than the source, would be in an opaque domain ; it would then be necessary for it :

- either to warm up to raise its emission spectrum in a transparent domain,
- or to find a strategy for re-emission by other means than radiation.

We will see later, for example, that this is the case for the oceans and how they are coping.

The frequency bands to which some bodies are opaque are their **absorption band(s)**.

In reality, no medium is totally opaque, even in its absorption bands, and any medium becomes opaque beyond a certain thickness (or density) : we will speak a little further on of "optical thickness" to measure opacity.

Liquid water, for example, absorbs all solar infrared in a few millimeters, and all thermal infrared in a few tens of microns (while nearby UV rays penetrate into the water to a depth of several tens of meters) ;

When a medium is opaque, it blocks and **absorbs** the radiation it receives and heats up, until it reaches an equilibrium, depending on the temperature of the emitting body, and its absorptivity, in accordance with Planck's Law.

Similarly, in accordance with the same law, it **emits** radiation according to its own temperature and emissivity. But it can only transfer heat to a body colder than itself, and proportionally to the difference in T^4 (absolute temperature to the 4th).

3.4.2. Reflection

A perfect **reflecting** body (mirror) fully restores the radiation it receives, without changing its intensity or wavelength spectrum. A mirror is a (almost) perfect reflective body, but in nature, none is a perfect reflector.

3.4.3. Scattering, Backscattering

When the medium contains aerosols, droplets, or ice crystals, they **scatter** or even **backscatter** the radiation they receive in certain directions, over part of the spectrum, the incident flux and only a fraction of the continuous light radiation in the initial orientation. The scattering of the blue-violet spectrum of the solar flux explains the blue sky.

While the thermal infrared flux emitted by the Earth is diffuse, due to its origin, the solar flux received at the surface is partly diffuse and partly directed in the direction of the sun. Clouds promote diffuse radiation and often even suppress direct radiation.

3.5. Radiation in Gases (and Air)

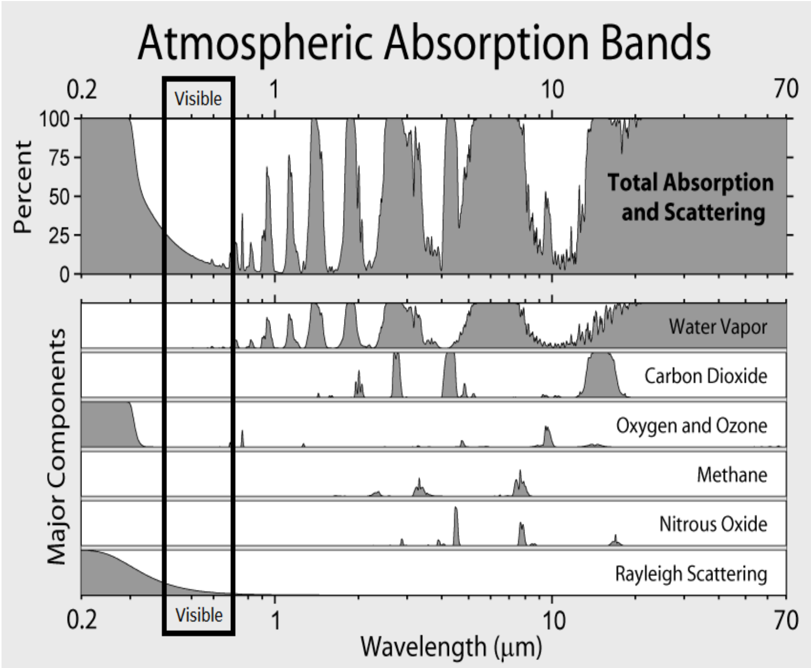
All gases are transparent to the human eye under normal conditions of temperature and pressure, although some, such as chlorine, are coloured.

But all gases have, outside the visible range, an absorption spectrum, i.e. they absorb radiation in certain wavelength lines or bands : they are opaque there, and also make the atmosphere that contains them opaque (more or less depending on their concentration).

This is very counter-intuitive, because our visible domain is not in these wavelengths, and we do not imagine living in an opaque atmosphere : fortunately, here again, nature is well made.

But this is the case for gases with different atoms, and in particular, carbon dioxide (CO_2) and water vapour (H_2O), triatomic molecules with an electric dipole moment, which absorb radiation at the natural frequencies of vibrations and vibrations-rotations of their molecules :

- for CO_2, around 2.7, 4.3, and 15 µm
- for water vapour (we are talking here about water in a gaseous state, and not clouds), over wide bands distributed between 0.7 and above 70 µm.



But, according to Stefan Boltzmann's law (**$M = \varepsilon\ \sigma\ T^4$**), they also radiate, and only, in these same bands, at their temperature : outside these bands, they are transparent.

The behaviour of this radiation poses a problem of understanding, which is often the cause of poor explanations of what is called the "Greenhouse Effect", and which we will clarify :

Inside the gas (atmosphere), beyond a certain concentration of "opaque" gases (CO_2 and water vapour), there is no heat transfer (or heat exchange) by radiation, because :

- in the transparent domain, a gas neither emits nor absorbs radiation, by definition,
- in the absorption bands, it is quickly opaque, and also, by definition, there is no heat transfer by radiation through an opaque body.

The question therefore arises only at the "surface" of the gas, i.e. at an interface between the gas and the outside world, and at the wavelengths corresponding to its absorption bands.

As far as the Earth is concerned, the atmosphere has only 2 interfaces :

- the **ground surface**, where the radiation emitted by the surface is gradually absorbed, in their IR absorption bands, by the opaque gases of the atmosphere (CO_2 and water vapour), over a few tens or hundreds of meters (depending on the frequencies), and therefore at the same temperature : **the heat exchange is negligible**, because the temperature difference is practically zero (statistically) :
- the **top of the atmosphere**, at a level where it becomes, due to its increasing scarcity at altitude, less and less opaque, and therefore allows radiation to escape, at the wavelengths of its absorption bands :
  - . on the way down, in the case of solar radiation, until it is blocked (by heating the atmosphere) (between 1 and 4 µm),
  - . on ascent (thermal infrared), by releasing it towards the cosmos from the altitude where the concentration of these "opaque" gases becomes insufficient to retain their radiation, with a power corresponding to <u>the temperature at this altitude</u> (= the temperature difference with the cosmos towards which it radiates).

3.6. Opacity Measurement : Optical Thickness

This notion is fundamental to a good understanding of how the climate works (or at least its "radiation" part), because it makes it possible to give a <u>numerical value</u> to what some people (wrongly) call the atmospheric "Greenhouse Effect".

In physics, transparency (or its inverse opacity) is measured by the **Optical Thickness** t, a dimensionless number that characterizes, when crossing a medium, the ratio between the light intensity (or radiative flux) recovered **M** at the output and the received intensity **M_0** (at a given frequency) :

$$\boxed{t = - Ln(M/M_0)}$$ (Ln = natural logarithm)

ou conversely, $M/M_0 = e^{-t}$

For diffuse radiation (leaving in all directions as in gases), the ratio is : 2 E3(t), where E3(t) is a special function called exponential-integral function of index three. 2 E3(t) is approached by :

$$\boxed{M/M_0 = e^{-t} / (1 + 0,65\ t)}$$

The absorption 1-2 E3(t) is 50%, 80%, 96% and 98.2%, respectively for t= 0.42, 1.07, 2 and 3 (or, more simply, **an optical thickness of 1.07 absorbs 80% of the radiation, a thickness of 2 absorbs 94%** : the greater the optical thickness, the more opaque the gas is.

A simple way to imagine the optical thickness is the paper sheet : a thickness of one sheet corresponds to an optical thickness of 1, 2 sheets to 2, 3 sheets to 3,... and so on.

The optical thickness t is zero at wavelengths where the gas is transparent ; it has meaning only in the gas absorption bands ; it then depends, for a given concentration of this gas and a distance traversed, on the frequency of the radiation.

In the rest of the document, we will identify, for each radiation frequency, the altitude at which the optical thickness is equal to 1, considering that it is at this altitude that the "surface" of opaque gases at the top of the atmosphere is located, i.e. the level at which they become sufficiently rare to gradually let their own radiation pass towards the cosmos (this is the radiative interface between the atmosphere and the cosmos).

The optical thickness of the air at a given frequency is the sum of the optical thicknesses, at the same frequency, of all the gases it contains : the air is perfectly transparent only between the absorption bands of the different gases it contains.

3.7. Corpuscular Approach

All the notions we have explained above are explained in a corpuscular approach (radiation considered as a set of photons instead of being considered as a vibration) :

Any molecule that absorbs radiation at a certain frequency radiates at that frequency but at its own temperature, which, for an atmospheric gas, is that of the air.

We therefore have shocks of H_2O or CO_2 or other with molecules (N_2, O_2, Ar) more or less fast and shocks more or less effective to excite vibrations or rotations of the structure of the molecule.

Near the ground : high pressure, high temperature, high "average" speeds : billions of collisions per second : after a collision that excites a vibration mode, the probability of emitting a photon before the next collision that will remove its vibration-rotation energy is very low : molecules that absorb a photon emitted from the surface or emitted by a molecule from the air above or below are almost immediately de-energized by a collision that transfers the vibration-rotation energy to the majority molecules N_2, O_2, Ar in the form of kinetic energy (molecular agitation = temperature).

At the top of the atmosphere, fewer exciting collisions due to lower concentration and temperature, so the excited molecule has "on average" more time to de-excite itself by radiating.

Molecules emit in all directions, but not because they have absorbed a photon from the surface : **they radiate at their own temperature** (that of the gas in which they are located).

4. The Earth's Atmosphere

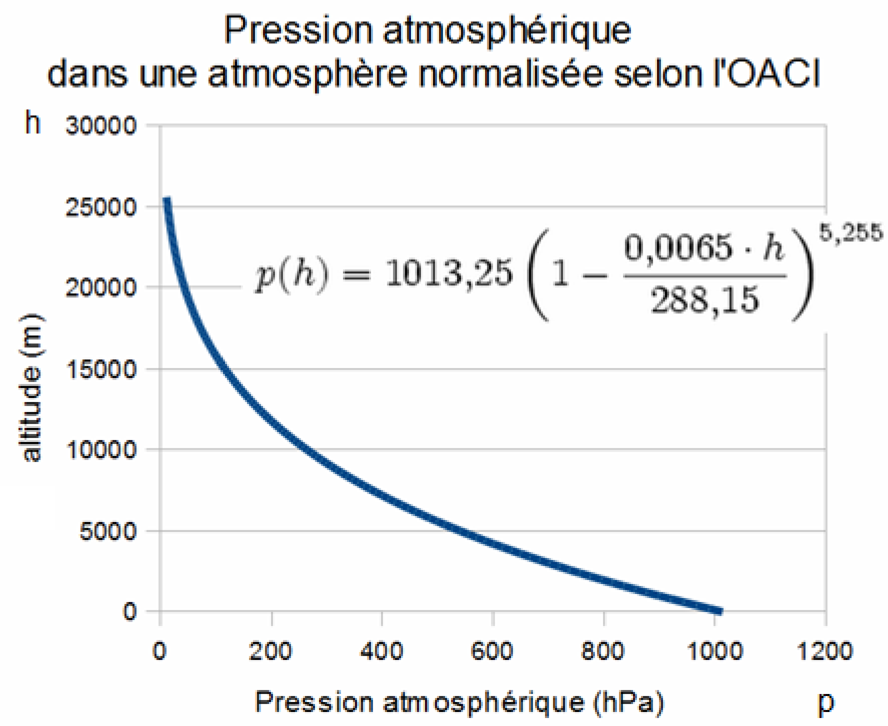
4.1. Overview

The atmosphere is traversed both by solar radiation reaching the Earth and, in the other direction, by "thermal" radiation emitted by the Earth to the cosmos. And so, before analysing the path of this radiation in the atmosphere, it is good to take a closer look at its constitution and structure.

4.2. Atmospheric Pressure and Relationship with Altitude

Each m^2 of the Earth's surface is overhung by 10 tons of air (1 kg/cm^2) ; but the atmosphere is compressible, under the effect of its own weight, which explains why its pressure decreases as a function of altitude.

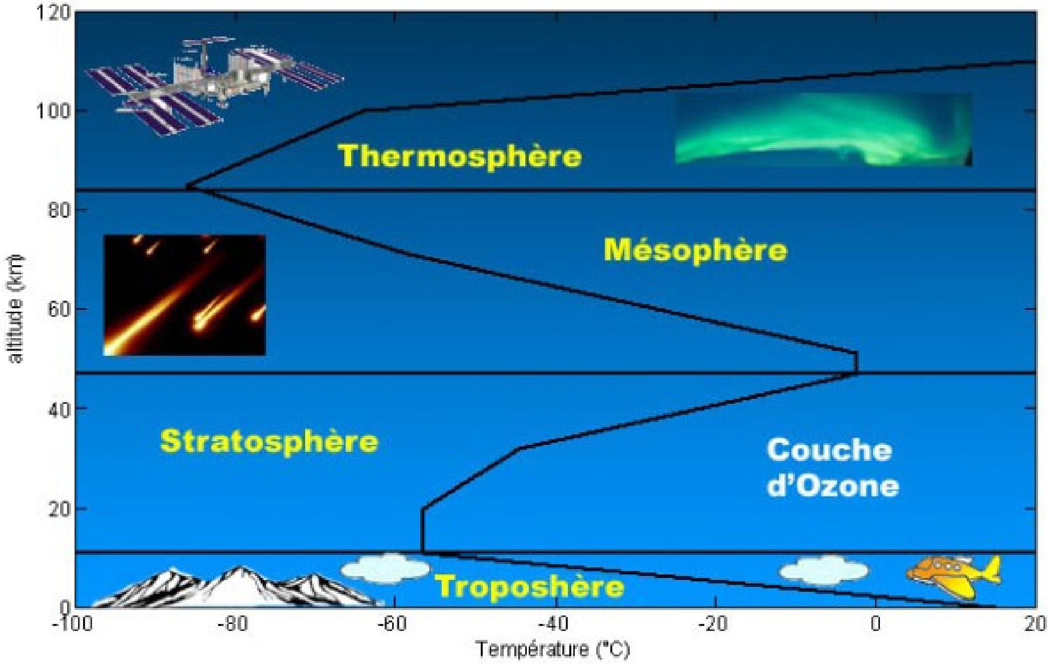
(In some graphs in the following, the altitude will often be expressed in pressure, because many properties depend more on the pressure than on the altitude itself : the existence of this relationship must be kept in mind).



4.3. Layered structure

The atmosphere is composed of several layers : from the ground up :

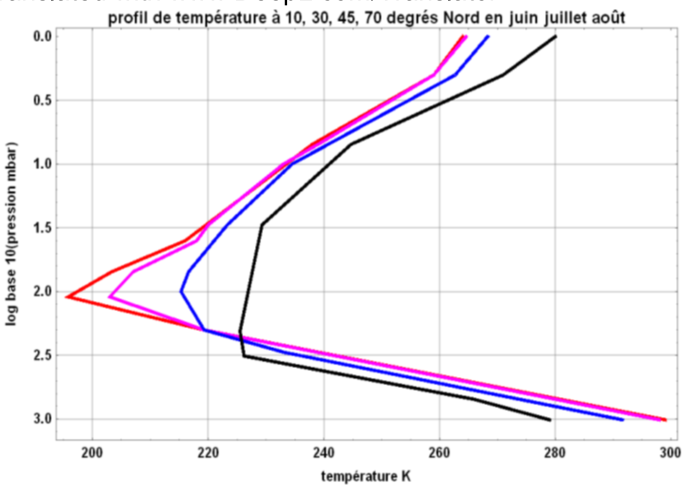
- the **troposphere** (up to about 12 km altitude or 200 mb pressure) : this is the atmosphere in which we live : it is characterized by a negative average temperature gradient : the higher we rise at altitude, the lower the temperature, up to about -50 to -60°C (210 to 220 K), which maintains a strong convection, the importance of which we will see below ;
- the **stratosphere**, where the temperature, on the contrary, rises to -3°C, around 40 km above sea level, the seat of the ozone layer, and which is therefore in **temperature inversion, which prevents any convection** : this part of the atmosphere is therefore "stratified", hence its name ;
- the **mesosphere**, up to about 80 km, where the air resumes cooling to around -80 to -100 °C
- then finally the **thermosphere**, where the air is so rarefied and ionized that it does not participate in the climate : these last 2 layers can therefore be neglected.

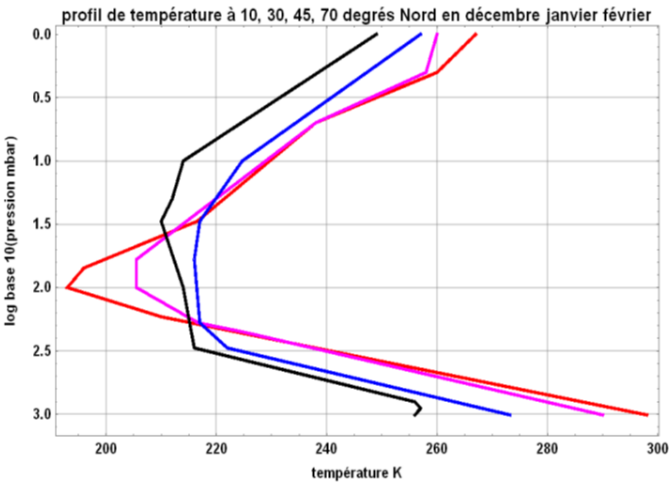


The boundary between the troposphere and the stratosphere is called the **tropopause** : it is, by definition, at the altitude at which the temperature gradient of the troposphere reverses or undergoes a very strong discontinuity, or in other words, at the altitude at which convection is interrupted.

One of the difficulties lies in the fact that this altitude is not fixed : the tropopause leans between the intertropical zone where it is well fixed, high (16 km) and cold (-90 °C) (equatorial chimney : red curves below), and the sub-polar zone where it is more fuzzy, low (8 km) and warm (relatively : -50 °C) (black curves below), as shown by the graphs below, taken from balloon soundings :

Translated with www.DeepL.com/Translator





The y-axis is expressed in logarithm of the pressure in mb :
3 corresponds to 1000 mb (or 1 atm), i.e. the ground level
2 corresponds to 100 mb (or 0.1 atm), i.e. an altitude of about 16 km

The causes of this temperature profile in the troposphere and this minimum temperature at Tropopause level will be discussed below.

4.4. Atmospheric and ocean currents

On the one hand, the oceans :

- have considerable thermal inertia,
- are the site of currents that carry large quantities of heat (e. g. Gulf Stream),

- are an almost infinite source and potential reserve of both dissolved CO_2 and water vapour (of course !), the importance of which for the climate will be discussed below,
- but, above all, evaporate thus evacuate considerable quantities of latent heat, due to a change of state (vaporization).

The atmosphere is also the site of very important movements (convection and advection) that ensure the transport and mixing of very large quantities of heat :

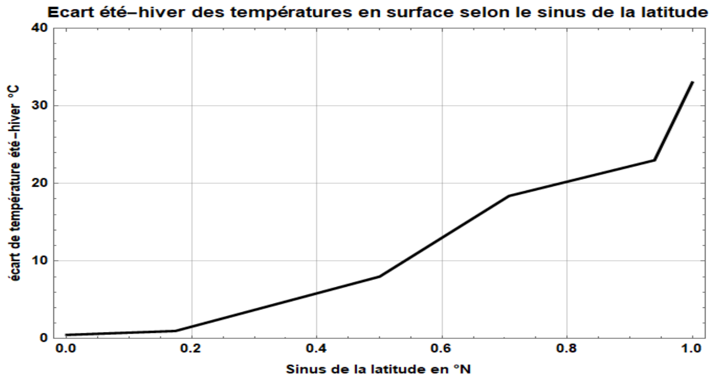
- Sensible heat (heat capacity) (1005 J/kg/K for air),
- and especially latent heat of vaporization-condensation in the form of water vapour, transported by convection between the ground surface and the clouds where it condenses : we will see its importance (2500 kJ/kg/K).

All these energy transports level and average the temperatures at the Earth's surface, which have nothing to do with the temperatures on the surface of the Moon, our neighbour, for example, where temperature differences, over time and geography, can reach 300°C.

On Earth, average atmospheric temperatures in the inter-tropical zone vary very little between the summer and winter months while they vary from 35°C (and sometimes 50°C in Siberia) near the Arctic Circle ; 35°C and more also between day and night in hot desert areas.

The following figure shows the summer-winter difference as a function of the sinus of latitude ; this is to reflect the surface of the globe between the different parallels : sinus (30°) = 0.5 limits half of the surface of the globe, the tropical zone itself going up to 23°27' with sin (23°27') = 0.398 and therefore 40% of the surface of the globe between the Tropics of Cancer and Capricorn.

The latitude sinus gives an idea of the surface of the globe concerned : 40% of the globe has less than 6°C difference between summer and winter, a few percent have 30°C and more.



Note : The fact that in tropical areas the difference between the summer and winter averages is small does not prevent the difference in temperatures between the maximum daytime afternoon and late night temperatures in desert continental areas near these latitudes from reaching 30°C or more. As a reminder, Paris is located at 48.2° latitude.

4.5. Composition

Each m^2 of soil is overhung by 10 tons of air (1 bar = 1 kg/cm^2), mainly almost perfectly transparent gases :

- 7.55 tons of nitrogen,
- 2.32 tons of oxygen
- 0.13 tons of Argon

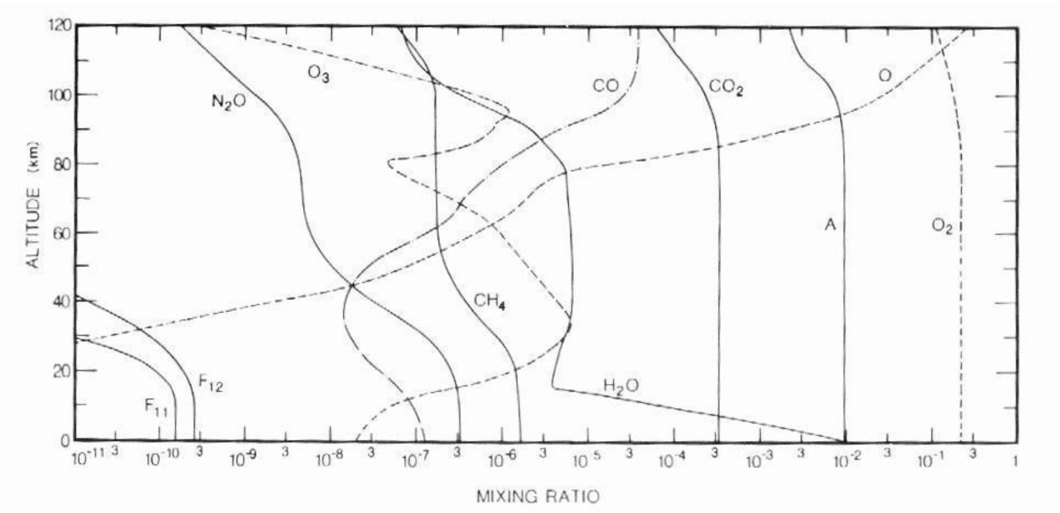
... but also other minority gases (trace gases), the proportion of which may vary according to different factors, including, in particular, altitude, and which, due to their triatomic composition, have absorption bands that will opacify the atmosphere in certain frequency bands :

- 5 to 80 kg/m2 of water vapour (average 25 kg/m2), present, but **in decreasing proportion** from the surface to the tropopause, which has many absorption bands in the solar spectrum, and which is almost opaque in the thermal infrared (above 4.5 µm wavelength (or less than 66 THz)),
- 6.3 kg/m2 of carbon dioxide (CO_2) (400 ppm by volume), in **almost uniform proportion throughout the atmosphere**, which has some absorption bands in the solar spectrum, and a significant one in the thermal infrared, the impact of which will be seen,

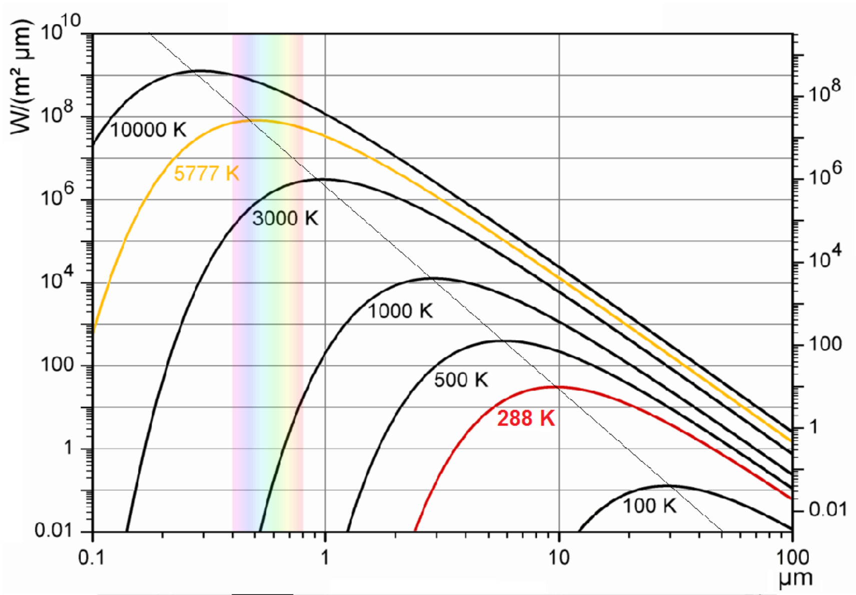
- 6 g of ozone, **mainly in the upper stratosphere** (see below), opaque to ultraviolet light,
- traces of other gases (CH_4, N_2O,...).

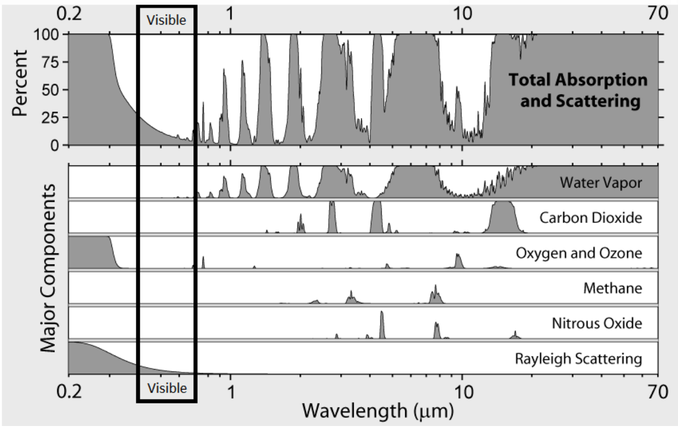
The figure below shows the distribution of the different gases according to altitude (the altitude of interest to us is limited to about 50 km : top of the stratosphere) ; we see in particular, according to altitude :

- a perfect constancy of the CO_2 concentration (the figure, quite old, shows a little more than 300 ppm, whereas it is now above 400 ppm),
- a very strong decrease in water vapour concentration (from 1.6% on the ground to 3 ppm at tropopause (where the H_2O curve reverses)),
- an increasing concentration of ozone up to a maximum at the top of the **stratosphere** (around 40 km).



4.6. Radiation behaviour inside the atmosphere





The figure above shows in superposition :

- Radiation curves :
    . yellow for sunlight (at 5777 K)
    . red for terrestrial radiation at ground level (average at 15°C or 288 K)
- The absorption bands of the different gases (traces) contained in the atmosphere, according to wavelength.

With their double logarithmic scale, the curves can mislead on the orders of magnitude, but we do not speak of the same thing between "solar" infra-red (those of the curve 5777 K) and terrestrial infra-red, or "thermal" or "distant" emitted by the Earth at 288 K (15°C at the soil surface on average) :

- the former play a relatively large part in relation to the radiation received from the sun,
- the latter are negligible in (and compared to) solar radiation, but predominant in the radiation re-emitted by the Earth.

It can be seen that part of the solar and/or terrestrial radiation is absorbed by absorption bands :

- ozone and oxygen (mainly stratospheric) in UVs,
- water vapour contained in the atmosphere (mainly : absorption bands between 1 and 4 µm),
- CO_2 (absorption bands at 2.7 and 4.3 µm),
- and other trace gases : Methane (CH_4), Nitrous oxide (N_2O),...

These absorptions of the solar flux contribute, of course, to warming the atmosphere at the altitude at which they occur, both for downward (solar) and upward (thermal) radiation.

4.7. Clouds

Clouds, made up of fine spherical water droplets in a humid atmosphere, combine all the behaviours, of which they provide a good example :

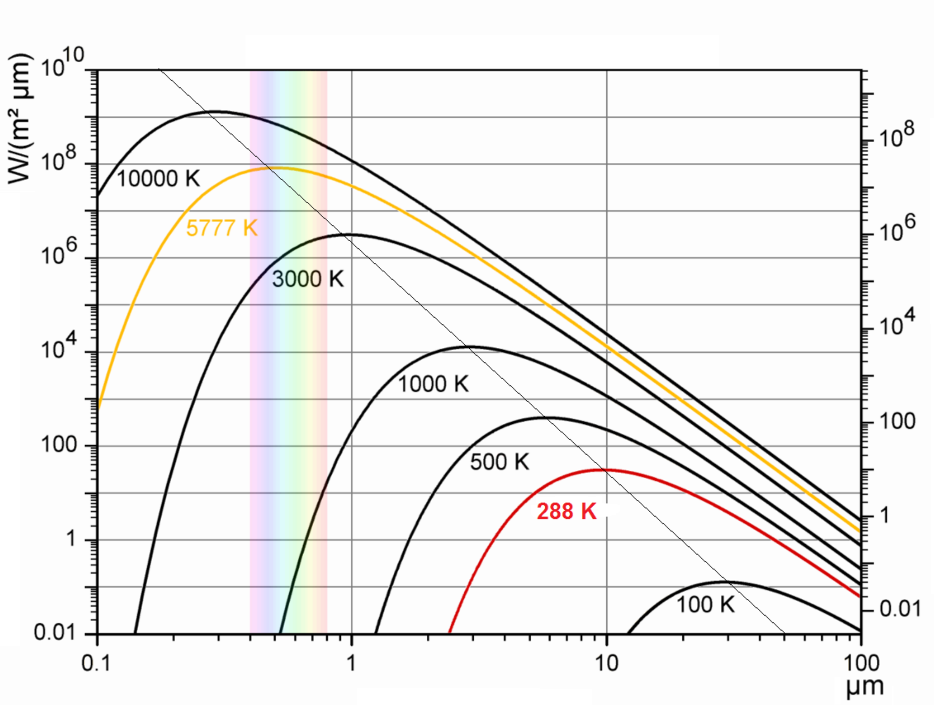
- they are partially **transparent** : we perceive sunlight through them ;
- made of liquid water, they **absorb** a very large part of the infrared solar radiation, which helps to warm the atmosphere around them, but deprives the surface of the ground of this heat ;
- bathed in saturated water vapour, they **absorb** most of the radiation from the thermal infrared (emitted by the Earth's surface) ;
- they **backscatter** another part of the rays from the sun into space, thus contributing to the Albedo, whose importance on Earth will be seen a little further on.

5. Radiation monitoring from the Sun

Let us now turn to the heart of the matter.

5.1. Starting point : the radiation from the Sun

The thermal energy received by the Earth and its atmosphere comes **entirely from the Sun**, without any damping or wavelength modification : we are in a vacuum, and **there is no other significant heat source** : the other stars are too far away, and geothermal energy is a negligible source.



The sun is shining at 5,777 K (yellow curve above).

In accordance with Stefan Boltzmann's Law ($M = \sigma T^4$), the energy emitted by the surface of the Sun (at a temperature of 5777 K) is equal to :

$$\mathbf{M_{sun} = 5{,}67 \times 10^{-8} \times 5777^4 = 6{,}32\ \ 10^7\ W/m^2}$$

The Sun has a radius R_0 of 695,600 km and is located at an average distance R = 150,000,000,000 km from the Earth.

$\mathbf{M_{earth} = M_{sun}\,(R/R_0)^2 = 1\,360}$ **W per m²** of surface perpendicular to the direction of the Sun.

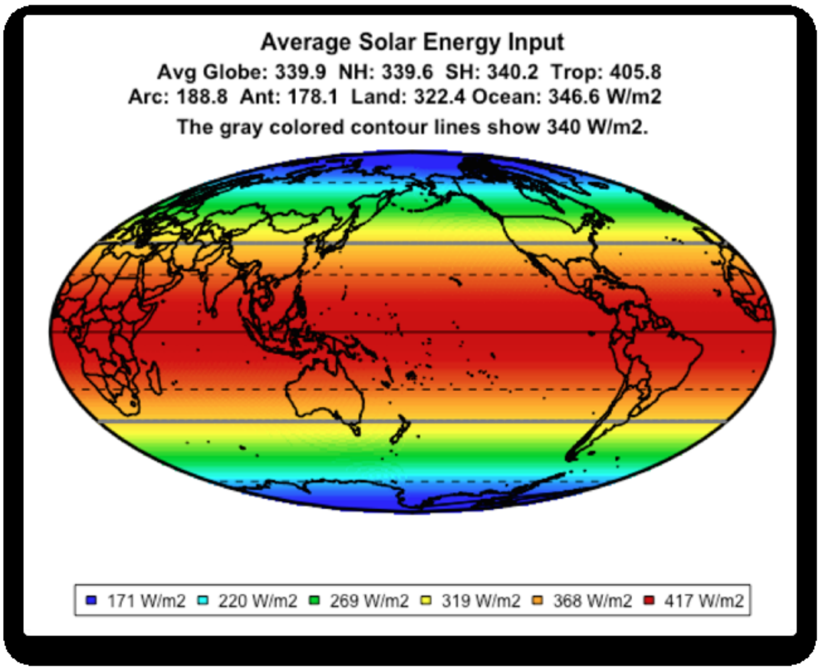
In fact, this is an average value between aphelion (in July : 1321 W/m²) and perihelion (in January : 1417 W/m²) of the Earth, whose orbit has a (current) eccentricity of 0.0167.

The surface of the Earth (sphere) is equal to 4 times the surface of the disc it presents to the sun (4πR2 instead of πR2), so :

$\mathbf{M_{terre} = 1\,360 / 4 = 340}$ **W per m²** of real earth surface (sphere)

This is, of course, again an average value, commonly accepted, but :

- whose local values range from 0 (dark side of the Earth) to 1,360 (sun at its zenith),
- whose frequency distribution is approximately :
  - 10% ultraviolet (UV)
  - 43% visible (0.4 to 0.7 µm)
  - 47% in "near" or "solar" infrared (IR)
  - negligible in "distant" infrared (IR)
- whose latitude averages are distributed as follows :



(CERES data over 15 years, from 2000 to 2015 : the horizontal grey lines correspond to the average value of 340 W/m^2)

5.2. Deduction of the part backscattered by the Earth : the Albedo

If we see the Earth from space in the visible, but also in infrared, it is because it reflects or diffuses part of the solar radiation :

- at high altitudes by clouds, which are the main factor,
- on the Earth's surface, by land and polar ice, but also by all terrestrial environments that reflect some of the light they receive : deserts, forests, oceans, etc.

The proportion of reflected light in relation to incident light defines the **albedo**.

The Earth's albedo is difficult to measure accurately, as it varies and is very different depending on the positioning of clouds over normally poorly or highly reflective terrestrial surfaces (which they replace in terms of albedo), particularly according to the proportion of clouds positioned over oceans or over land ; moreover, their positioning varies greatly over time and space, and it therefore takes a long time to establish a reliable average.

The albedo is more important in the northern hemisphere (whose land surfaces are more reflective), than in the southern hemisphere, which is essentially oceanic and less reflective. Nevertheless, it is commonly estimated overall at an average of **30% of solar radiation, or 100 W/m^2** (the exact value does not matter in our debate, as long as it is considered constant).

Most of the albedo comes from clouds : about **75 W/m^2**.

The remaining 30% of the total albedo, or about **25 W/m^2**, is backscattered by the Earth's surface as follows :

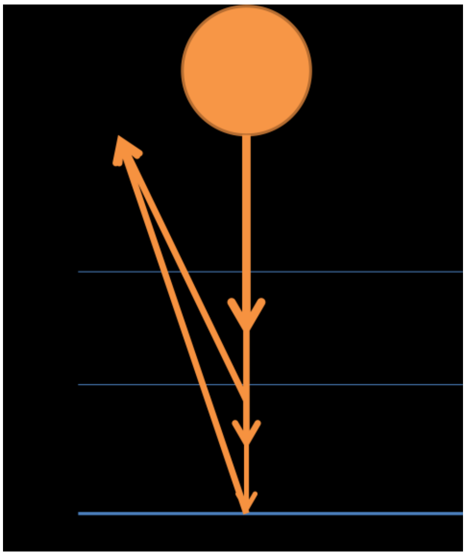
- the oceans, which occupy 71% of the Earth's surface, have a low albedo : generally between 5 and 10% (depending on the angle of incidence of the rays) ;
- sand between 25 and 40% ;
- ice about 60% ;
- deep and fresh snow up to 90%.

But polar ice, although highly reflective, plays a secondary role, due to the fact that :

- the grazing incidence of the Sun's rays, which means that they are poorly lit,
- that they are often covered with clouds,... already counted.

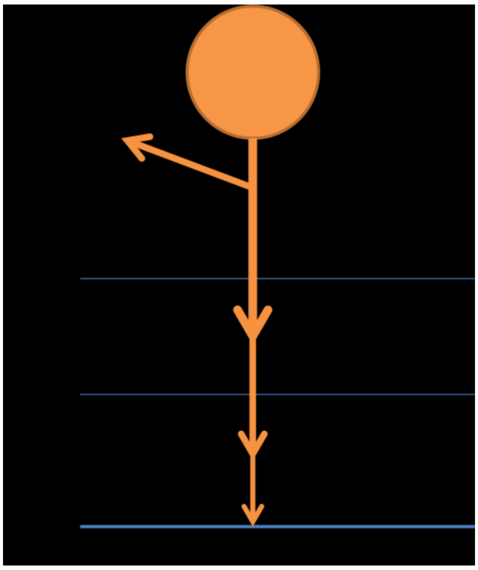
Of course, this would not be the case if polar ice were to descend in latitude (as it may have been the case during periods of glaciation, for example 20,000 years ago when the temperature was colder by 8 to 10°C at 45° North, with vegetation in Paris of the polar tundra type) : in this case, the albedo would be much more important (which would not help in terms of cold).

Similarly, if cloud cover were to vary, the impact on albedo could be very significant.



The fact that albedo results from reflections at different levels (mainly cloud tops and terrestrial (and maritime) surfaces) has no effect on the heat balance at these different levels : this energy only enters and exits the system without changing it : from a climate point of view, it simply does not exist.

And so, for the future, we will reason globally with deduced albedo, i. e. on the basis of an average total "absorbed" solar radiation of 240 W/m².



But again, this is an average ; locally (over time and/or on the Earth's surface), the albedo can be much lower.

5.3. Can we deduce an Average Temperature of the Earth from it ?

We often hear that, without the "Greenhouse Gases", the average temperature of the Earth would be -18°C (255K) : we mean an Earth without an atmosphere, like the Moon.

This statement is the result of a simplistic calculation, widely taken up by the media, which assumes that the whole Earth is developed (flattened), and receives directly and permanently all the average solar radiation (**240 W/m²**, if we simply deduce the albedo) :

$$M = \sigma T^4$$

donc $T = \sqrt[4]{M/\sigma} = \sqrt[4]{240/(5{,}67 * 10^{-8})}$ = 255 K = <u>- 18 °C</u>

However, this calculation is mathematically wrong (and not only a little bit wrong !) : we cannot reason on this average radiation received, to deduce an average temperature of the Earth : T is locally proportional to $\sqrt[4]{M}$, but the average of the local $\sqrt[4]{M}$ is not at all equal to $\sqrt[4]{\text{Local M average}}$..

Indeed, suppose for example a surface, which, instead of receiving a total permanent radiation of 240 W/m², receives on one half a zero radiation, and on the other half a radiation of 480 W/m² (which gives the same average of 240 W/m²) :

- Temperature of the half-surface receiving zero radiation : 0 K
- Temperature of the half-surface receiving 480 W/m² radiation : $T = \sqrt[4]{M/\sigma} = \sqrt[4]{480\,/(5.67 * 10^{-8})}$ = 303 K
- Mean temperature : 303 / 2 = 151.5 K, <u>i. e. -122 °C</u>

We are far from -18°C, for the same average radiation energy received.

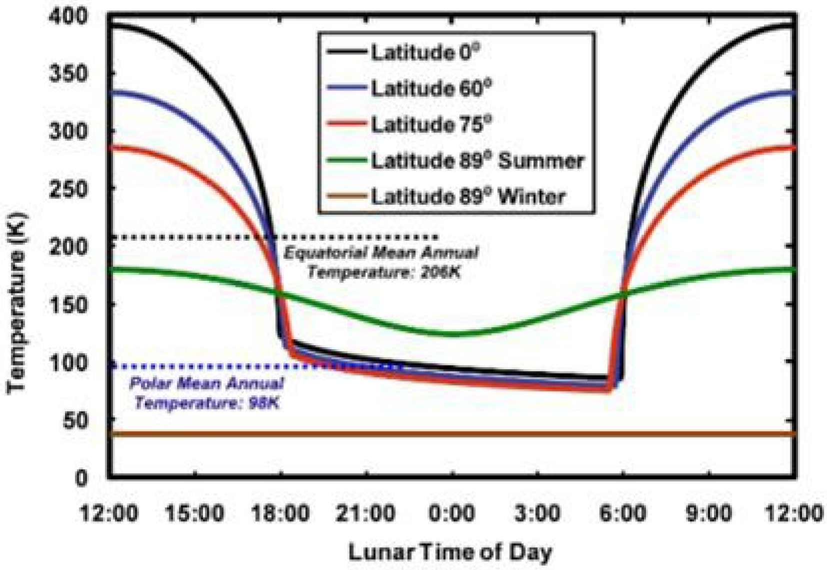
That being said, we can deduce 2 conclusions from this calculation :

1. The average temperature of an Earth without an atmosphere or oceans would be between these two extremes (-122°C, -18°C) ;
2. -18°C is the temperature of a body receiving 240 W/m² uniformly over time and space ; but any fluctuation in radiative flux compared to this average results in a lower average temperature : <u>-18°C is a maximum theoretical average temperature</u>.

For an Earth without atmosphere or water, to obtain an "exact" result, the calculation should be made at each point, on the basis of its local value of M (1360 W/m^2 sun at the zenith, 0 side dark side, 1360 cos θ according to the inclination, itself a function of latitude and time). But for the real Earth, we would also have to take into account the thermal inertia of the Earth, the atmosphere, ... and especially the oceans,... and an albedo expressed in terms of probability (depending on whether or not there are clouds).

In short, this is one of the limitations we mentioned in the introduction.

However, the Moon provides us with an order of magnitude of what the Earth's average temperature without atmosphere or oceans could be, since, apart from albedo, it receives the same average radiative flux as the Earth (340 W/m^2), and a maximum flux (sun at its zenith) of 1360 W/m^2.



If we assume that the Moon has an albedo of 7% and an emissivity of 0.975, we deduce the maximum temperature (sun at the Zenith) : 389 K, or 117°C.

The radiative flux M at a point on the illuminated face of the Moon is equal (by projection) to 1360 x (1-7%) x cos(latitude) x cos(longitude), and its temperature is equal to $\sqrt[4]{M/\varepsilon\,\sigma}$.

The integration from 0 to π/2 in latitude and longitude allows to calculate an average temperature of the illuminated face : we find 311 K (or 38°C).

On the dark side, the minimum temperature measured is 70 K (the coldest zones are at 40K) : as a first approximation, this temperature can be considered uniform over the entire dark side : indeed, the thermal inertia of the Moon is very low, and the Moon rotates very slowly on itself (28 days).

So we can consider that **the average temperature of the Moon** (as far as it makes sense), **is about (311 + 70) / 2 = 185 K = -88 °C**.

Given its larger albedo, the average temperature of an Earth without an atmosphere or oceans would be even lower.

And so, if the average temperature at the Earth's surface is around 15°C, and not -88°C, it is because **the atmosphere and the oceans necessarily play a very important role**.

... because, unfortunately, in addition, from a purely radiative point of view, the atmosphere does not improve the temperature at the Earth's surface, since, as we will see, it absorbs part of the sun's radiation itself and only lets part of it reach the ground.

6. Continuation of the route : crossing the atmosphere

We can now look at the path of the sun's rays, inside the atmosphere :

6.1. Barrier #1 : Stratospheric Oxygen and Ozone

Before reaching the troposphere, the Sun's rays pass through the stratosphere.

Note : this is the totality of solar radiation, including albedo : the albedo factors for visible and infrared are between the tropopause and the ground surface, and therefore lower ; but since we reason with deduced albedo (based on 240 W/m^2), and since this has very little impact in the stratosphere, we neglect this aspect.

Conditions in the stratosphere induce phenomena of dissociation of oxygen molecules into atoms, which, in particular, create the ozone layer that protects us from ionizing radiation. Depending on their wavelength, UV rays :

- dissociate oxygen molecules into 2 atoms by photolysis,
- convert the molecules and atoms thus released into ozone molecules,
- re-dissociate ozone molecules into molecules and oxygen atoms.

The continuous forming or reforming of O_3 from O_2 and O atoms under the effect of high-energy UV radiation from the Sun is an exothermic reaction, which, by absorbing this radiation, warms the stratosphere in its upper part.

This is a chemical phenomenon, not a radiative one, which causes the temperature at the top of the stratosphere to reach around 0°C (273 K).

This temperature at the top of the Stratosphere is relatively stable (on average day/night), because it results in fine only from the concentration of oxygen and solar radiation (UV) at this altitude, which is not very subject to variation.

But, as a result, there is a warm layer at the top of the stratosphere, which radiates thermal infra-red at its temperature, and will transmit its heat to the atmosphere, by radiation and gradual absorption by stratospheric CO_2 (mainly), until the tropopause.

And so, the temperature drops by about 2°C/km between the top of the stratosphere and the tropopause : we therefore have a temperature inversion in the stratosphere, which explains the lack of convection there.

The stratosphere has its own radiative equilibrium : it restores directly to the cosmos, by radiating its CO_2, the energy it absorbs to maintain its chemical reactions, i.e. about **17 W/m^2** ; this seems small, compared to the heating produced (more than 50°C if we compare the top and bottom of the stratosphere), but the atmosphere is so rarefied at this altitude, that the heated mass is very low.

Of the 240 W/m^2 that are not reflected by the albedo, only 223 continue their journey in the troposphere.

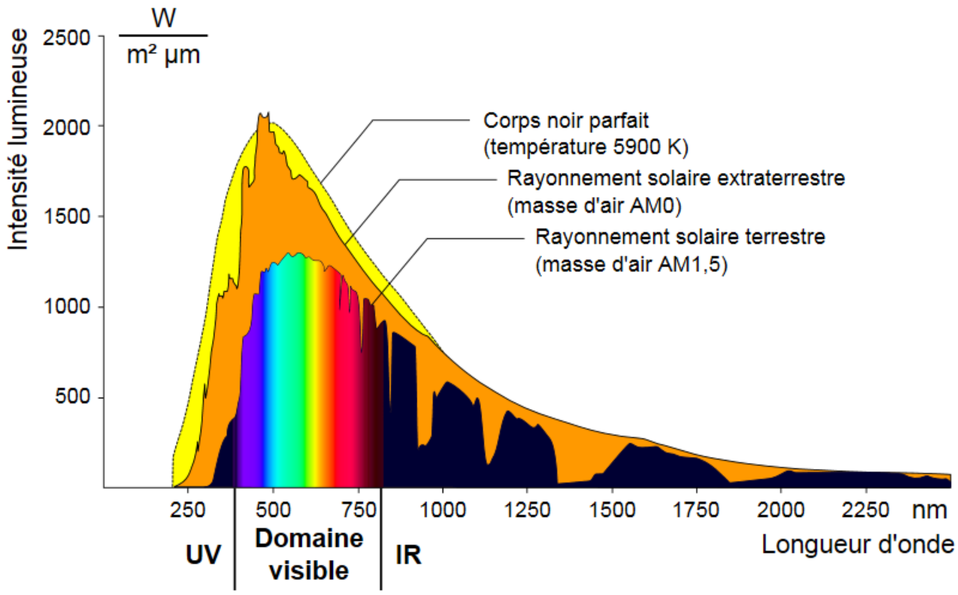
6.2. In the Troposphere : Absorption by Clouds, Water Vapour, and Carbon Dioxide of the Air

As we have seen above, clouds back-diffuse part of the radiation they receive, and let part of it pass through, but they also absorb almost all of the solar Infrared (a few tens of microns of water absorb almost all of the solar infra-red beyond 1 µm wavelength).

Moreover, water vapour (especially) and CO_2 (a little bit) have absorption bands in the "solar" infra-red, but what they absorb from solar radiation is outside the visible zone : we cannot see it (here again, nature is well done).

On average, this absorption in the troposphere is generally estimated to 67 W/m^2.

Compared to its initial form, the Solar Spectrum after crossing the atmosphere takes the following form, where we clearly see the impact of these absorption bands (cloudless sky) (the spectra correspond to a device pointing towards the sun, according to a standard used for photovoltaic devices and not to the flux received on a horizontal surface. The curve at the top of the air corresponds approximately to 1360 W/m², the curve at the surface (but aiming at the sun) to 910 W/m²).



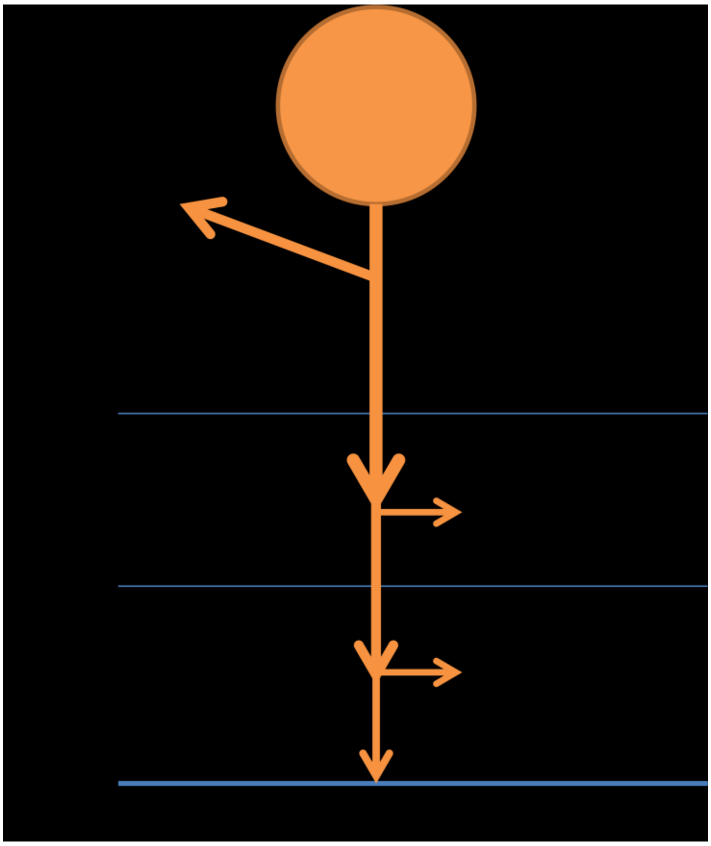
(Source : https ://fr.wikipedia.org/wiki/Raies_de_Fraunhofer)

(AM0 stands for the upper limit of the atmosphere ; AM1.5 stands for an inclined trajectory that multiplies the path in the atmosphere by 1.5 (corresponding to an average latitude))

6.3. Balance reaching the Earth's Surface

As a result, once the albedo and the various samples from the different layers of the atmosphere have been deduced, the average energy received from the Sun by the Earth's surface is equal to :

$$\mathbf{M = 240 - 17 - 67 = \underline{156\ W/m^2}}$$



Of course, this is again an average, between 0 (hidden face of the Earth), and around 1100 W/m^2 (maximum observed over the ocean, sun at its zenith, cloudless : oceanic albedo 5% deducted).

If this average value was applied everywhere, with the same false calculation giving -18°C, 156 W/m^2 would correspond to a maximum average temperature of 235 K (or -38°C).

But if we repeat the analogy with the Moon (average radiative flux 316 W/m^2, and average temperature 189 K) the temperature at the Earth's surface should be :

($M = \varepsilon\ \sigma\ T^4$ donc $M/M_0 = \sqrt[4]{T/T0}$) thus $T/189 = \sqrt[4]{156/316}$ = 0,84 => **<u>T = 158 K = - 115 °C</u>**

But this analogy is not totally valid : the Earth rotates 28 times faster than the Moon, and, moreover, the oceans give it a thermal inertia that the Moon does not have.

As a result, the average (theoretical) temperature of the Earth should fall between these two values (-115°C, -38°C)

In short, we are still very far from the -18°C carried by the media and some manuals, and even more from reality (15°C) !

6.4. There is a Gap

... and even a big gap !

Indeed, radiatively, to justify the average temperature of the earth's surface (15°C or 288K), with an emissivity/absorptivity of 0.9, it would have to receive :

$$M = \varepsilon\ \sigma\ T^4 = 0,9 \times 5,67 \times 10^{-8} \times 288^4 = \mathbf{350\ W/m^2}$$

... **more than twice** what it actually receives from the Sun after absorption of its radiation by the atmosphere :

if we reason only in radiative, 194 W/m^2 are missing, on average,

However, in radiative, thermal transfers can only go from the hotter to the colder ; and therefore, to raise the Earth's temperature to 15°C, it would necessarily require a source of temperature above 15°C ; but, apart from the Sun, nothing is hotter than the Earth at 15°C,... and we have already exhausted this source.

... and so, the "radiative" cannot explain everything, and especially not what happens inside the atmosphere (which is what interests us most).

6.5. Nota

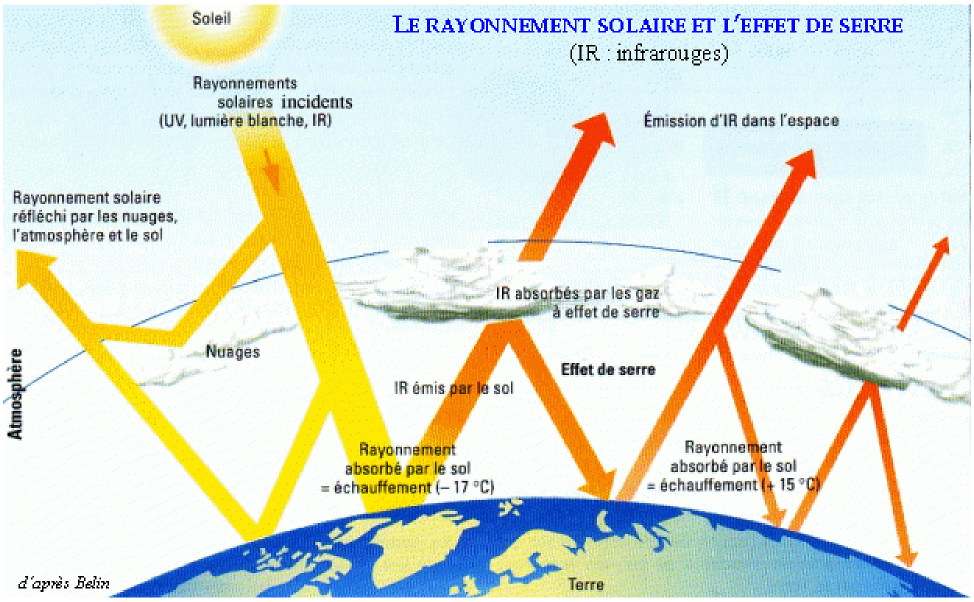
This is an average.

Locally, sunny at the zenith, and in the absence of clouds, the surface can receive more than 1000, even 1200, W/m^2, which gives temperatures of more than 90, even 110°C : largely enough to melt the tarmac, ... and burn your feet, or, above the oceans, enough to feed an enormous evaporation and a huge convection.

7. But then, where does the difference come from ?

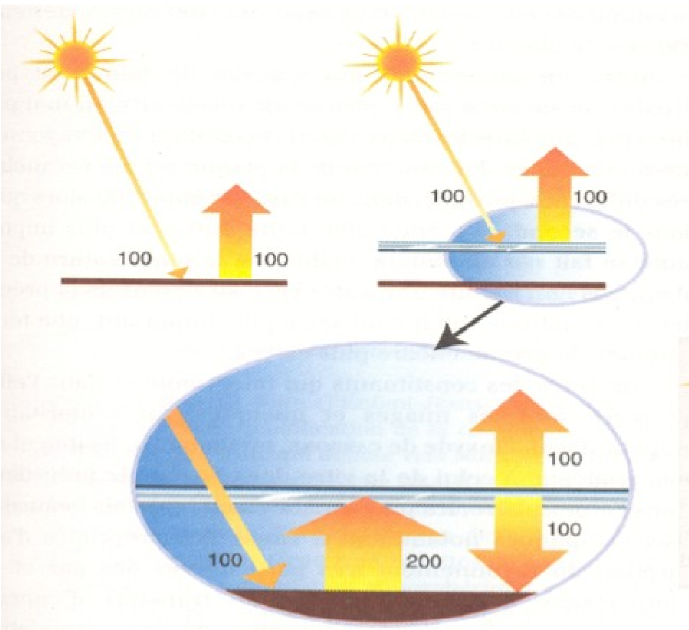
7.1. Let's go back to the mythical "Atmospheric Greenhouse Effect"

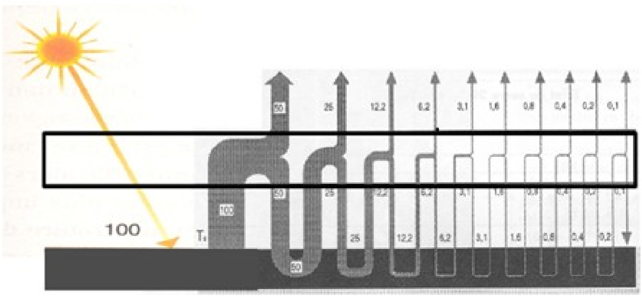
The "Atmospheric Greenhouse Effect" is a media-political representation of the functioning of the atmosphere, intended so that the average reader or listener has the impression of understanding how the climate works, and thus easily adheres to the message they are trying to convey.



The mechanism of the atmospheric greenhouse effect would be the following, in its original version, widely covered by the media, as stated by the Swedish Arrhénius, Nobel Prize winner in Chemistry 1903 (but who saw only advantages in it) :

- under the influence of radiation received from the sun, the ground surface heats up and emits thermal infrared rays (orange rising on the drawing) ;
- a part of them is blocked by the "greenhouse gases" of the atmosphere (in particular CO_2 and water vapour, opaque to most of these infra-red rays), which, as a result, like the glass of a conventional greenhouse, heat up, and then radiate themselves, depending on their temperature, half up and half down (the ground) (orange falling rays on the drawing) ;
- as a result, the ground surface heats up even more, and the mechanism repeats itself until it reaches an equilibrium, where it reaches a temperature higher than it would have due to direct solar radiation alone.





This mechanism is a physical nonsense :

- in radiative, heat flows exclusively from the hotter to the colder : to heat the ground, the "greenhouse gases" of the atmosphere would therefore have to be at a higher temperature than that of the ground, and therefore :
    . either the atmosphere containing these gases is itself at a temperature higher than the ground temperature, which is not actually the case (the lower atmosphere is on average at the ground surface temperature, and the upper atmosphere is colder),
    . or these gases, considered as isolated, are themselves at a temperature higher than that of the atmosphere containing them, a temperature that they would have acquired by accumulating radiation received from the ground, behaving like black bodies : without entering the theory of black bodies here, it is difficult to see how the "greenhouse gases" could have a temperature higher than the atmosphere containing them.
- Moreover, if these gases are opaque to infra-red (optical thickness > 1), they are opaque in both directions : if they block them on the way up, they necessarily block them on the way down : they cannot radiate through their own opacity (because if we follow this theory, as far as we are concerned, the "glass" is not above us : we are in) ;
- assuming that it even works : at each bounce we lose more than half of the radiation, which goes towards the cosmos ; however, the series 1 + 1/2 + 1/4 + ... converges at 2 : we cannot, mathematically, more than double the initial radiation, which would bring us, in the best of cases, to 156 x 2 = 312 W/m^2, which is still insufficient to justify the 15°C (with an absorptivity of 0.9, it would take 350 W/m^2).
- finally, even a conventional greenhouse does not work in this way, but essentially by blocking convection, whatever the material of the "glass" : repeated experiments have proven this : Woods (1909), Nasif Nahle (2011).

Of course, there is no question of this theory :

- nor in the minds of climate scientists (... well, not all of them, at least hopefully, fortunately !),
- or in models that predict future temperatures (as far as we can know).

But even if we ignore this somewhat caricatural representation, Gerlich and Tscheuschner have counted about ten different definitions of the Atmospheric Greenhouse Effect invoked by "climatologist" scientists, to the point that we no longer know what we are talking about, nor on which of these theories the models to which politicians and the media refer, to convince us.

Of course, the Greenhouse Effect would be welcome to explain and provide this lack if we were to reason in a purely radiative way.

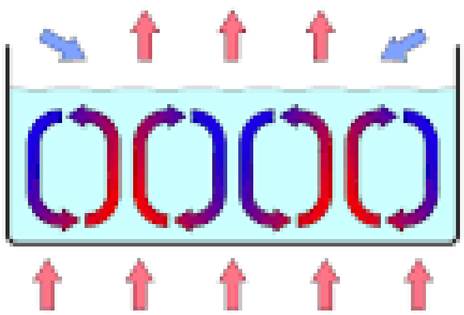
Fortunately, however, not all energy exchanges are radiative : not only in itself, but also because of the oceans, the atmosphere is the site of other phenomena that determine surface temperature.

7.2. Conduction ?

In conduction, heat flows also and exclusively from the hotter to the colder ; and therefore conduction is not an explanation either, especially since air is a very poor conductor of heat.

7.3. Convection ?

7.3.1. A word first about convection



Another mode of heat exchange that occurs at different levels, both in the atmosphere and in the oceans, is Convection.

Convection refers to heat exchanges within a fluid (liquid or gas) assumed to be non-conductive (e. g. water, air).

Convection is also Mixture.

Convection is the basis for the operation and calculation of almost all fluid/fluid exchangers in industry, and hot water radiators in homes, and boiling water in pots.

Convection can be natural (hot fluids, lighter, rise spontaneously, while cold fluids, heavier, fall : this is the case in the troposphere), or forced (by a pump or fan). It is all the more effective (speed of exchange) when the agitation (or turbulence) is strong (wind).

In the Earth's atmosphere, it is done in a natural way, the air being heated by the warmer (daytime) ground surface ; it is completed by Advection, migration of the warm air taken in the intertropical zone, towards the poles, and inversely of the cold air from the poles towards the intertropical zone, at low altitude (polar mobile anticyclones) with a kind of intermittent "atmospheric Gulf Stream", induced by the passage, every few days, of these high cold pressures.

Convection is a fundamental driver of heat exchange within the troposphere (there is no convection in the stratosphere, where there is a temperature inversion) :

- in itself, first of all, by the mixtures, currents, and winds it induces, which contribute to "averaging" the temperature, and to a certain extent, the heat flows, which contributes to (mathematically) increasing the average temperature ;
- but also indirectly, as will be seen in the following paragraph : " Lapse Rate".

7.3.2. As far as we are concerned

No ! : here again, Convection cannot explain that the average temperature at the surface of the ground is 15°C : as for radiative and conduction, in convection, heat exchanges go exclusively from the hotter to the colder, and we have no source hotter than the ground : it can only cool it.

But, even if Convection cannot directly explain this difference, it is one of the driving forces, as we will see below.

7.4. The Lapse Rate

Even if you don't know the name, you know it : that's what makes the higher you go, the colder it gets, and conversely, the lower you go, the warmer it gets.

7.4.1. Physical Theory (in dry Air)

Everyone has experienced, when inflating their bicycle, the heating of the pump as the pressure increases : this corresponds to a transformation of muscular energy into heat : whether it is energy or heat, they can be expressed in the same physical unit (the Joule).

Likewise, when you clean your PC with a compressed air bomb, you notice that the air escaping from the bomb is freezing and your bomb is cooling down : the opposite is true.

Each m^2 of Earth receives, due to gravity, the weight of 10 tons of atmosphere (1 kg/cm2).

But the distribution of these 10 tons is not uniform according to altitude, because air is a compressible body, and is therefore less dense at altitude, than on the ground where it is compressed under its own weight.

The troposphere is the permanent site of these compression/slackening phenomena, due to Convection currents, between the tropopause (0.1 to 0.3 bar), and the ground surface at 1 bar, and vice versa, which result in a higher ground temperature where the pressure is 3 to 10 times that of the tropopause.

Laplace's law (compression and adiabatic relaxation) is stated : $\mathbf{PV^{\gamma} = Cte}$ => $V\,dP = -\ \gamma\,P\,dV$, where

> $\gamma = C_p / C_v$ with (for air) :
> C_p = Specific heat at constant pressure (1005 J/(kg.K) for air),
> C_v = Specific heat at constant volume (717 J/(kg.K) for air).

In adiabatic compression, the internal energy variation of U is equal to the work received dW : $\mathbf{C_v\,dT = -\,P\,dV}$
Thus, for a mass m of air : $\gamma\,P\,dV = (C_p/C_v)\,P\,dV = -\,m\,C_p\,dT$
Thus, applying Laplace's law : $V\,dP = m\,C_p\,dT$

And in addition, depending on the altitude : $dP = -\,\rho\,g\,dz$ with density $\rho = m/V$; thus $V\,dP = -\,m\,g\,dz$

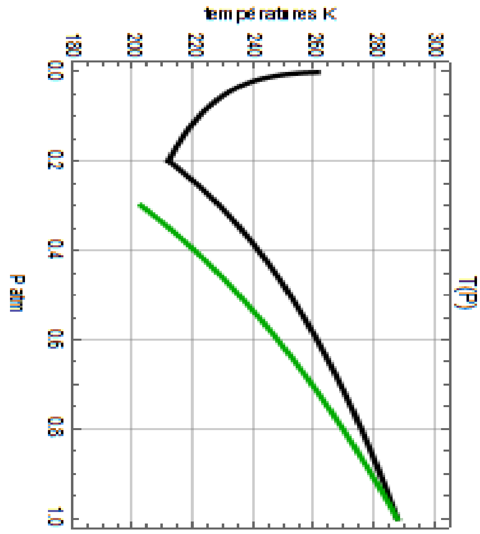
And thus : $$\mathbf{dT / dz = -\,g / C_p = -\,9{,}8\ °C/km}$$

In a dry atmosphere, the temperature decreases by 9.8°C every km of altitude

Note : if the altitude is expressed in terms of atmospheric pressure, the Lapse Rate can also be expressed according to the formula : $\mathbf{T = T_{ground}\ P^{0,19}}$ (P in atm., T in K).

7.4.2. In Practice, in a humid Atmosphere (general Case on Earth)

In reality, due to the condensation of air humidity, on the one hand, which gradually releases latent heat of condensation at altitude, and on the other hand, to the heating of the atmosphere due to the absorption of solar radiation by the water vapour it contains, and by the clouds, the denominator is corrected by a (negative) value C_h, and the formula becomes :



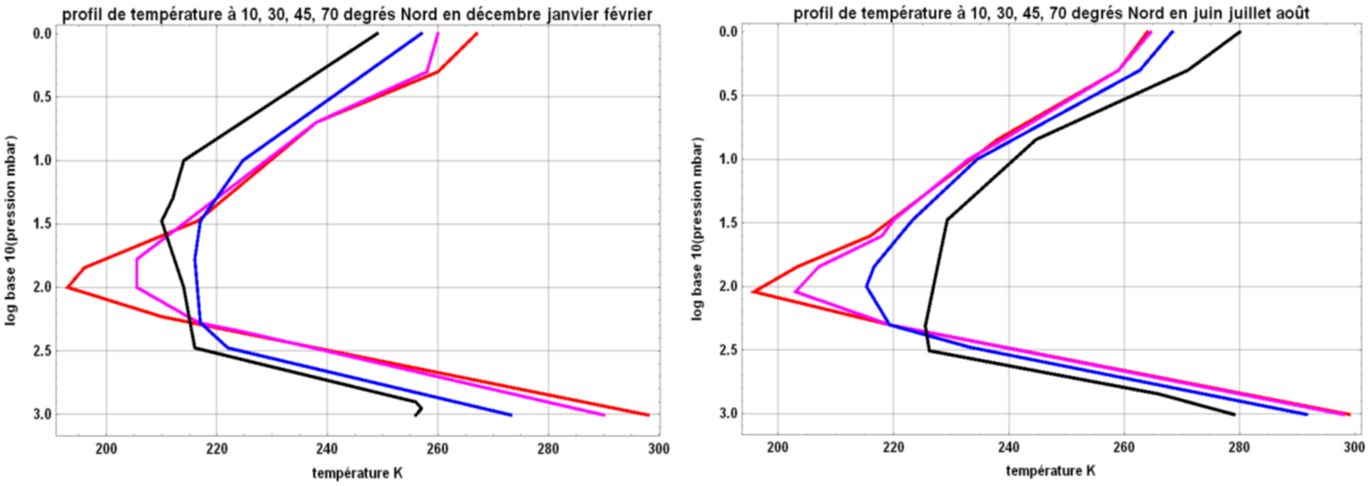
$\mathbf{dT / dz = - g / (C_p - C_h) = -6,5\ °C/km}$

(C_h = - 509 J/kg/K)

The gradient is less important (see black (vs. green) curve) :

This Lapse Rate is well known to climbers and especially aviators : the value of -6.5°C / km has been standardized by civil aviation, to calculate the risk of icing at altitude.

This gradient is perfectly verified, in the troposphere, by the sounding balloons, until the tropopause (where the discontinuity that defines it intervenes) ; indeed, the Lapse Rate requires that convection is possible (it is the engine) ; there is no convection in the stratosphere (which is in temperature inversion).



The y-axis is expressed in logarithm of pressure in mb : 3 corresponds to 1000 mb (or 1 atm), either the ground level, 2 corresponds to 100 mb (or 0.1 atm), or an altitude of 16 km (tropopause altitude in intertropical zone).

Starting from the top of the atmosphere, the Thermal Gradient starts at the altitude at which the radiation is released from the atmosphere into the cosmos, and therefore, as we will see later, in the vicinity of the tropopause.

The more humid the air, the lower the absolute value of the Gradient decreases : for example, in a cloud, it can fall to 5°C/km.

Ex. 1 : in intertropical areas, on average :

- Tropopause : -80°C at 16 km altitude
- Surface : - 80 + 6.5 x 16 = 24°C

Ex. 2 : in temperate zones, on average :

- Tropopause : -63°C at 12 km altitude (on average)
- Surface : - 63°C + 6.5°C/km x 12km = 15°C

7.4.3. Note : the Case of Venus

Venus is often cited as an example of the Atmospheric Greenhouse Effect, with its ground temperature of 470°C, and its dense atmosphere (92 bar at the surface) and essentially composed of CO_2 (95%) ; the Venera missions from Venera 1 (1961) to Venera 14 (1981) and the Vega balloons (1984, 1986) have shown that the solar flux on the surface is negligible (30 W/m² on the illuminated side) ; the solar flux is indeed absorbed and essentially backscattered by layers of dust and aerosols at an altitude of 60 km, where violent winds prevail (300 km/h ?) that equalize the radiation temperature of these layers under the Venus tropopause.

The mass of Venus' air is a thousand tons per m², a hundred times the mass of the earth's air.
(On Earth the carbonates at the bottom of the oceans and in the mantle are, in quantity of carbon, comparable to the carbon of the CO_2 in the Venus air, which remained in its air due to lack of ocean)

But this same Lapse Rate exists in the Venus troposphere, but at 8°C/km instead of 10°C/km in dry air, due to :

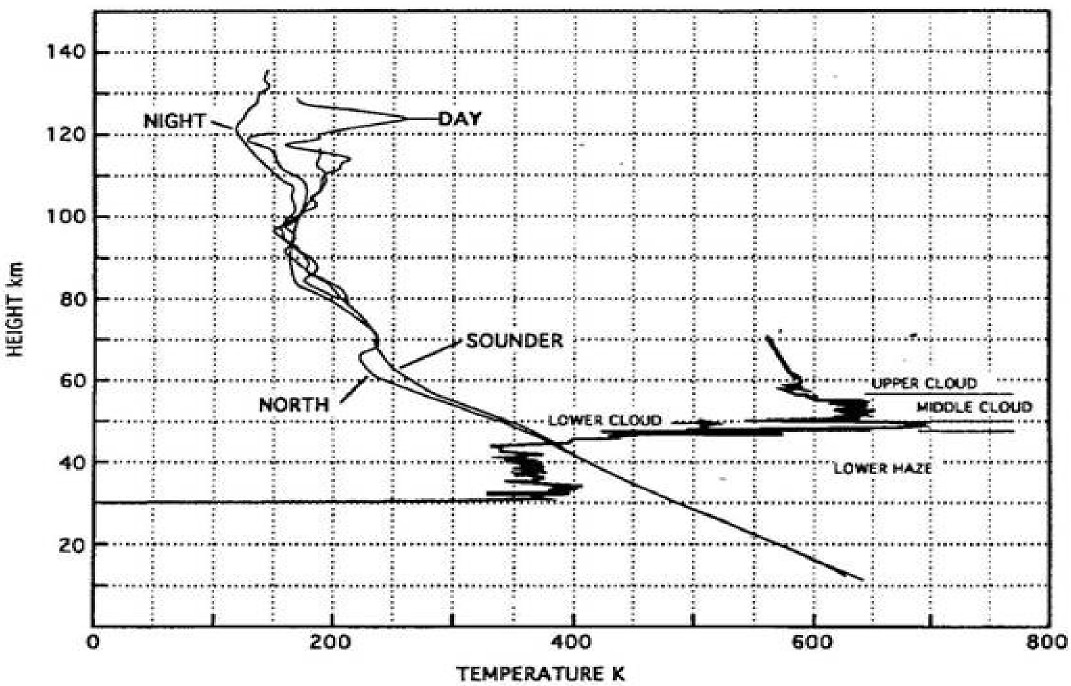
- g = acceleration of gravity = 8.87 m/s^2 for Venus
- Cp = heat capacity = 850 J/kg.K for CO_2
- Ch = - 300 J/kg.K

dT / dz = - g / (Cp - Ch) = - 8 °C/km

(from 735K to 230K in 63km (from 92 bar to 0.1bar)

The clouds, located at an altitude of between 45 and 70 km, are made up of fine droplets of sulphuric acid in aqueous solution, 75% of which is sulphuric acid (H_2SO_4) and 25% water (H_2O). Their diameter varies between a few tenths of a mm and ten mm (1 mm = 10^{-3} m). The lower atmosphere of Venus does not receive sunlight at wavelengths below 400 nm. Barely 5% of the visible light from the sun reaches the surface.

The figure below shows the temperature variation of the Venus atmosphere as a function of altitude, obtained in situ during the descent into the atmosphere of four automatic probes during the Pioneer-Venus mission in 1979 (continuous lines).



The temperature of Venus has nothing to do with a "greenhouse effect" due to CO_2!

And it should be noted that this calculation applies to ALL planets (or satellites : e. g. Titan) which have an atmosphere : only the weight of the atmosphere counts.

7.4.4. Impacts of the Lapse Rate

As we have just seen, the Lapse Rate explains that the average temperature at ground level is much higher than if the Earth had no atmosphere (6.5°C per km from the tropopause).

But it completely denies the influence of CO_2 and its famous "greenhouse effect", because, if we ignore the physical transformations of water, it is only due to the weight and compressibility of the atmosphere.

But it has another impact, on the radiation emitted by the Earth, which will interest us further : the higher in altitude this radiation is released (because it cannot lower due to opacity), the colder its source is, and therefore the less powerful it is (according to Planck's Law). To simplify things, we will say : "higher, colder".

Finally, it has a final impact : it is this Gradient that determines, by interposed temperature (Clausius-Clapeyron law), the maximum concentration (saturated vapour pressure) of water vapour as a function of altitude.

8. Return to Earth : Restitution of the solar radiative Energy received

To balance its energy (without which it would warm up indefinitely), the Earth must return the energy it has received, namely :

- **156 W/m² at ground level**, to prevent the ground from warming indefinitely,
- **240 W/m² at the top of the atmosphere** (TOA) (minus the albedo that only enters and exits), to prevent the atmosphere from warming indefinitely, which would have the indirect effect of warming the ground (via the Lapse Rate).

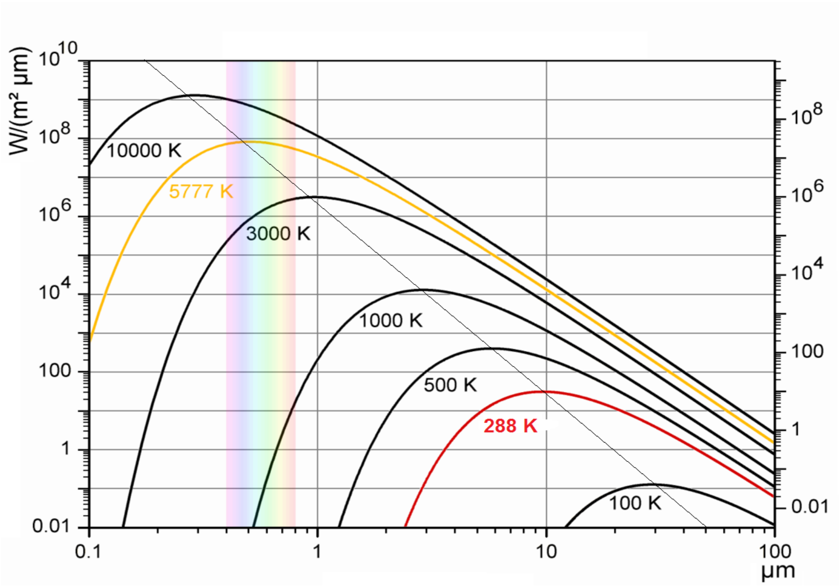
8.1. At Ground Level : 156 W/m² (daily Average)

8.1.1. Overview

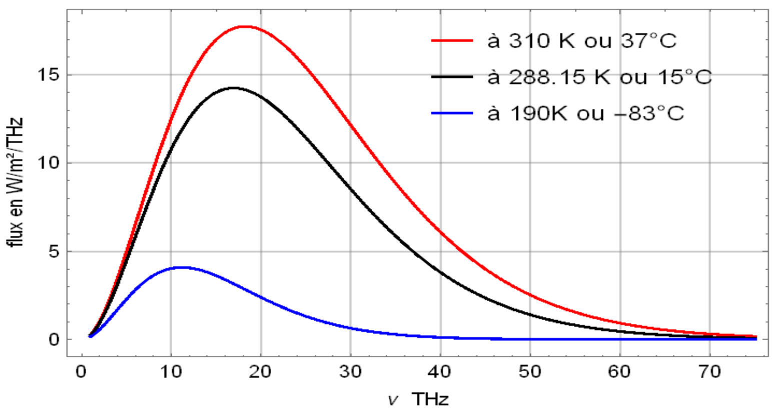
As a result of convection, and the transient storage of heat by the first centimeters or decimeters of the oceans and land, during the day, the surface and lower atmosphere are on average at the same temperature (15°C on average worldwide, although over short periods there are deviations, in either direction by a few degrees for example between day and night) ; **the surface and the lower atmosphere therefore exchanges, on average over 24 hours, almost no radiant heat**, and, from the temperature point of view, we can therefore speak of either one or the other.

We will see later (Discussion) that things are a little more complicated, without questioning this reasoning.

The Earth's surface, which is on average at 15°C (288K), therefore radiates (on average) at this temperature, according to the red curve 288K below :



But for this and the following chapters, which concern "terrestrial" thermal infra-red (i.e. temperatures below 288 K), we will reason in frequencies, and no longer in wavelengths. Thus, a frequency of 1000 cm-1 (or 30 THz) corresponds to a wavelength of 10 µm. The horizontal scale is then inverted, and the maximums of the curves do not correspond, due to a Flow also expressed in inverse units.



If the atmosphere were a transparent medium in thermal infrared, the **surface** at T = 288 K (15°C) with an emissivity ε of 0.9 would radiate directly M = 350 W/m^2 (in accordance with Stefan Boltzmann's Law $\mathbf{M = \varepsilon\,\sigma\,T^4}$) to the cosmos at 0 K.

But this is only the case in a limited frequency band, where the atmosphere is a little transparent to thermal infra-red while it is totally opaque elsewhere.

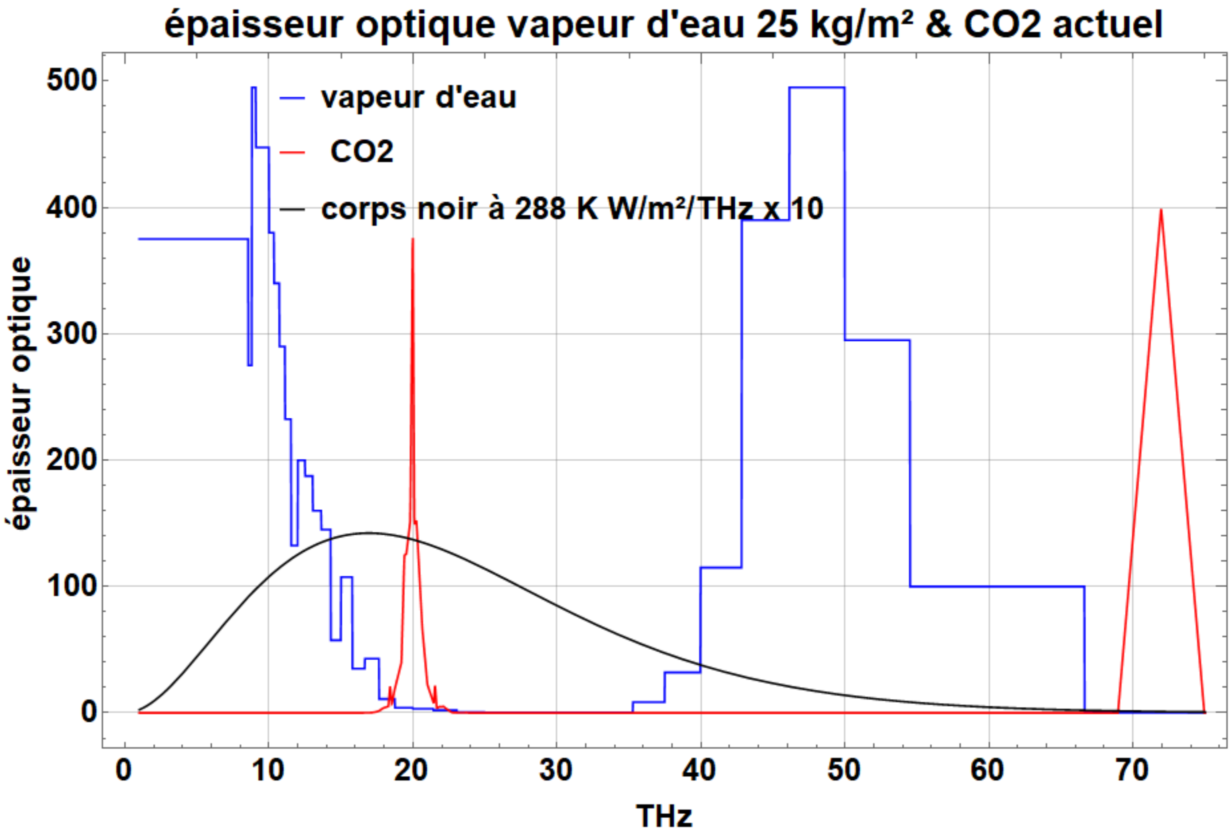
8.1.2. Heat Transfers by direct Radiation from the Ground : the "Atmospheric Window"

The graph below shows the opacity of the atmosphere to terrestrial infra-red in optical thickness, at ground level, between 4 µm wavelength (2500 cm^{-1} in frequency) and radio frequencies (10 cm^{-1} or 0.3 THz), i.e. globally over the entire infra-red emission spectrum of the ground surface.

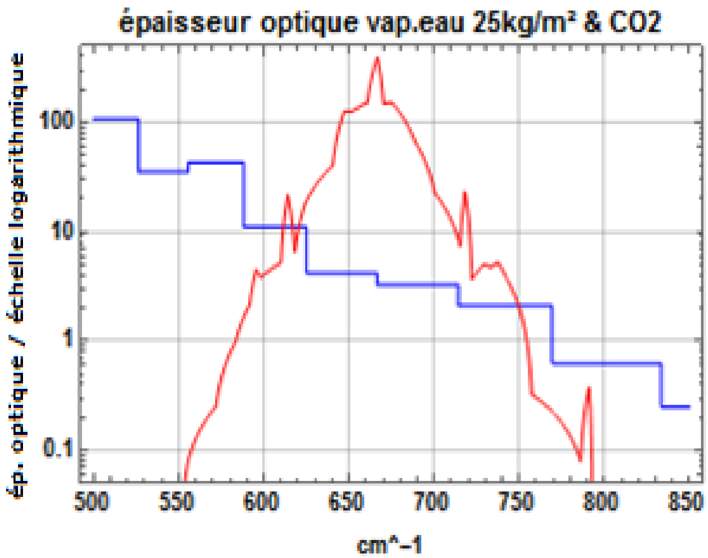
The black curve shows the blackbody emission at 15°C (288K), i.e., on average, at ground level : it is the equivalent in W/m^2/THz x 10 (and inverted scale) of the above black curve.

The blue and red curves show the optical thickness of the atmosphere in the respective water vapour and CO_2 absorption bands (data from the work of Kondratiev and Petschauer respectively : see Appendix A6).

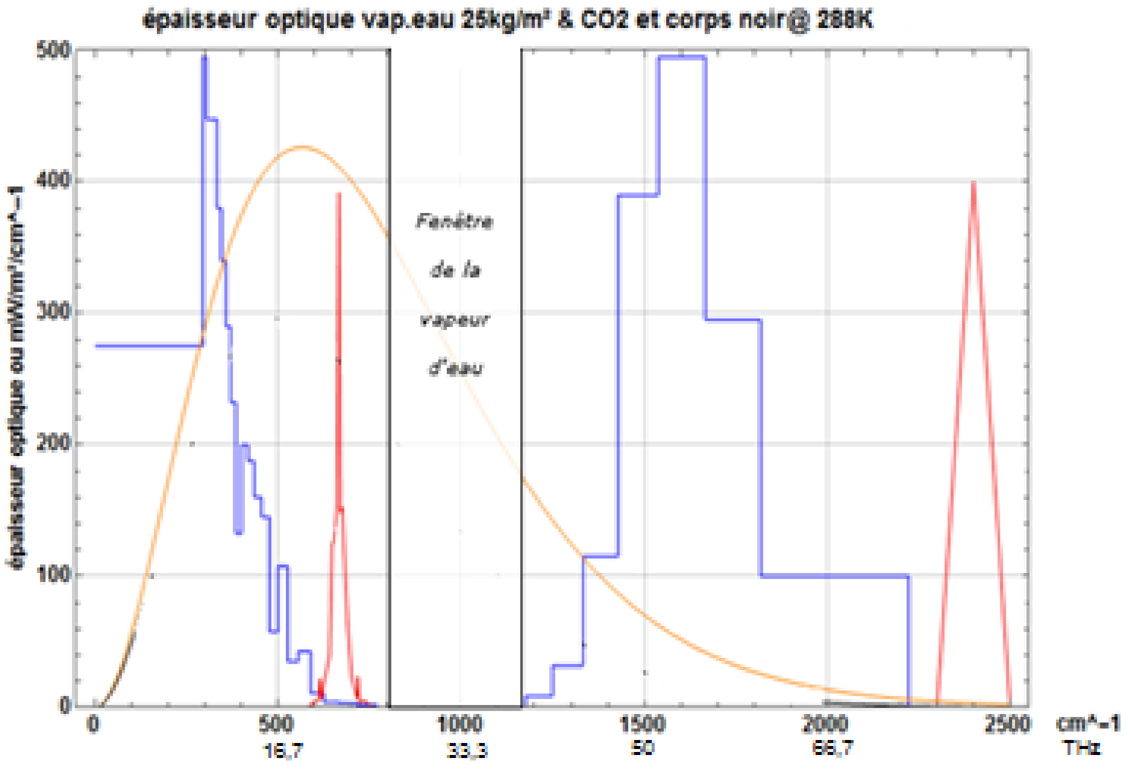
The optical thickness of the atmosphere can be calculated for each emission line, and is corroborated quite precisely by satellites and sounding balloons (at different wavelengths, and at different altitudes). At certain wavelengths, it is worth <u>several hundred</u>, whereas an optical thickness of 2 already blocks 94% of the radiation (the atmosphere is therefore very, very opaque).



The graph below zooms in on the CO_2 absorption band around 20 THz with a logarithmic vertical scale : the optical thicknesses being added, we can consider that the atmosphere is totally opaque, except between 23 and 35 THz (or between 800 and 1150 cm^{-1}) : optical thickness of the order of 0.5. (Remember that an optical thickness of 1 already blocks 80% of the radiation).

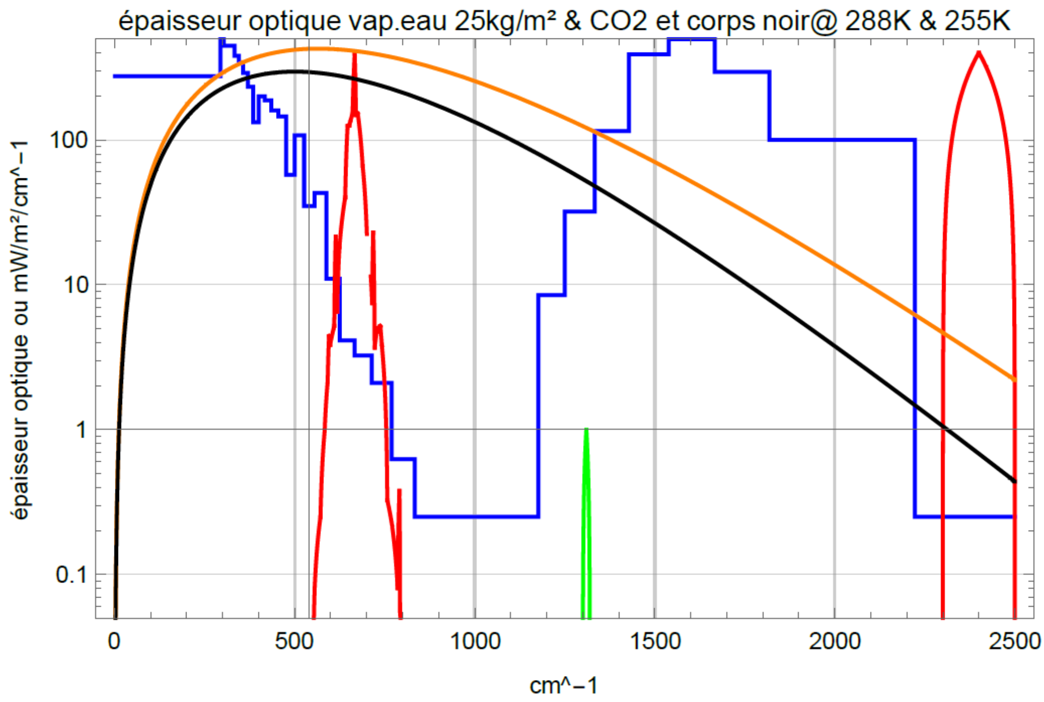


This transparency band (between 23 THz and 36 THz or between 750 and 1170 cm^{-1} or between 8.5 µm and 13.3 µm) is called the "Atmospheric Window" or "Water Vapour Window" : it is the only frequency band in which the ground surface can radiate directly to the cosmos : elsewhere, the atmosphere, totally opaque, blocks and absorbs any direct radiation from the ground to the cosmos.



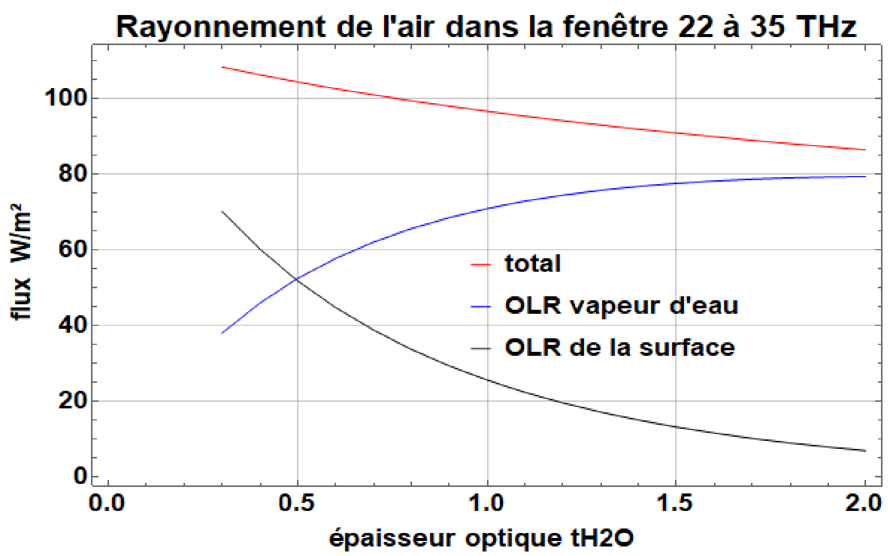
Epaisseur optique vapeur d'eau (25 kg/m²) & CO_2, et radiance corps noir à 288 K (W/m²/cm⁻¹)

In fact, this window is not even totally transparent : the "continuum" of water vapour absorption maintains an optical thickness between 0.5 and 1 (visible if we take a logarithmic vertical scale) :



Within this "atmospheric window", i.e. between 23 and 35 THz or 750 and 1170 cm-1, if we reason statistically (dry or humid zone, clear or overcast sky,...) :

- it is generally accepted that the ground surface would radiate (at 15°C or 288 K) about 110 W/m^2 towards the cosmos (at 0 K), by clear sky (optical thickness = 0), if there were no continuum of water vapour or clouds ;
- but in this continuum, water vapour, with an average optical thickness of 0.5 absorbs about half of it at low altitude ;
- and, on the half that crosses it, the clouds block (statistically) 60% (depending on whether they are present or not).



On average and depending on the clouds, the optical thickness is equal to 1, and the ground surface, at 15°C, therefore radiates directly 22 W/m^2 towards the cosmos.

But outside this "atmospheric window", the Earth, at ground level, cannot evacuate its heat by radiation, since the atmosphere is totally opaque (optical thickness greater than 5).

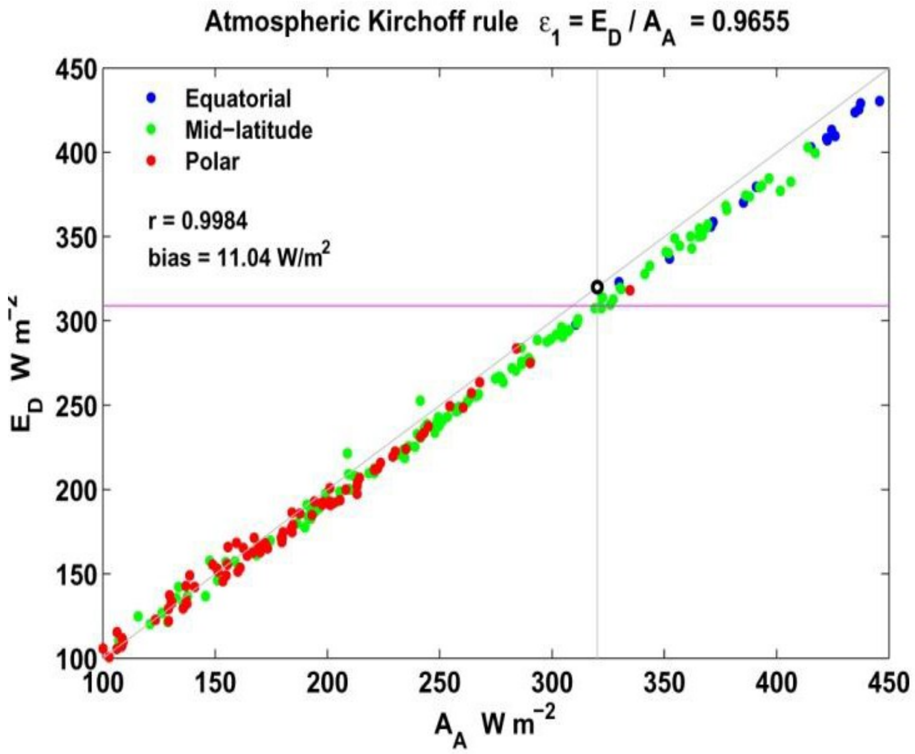
... and yet, it must evacuate this energy, otherwise it would heat up indefinitely : it has two means other than radiation to do so :

- by evaporation,

- by convection.

Note : outside the atmospheric window, we have seen in Chapter 3.5 that the very opaque lower troposphere is at the same temperature as the ground surface : there is therefore no heat transfer by radiation between the two.

Flux rayonnés par l'air vers la surface (E_D) et flux de la surface absorbé par l'air (E_A) (296 profils observés par ballons-sondes).
Source : F. Miskolczi, Development in Earth Science volume 2, 2014, pp. 31-52 (http ://www.seipub.org/des)



8.1.3. Heat Transfers by Evaporation and Rainfall

The oceans are at the heart of the system :

- they receive, like the rest of the soil surface, 156 W/m^2 (in fact even a little more, due to their low albedo), and absorb almost all of them on the surface over a few millimeters of thickness ;
- the temperature of the first meter would then increase by more than 3°C per day (calorific capacity = 4180 J/kg/°C) ;
- they cannot re-emit this energy by radiation, because the air with water vapour that covers them is almost totally opaque in the thermal infrared range (except in the atmospheric window) ;
- they cannot cool down by mixing with the deeper layers either, because, heated from above, they are in temperature inversion.

The oceans (and wet soils and vegetation) then use a totally different strategy to stabilize their temperature : **evaporation**,... until they reach an equilibrium with the air that covers them, which maintains a small temperature difference : in a way, it is the air that cools the oceans (and not the opposite).

Changes in physical state (melting<>solidification or vaporization<>condensation) involve the state change "**latent heat**", defined (in Joules) as the energy required to change the state of one kg of water.

Considering the abundance of water on the Earth's surface (the oceans occupy 71% of it) and in the atmosphere (on average 25 to 30 kg/m2), this process is very significant : water consumes **590 times more energy** to vaporize (or evaporate) than to rise by 1°C. And all this energy is released when it condenses into clouds, then into rain, at altitude.

... because there is no rain that has not been preceded by evaporation.

In addition, the warmer the weather, the more water evaporates, at a rate of +7% per °C under average terrestrial conditions (Dalton's Law of Evaporation).

Evaporation from the earth's surface is estimated at 502 800 km3 of water per year (oceans) (according to http ://www.planetoscope.com/atmosphere/117-evaporation-de-l-eau-des-oceans-dans-l-atmosphere.html) (495 000 according to http ://earthobservatory.nasa.gov/Features/Water/page2.php) + 74 200 km3/year (land surfaces : lakes, forests, plants, etc.), **for a total of 576 000 km3/year, or 18.25 x 10^9 kg/s**.

The latent heat of water vaporization (energy required) at 15°C is 2.470 x 106 J/kg

So this evaporation consumes 2.470 x 18.25 x 10^{15} = 45 x 10^{16} W

The Earth's surface area is 510,000,000,000 km2, or 510 x 10^{12} m2

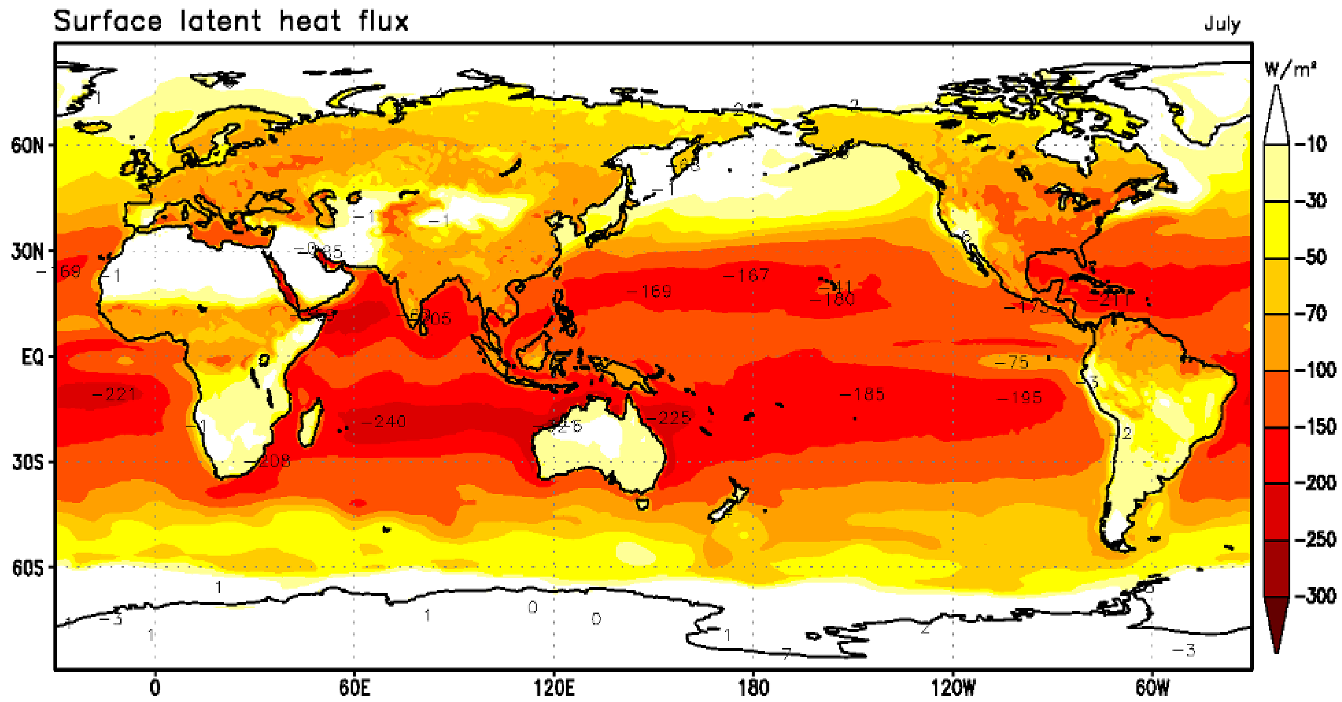
Thus, evaporation at the Earth's surface consumes an average of 45,000 / 510 = 88.4 W/m^2, which corresponds to an average of about 1.13 m of rain per year.

These figures have recently been revised upwards (almost 10%), particularly in the oceans (satellite observations and increased evaporation due to temperature rise : 7% per °C).

In total, we can therefore consider that it is about 96 W/m^2 that bypasses the opacity of the lower atmosphere, and are directly transferred by convection (like a kind of heat pipe), at an altitude where this vapour condenses into clouds by restoring the energy it contains.

We will see further on that this energy is then radiated into the cosmos at an altitude where water vapour is no longer an obstacle to its own radiation.

Of course, this is an average : overall, depending on the latitude, this consumption is distributed between 0 and 250 W/m^2 :



8.1.4. Heat Transfer by Convection

The surface of the warm ground also transfers some of its heat to the air that sweeps it : this lighter air rises and heats the troposphere.

This transfer is estimated at about **38 W/m^2** (order of magnitude in the absence of precise measurement).

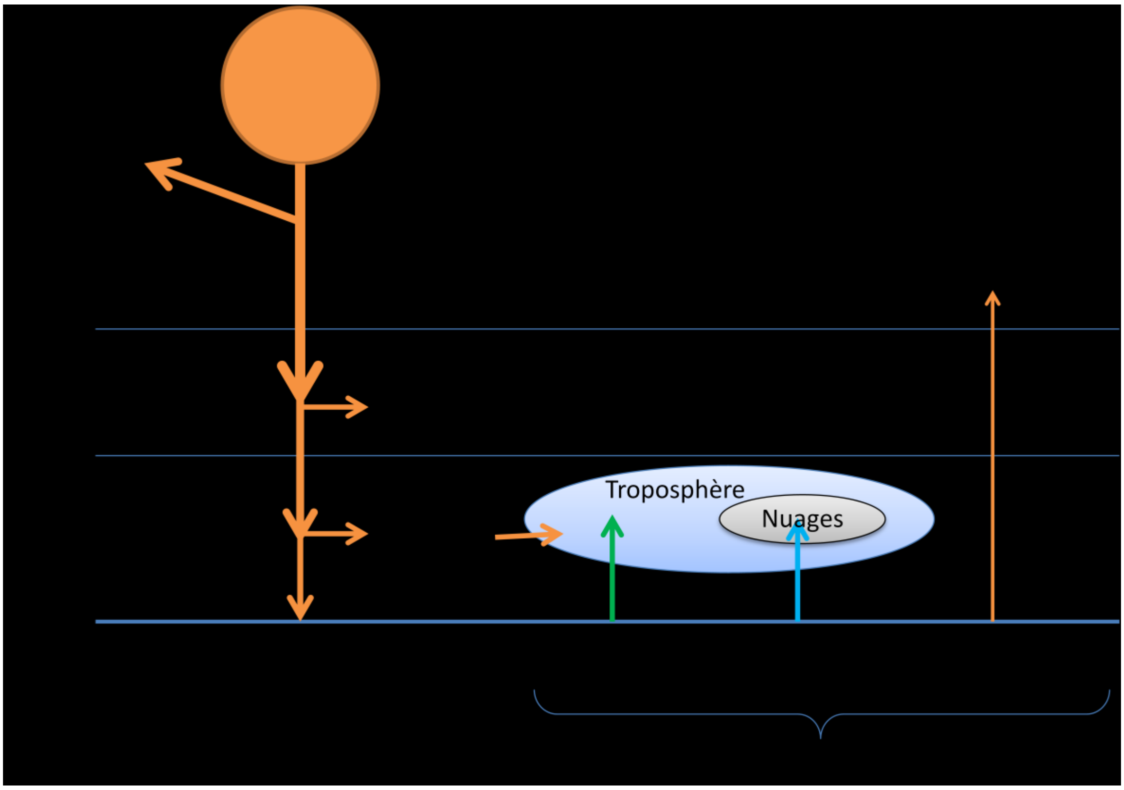
This is another "heat pipe", parallel to the previous one, which also crosses the opaque atmosphere to the top of the troposphere.

8.1.5. Overall Balance on the Ground Surface

As previously discussed, after deducting albedo, and after atmospheric sampling, the ground surface receives about **156 W/m^2** from the sun.

To balance its temperature, it releases this energy in several forms :

- a part by direct radiation through the "atmospheric window", but partially blocked by the "continuum" of water vapour, i.e. **22 W/m^2**,
- a part by latent heat transfer from ocean evaporation and plant evapo-transpiration, i.e. about **96 W/m^2**.
- finally, a part by convection of heated air on the ground surface, i.e. approximately **38 W/m^2**.



We will see later that, even if these figures are questionable (and they are, of course), evaporation totally regulates the temperature at the Earth's surface.

8.1.6. Discussion

At the beginning of this chapter, it was said that the soil and lower atmosphere were at the same temperature.

However, the temperature of the lower troposphere cannot be used to justify the temperature at the ground surface, particularly at the ocean surface : a bathtub cannot be heated with a hair dryer.

In fact, things are as follows :

- the surface of the ground (and oceans that cover more than 70% of it) receives these 156 W/m^2 (on average) by radiation ;
- as we have just seen, it can hardly evacuate them by radiation, due to the opacity of the atmosphere to thermal infra-red ;
- so it is warming up ;
- but, due to convection, and especially evaporation (especially on the oceans, but not only), this heating is limited by the temperature of the air overhanging it, ... until the two temperatures are balanced.

... and therefore, indirectly, it is still the Lapse Rate that determines the temperature of the soil (including see) surface.

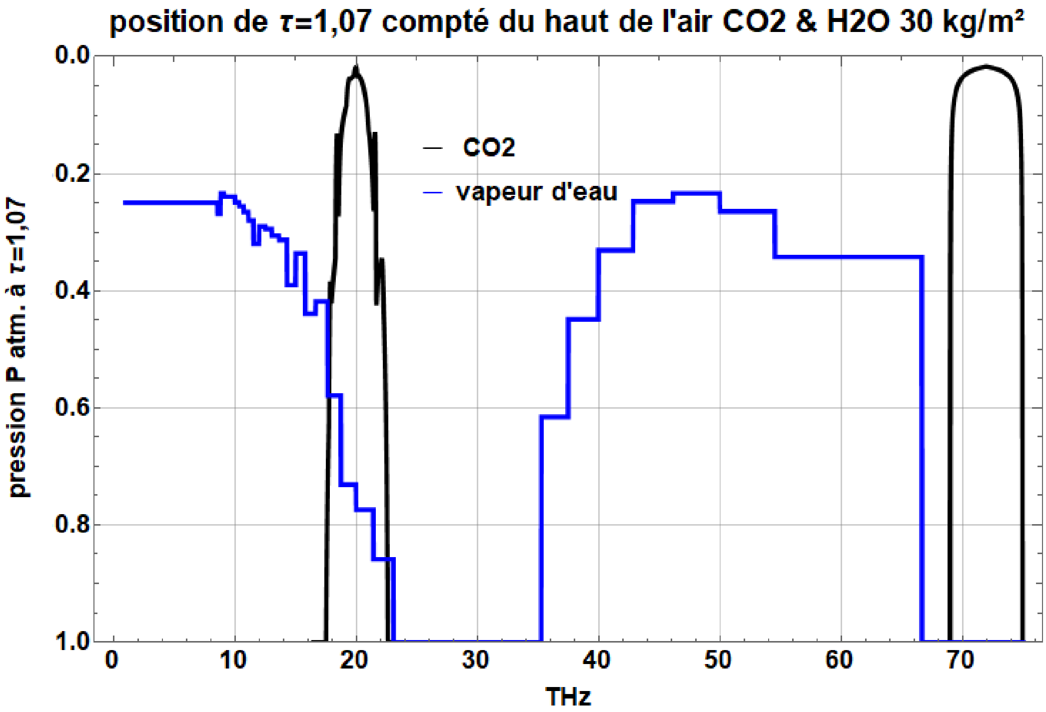
And, since the lower troposphere is at the same temperature, they do not exchange by radiation (hypothesis put forward at the beginning of this chapter).

8.2. On Top of Atmosphere (TOA) : 240 W/m²

It would be pointless if the radiative budget were balanced on the ground, and not at the top of the atmosphere : if it were not balanced at the top of the atmosphere, the temperature increase at the top of the troposphere would result on the ground, due to the Lapse Rate

8.2.1. Release Altitudes

The graph below gives the altitude (expressed as atmospheric pressure) where, as the atmosphere becomes thinner, the optical thickness, seen from the cosmos, is equal to 1, at which altitude the atmosphere begins to radiate towards the cosmos (below, it can be considered totally opaque).



(For the record, 0.2 atm. corresponds to an altitude of 12 km : it is also the altitude of the tropopause in temperate zones, at an average temperature of -60°C or 213 K).

All this energy, which is found in the atmosphere (latent heat of water vapour, radiation absorbed on descent, convection from the ground) is gradually released by radiation from the atmosphere at altitude, as the atmospheric window widens, to above the clouds, where the water vapour is sufficiently rarefied so that its optical thickness is less than 1, or at most :

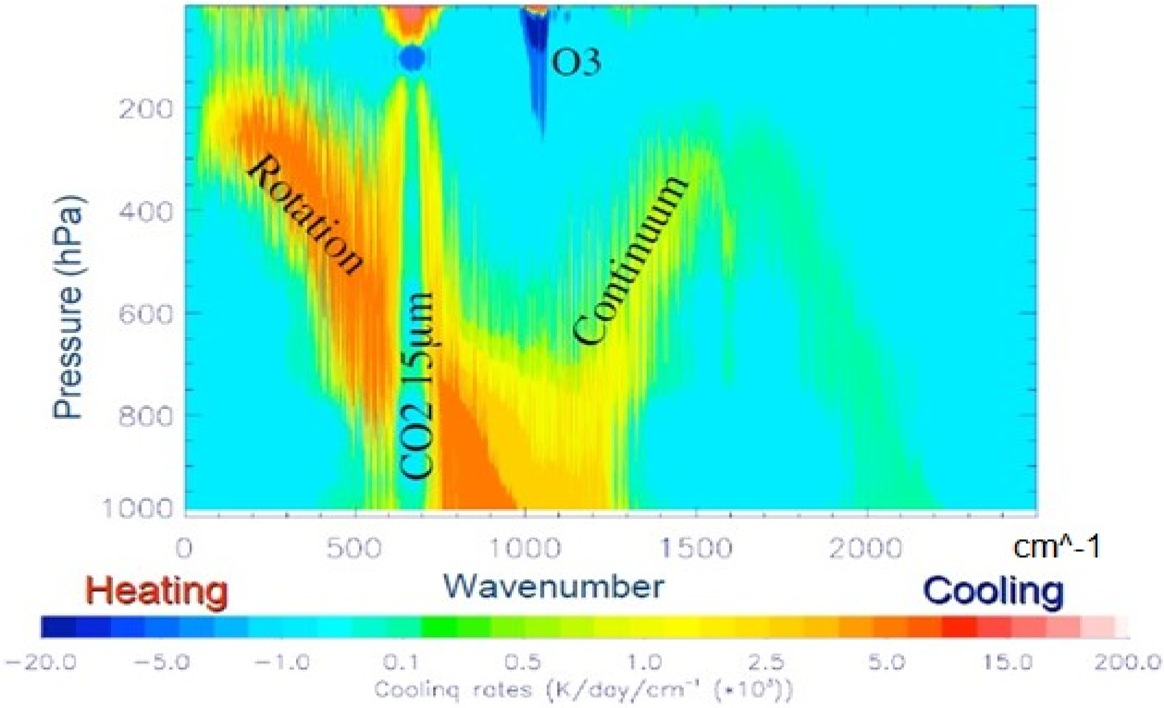
- to the top of the troposphere in warm (inter-tropical) areas where the troposphere is high and cold (about -75°C) (as seen in the paragraph on the Lapse Rate),
- to the bottom of the stratosphere in cold areas (temperate and circumpolar) where the troposphere is low and warm (about -50°C)

... and to the top of the Stratosphere in the frequencies blocked by CO_2, where CO_2 (in black above) is sufficiently rarefied so that its optical thickness is less than 1.

8.2.2. Translation in Heating/Cooling

When the atmosphere radiates, it cools down ; conversely, when it absorbs radiation, it warms up.

The graph below, resulting from a calculation line by line, shows the altitudes (expressed in atmospheric pressures) at which heat is exchanged, i.e. where the atmosphere cools (yellow-red) or warms (dark blue) by thermal radiation as a function of the radiation frequency (Source : Brindley & Harries 1998 (SPARC 2000)) :



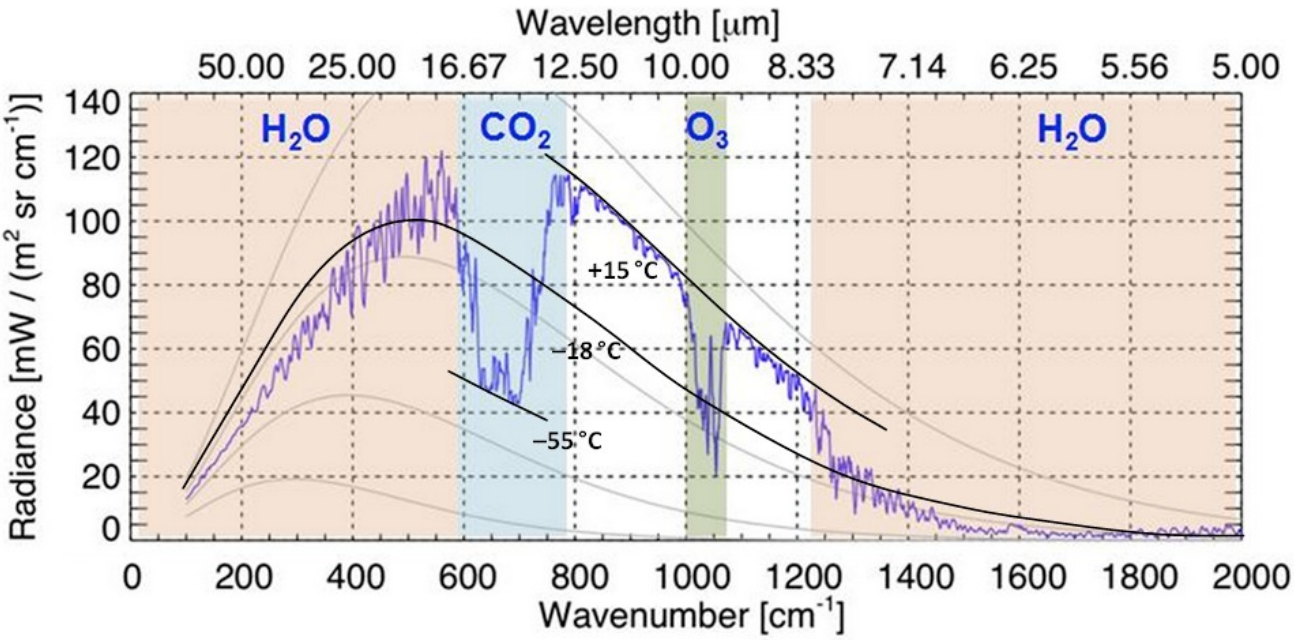
- In the light blue areas, there is no heat exchange :
    - . either because the atmosphere is **opaque** (under the curves of water vapour or CO_2 in the top graph (optical thickness > 1)) : there is no energy transfer by radiation inside an opaque body ;
    - . or on the contrary because the atmosphere is **transparent** (above these same curves) : the radiation, wherever it comes from, passes through it freely, without heating it ;
    - . or because the radiation is negligible (frequencies above 2000 cm-1, where the radiation curve becomes very low).
- The band between 750 and 1170 cm-1 (22.5 to 35.1 THz) corresponds to the water vapour window, where the soil surface radiates in the continuum : in this band, the atmosphere starts cooling from the ground, especially as the radiation is more intense (Planck curve).
- The other vermilion and yellow areas show the altitudes where the atmosphere radiates (and thus cools) :
    - . above the clouds for water vapour,
    - . in the stratosphere with respect to the upper CO_2.
- The dark blue zone between 1000 and 1100 cm-1, corresponds to a band of absorption of ozone radiation from the top of the stratosphere absorbed by the colder ozone of the lower stratosphere ;
- The dark blue spot at the top of the CO_2 line (between 600 and 750 cm-1) corresponds to the absorption by CO_2 of the tropopause (here the tropical tropopause around 100 millibar or 100 hecto-Pascal, the coldest layer in the atmosphere) of CO_2 radiation from the warmer layers below and above.

8.2.3. Quantification : the OLR (Outgoing Longwave Radiation) Spectrum

The Earth's Outgoing Longwave Radiation (**OLR** spectrum) (graph below) shows the Earth's radiance, seen from the cosmos, as a function of the radiation frequency (in the different emission bands) : the energy dissipated (in W/m^2) is proportional to the area under the curve (or in other words, proportional to the integral of the curve), **the total area being 240 W/m^2**.

Note 1 : This graph is an example : depending on the place and time, it may have different values, but its appearance is always the same.

Note 2 : graph in W/m²/steradian/cm^{-1} multiply by 3.14 to change to W/m² and by the width of the frequency band : for example, stratospheric CO_2 is about 3.14 x 50 W/m^2/sr/cm^{-1} x 100 cm^{-1} = 15 W/m².



(This spectrum is deduced from a ray by ray calculation ; it is very well verified by satellites).

The different portions of the curve each roughly follow a (mean) isotherm corresponding to the altitude (and therefore the power) of radiation (radiance) according to the different absorption (or radiation) bands :

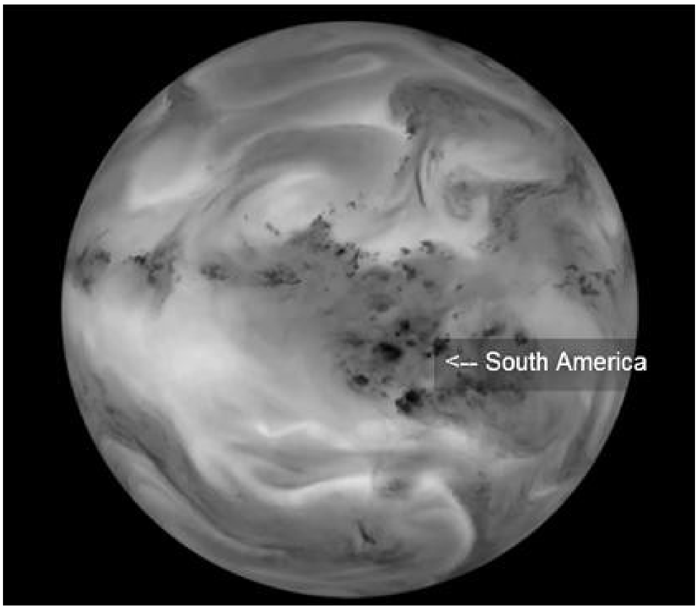
- +15°C (or 288K) for direct radiation from the ground surface or lower atmosphere (< 2 km) to the cosmos (white vertical bands), in the atmospheric window,
- -55°C (or 228K) for radiation at the tropopause (coldest altitude, and therefore where the radiation is least powerful) (blue vertical band corresponding to CO_2 : the small redent is noted in the centre, due to the fact that the CO_2 radiates, in the middle of its band, in the stratosphere, which is warmer, as well as the two lateral pins, also a little warmer),
- of the order of -18°C (or 255K) approximately, for the radiation :
  . of water vapour at the average altitude of the cloud top (pink vertical bands) (rather -33°C or 240 K below 400 cm^{-1}),
  . but also from the top of the ozone (grey absorption band) to the top of the stratosphere, where the temperature is higher than at the tropopause.

The total OLR being equal to 240 W/m², the Earth evacuates them to the cosmos by radiation as follows :

- **17 W/m²** from the Stratosphere (grey band O3) (the stratosphere has its own balance and restores what it has absorbed),
- the **22 W/m²** radiated directly from the ground to the cosmos (seen above : atmospheric window),
- **190 W/m²** from atmospheric water vapour
  . a part in the band of the atmospheric window (between 800 and 1200 cm-1), coming from a relatively low altitude (top of the continuum) to a high temperature (white bands),
  . a part, outside this band, at the top of the water vapour, therefore higher, therefore colder between 500 millibar and the tropopause ;
- **10 to 12 W/m²** by the top of the tropospheric CO_2 (in the band 610-7350 cm-1, or 18 to 22 THz : blue band).

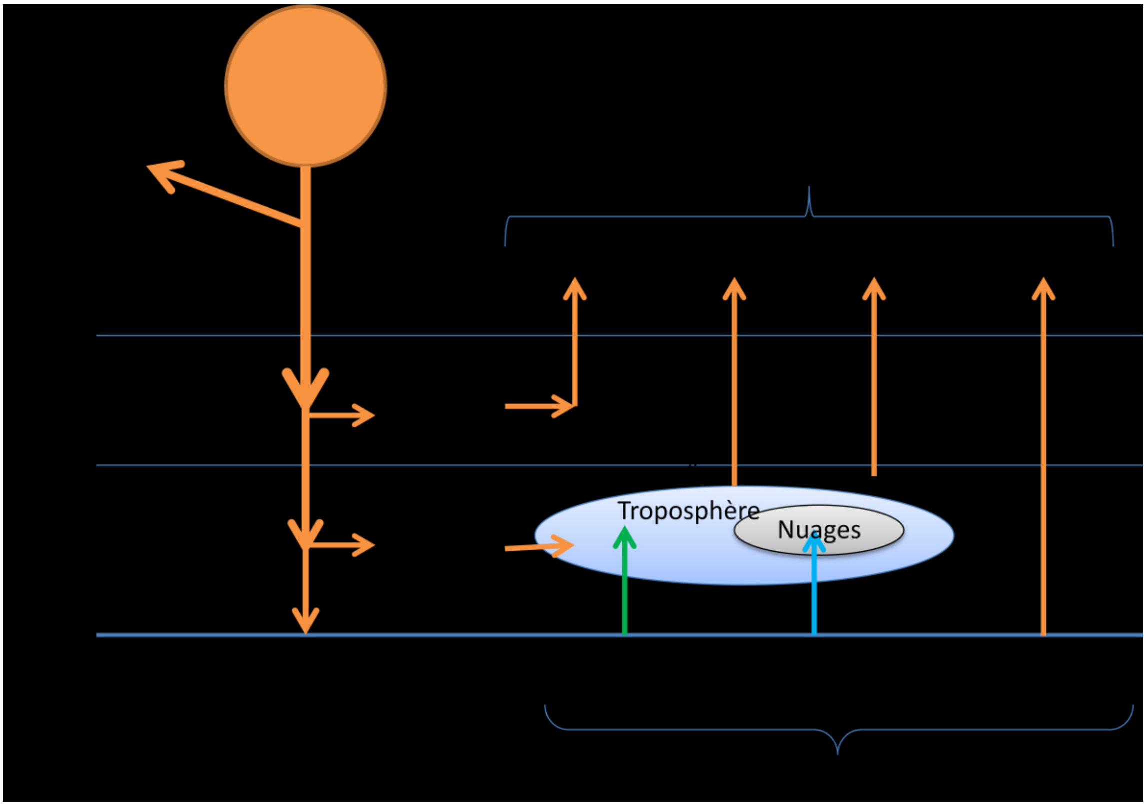
(These are, of course, orders of magnitude, as the boundaries between bands are not clear).

It is the sum of these four **very different bands** that makes the total of 240 W/m², but each of the four bands has its own regulation ensured by the movement of air and the transport of water vapour.



Infrared view of the earth (January 2015). (grayscales correspond to the temperatures (and therefore altitudes) of emissions into space. Black = cold, thus high)

We therefore have the following overall radiation balance :



9. What about the CO_2 in all this ?

We have seen in the above that the influence of CO_2 seems to be completely secondary :

- it does little to warm the Earth in the radiation from the Sun,
- it blocks very little of the earth's radiation towards the cosmos : 11 W/m^2, or barely 5% of the OLR.

Nevertheless, given the importance that "climatologists", media, and politicians attribute to it, we cannot avoid the subject.

Two questions arise :

1. The concentration of CO_2 in the atmosphere is currently increasing by about 2 ppmv/year : what is the share of man in this increase? How far can it go up?
2. What would be the impact on temperature (and therefore climate) of a doubling of this concentration? It is indeed a reference for the IPCC to assess its dangerousness.

At the beginning, we wanted to devote a specific chapter to CO_2 and its cycle to answer the first question.

But the subject proved too vast and complex to be the subject of a single chapter, and we preferred to deal with it in a separate book.

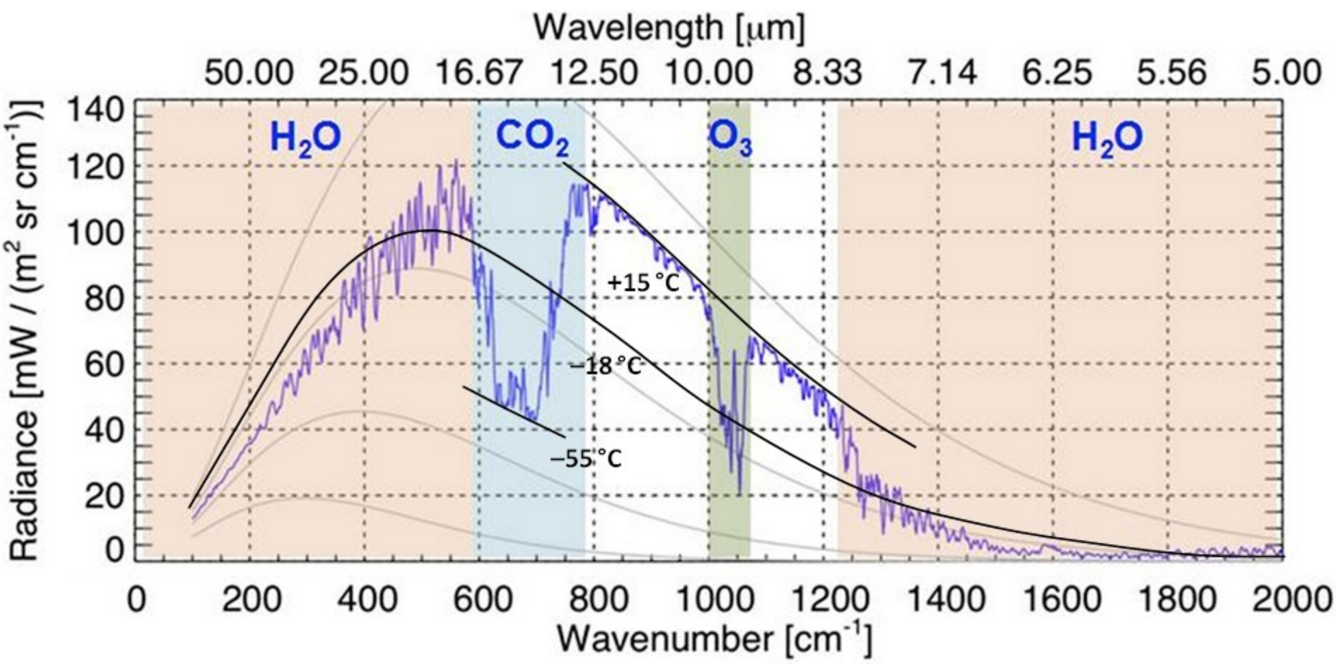
We will therefore only deal with the second question here, knowing that at the current rate of increase of 2 ppmv/year, a doubling of concentration will take 200 years.

10. Climate Sensitivity to CO_2

By definition, **climate sensitivity** to CO_2 is the increase in temperature that would result from a **doubling of the atmospheric concentration of CO_2**.

10.1. Overview

As we have seen, after deducting albedo, the Earth receives an average of **240 W/m²**, and currently evacuates them, to remain in equilibrium, according to the **OLR** (Outside Longwave Radiation) spectrum below as an example :



If the albedo does not change (and we will ignore such a possible change here), this value of 240 W/m² remains unchanged regardless of the Earth's atmospheric changes : it is solar radiation that must be returned to the cosmos.

However, the distribution in this spectrum may change, depending on how :

- how these 240 W/m² are redistributed when they cross the atmosphere on the way down,
- how soil surface and atmosphere restore 240 W/m² to the cosmos,
- how, in the end, establishes a new balance :
  - . at ground level (which is what we are most interested in as inhabitants of the Earth)
  - . but also at each remarkable altitude of the atmosphere, depending on what is radiated at that altitude.

10.2. CO_2 alone

Before analysing the other parts of the OLR diagram, let us focus on the CO_2 itself : as soon as the CO_2 concentration doubles in the atmosphere, two absorption phenomena occur :

1. Absorption of radiation from the Sun,
2. Absorption (or retention) of terrestrial infrared radiation :
   - . at the top of the troposphere,
   - . at the bottom of the troposphere (near the ground),
   - . on the edge of the Atmospheric Window.

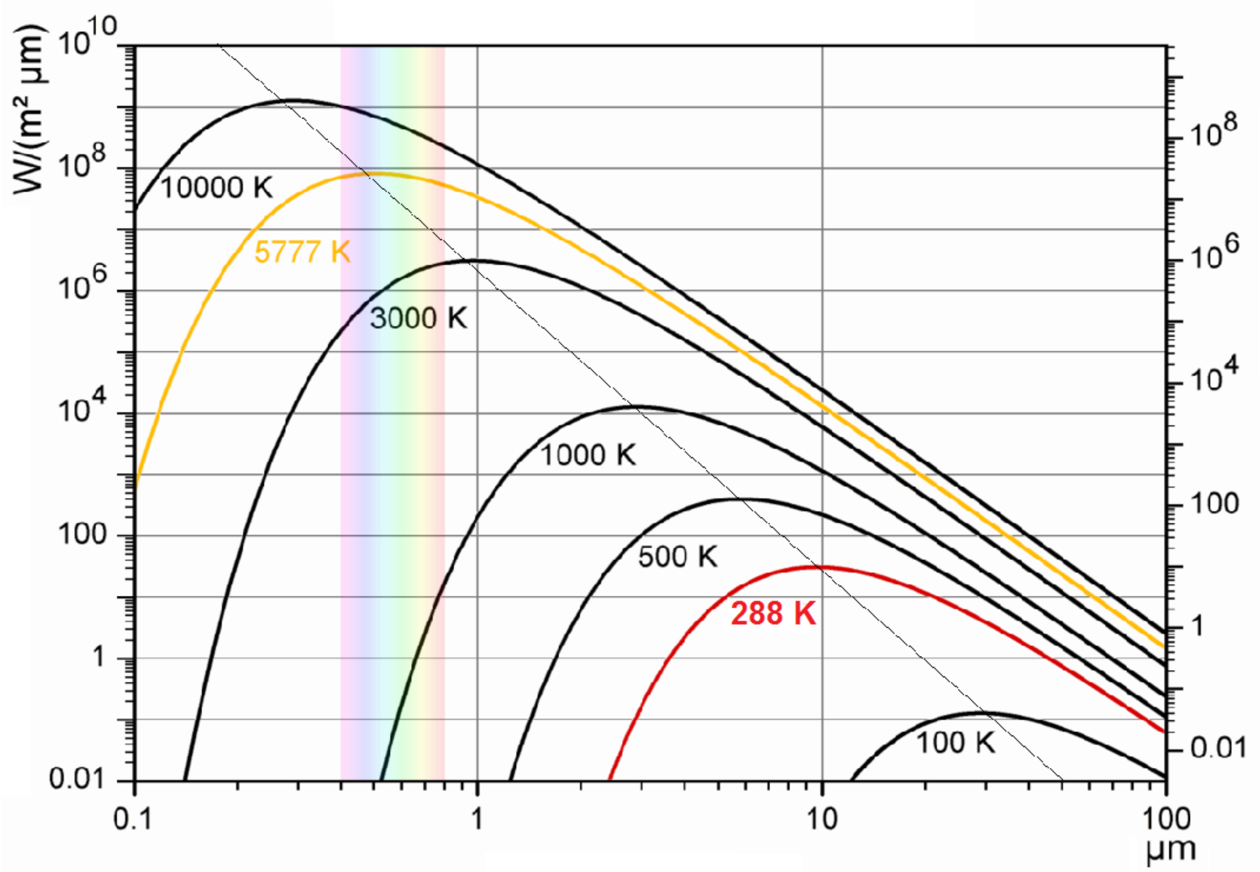
We will analyze these factors successively :

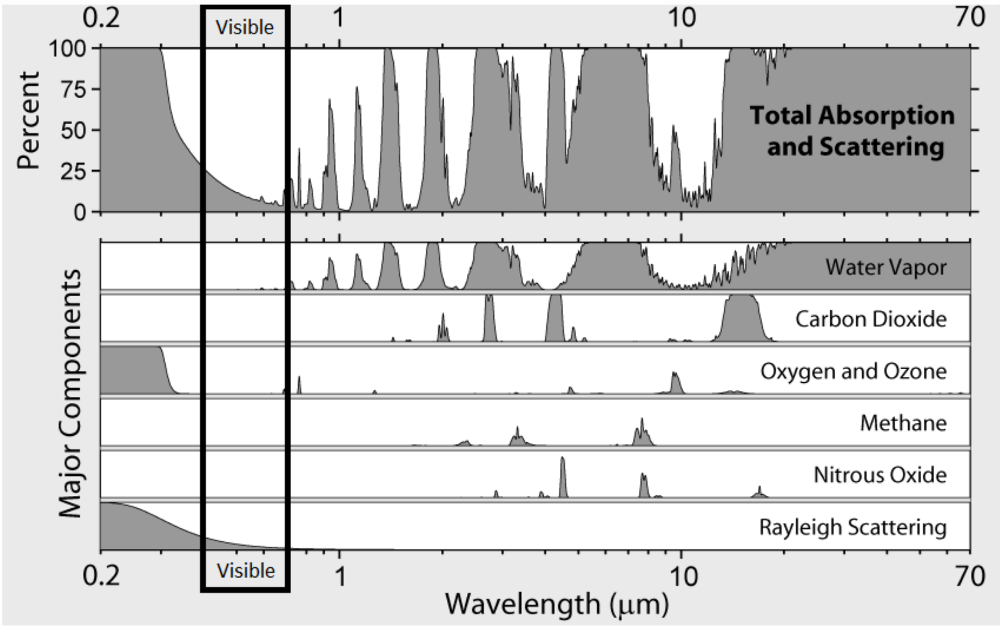
10.2.1. Impact on Solar Radiation

The CO_2 absorption bands located in the solar spectrum (yellow curve 5777 K) (around 2, 3, and 5 µm) will absorb, in the stratosphere, a larger part of its radiation, in the order of **0.4 W/m^2** (generally accepted) on daily average, for a doubling.

This absorption will contribute to warming the stratosphere instead of warming the troposphere and the surface.

And because of its stratification, the stratosphere will directly return this supplement by radiation.



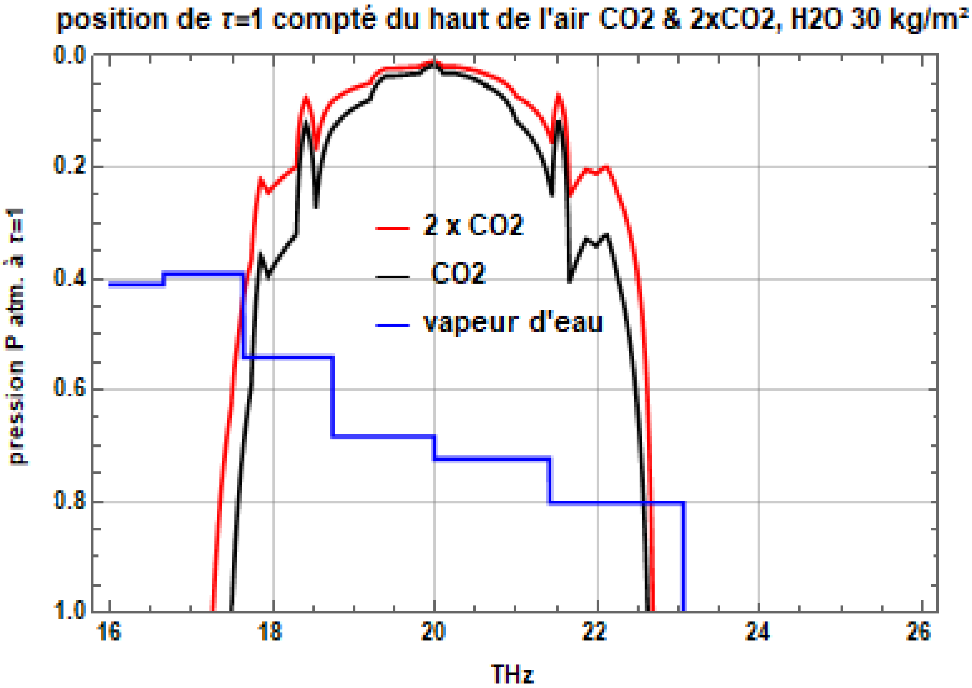


Solar radiation balance :

- **the stratosphere gains 0.4 W/m^2 and re-emits it directly,**
- **the troposphere and the surface lose 0.4 W/m^2.**

10.2.2. Impact on thermal infrared radiation "at the top of the CO_2".

The main CO_2 absorption band (600-750 cm-1 or 18 THz at 22.5 THz) is increasing, and therefore, at the "top" of the CO_2, the tropospheric thermal radiation is released higher (red against black) :



When zooming in, we see that a doubling essentially affects the emission altitude of two small dewclaws, located on either side of the absorption band.

Note : the deviation on the left side band (17.2 to 17.7 Thz) can be ignored, as it is included (and therefore already counted) in the water vapour band.

The rising radiation, above the two dewclaws of 0.7 THz width, is therefore released higher (approximately from 0.35 to 0.25 atm. (or from 8,500 to 11,000 m), at an altitude where the air is colder : due to the Lapse Rate, the evolution of the temperature T (from the ground at 288 K) as a function of the altitude expressed in pressure (in atm.) is : $T = 288\ P^{0.19}$.

Note R(f, T) the radiation power [3] in W/m²/THz at the frequency f (in THz) of a surface at the temperature T (in Kelvin):

- Before doubling : $0.7\ (R(18,\ 288 \times 0.350^{0{,}19}) + R(22,\ 288 \times 0.3^{0{,}19})) = 0.7\ (7.1 + 4.9) = 8.4$ W/m²
- After doubling : $0.7\ (R(18,\ 288 \times 0.250^{0{,}19}) + R(22,\ 288 \times 0.2^{0{,}19})) = 0.7\ (5.6 + 3.4) = 6.3$ W/m²

Following a doubling (CO_2 only), the upper troposphere retains : 8.4 - 6.3 = 2.1 W/m².

Note : Strictly speaking, since gases are not black bodies, and their absorption bands are made up of non-jointed lines, a more precise calculation would require taking them into account, for example by making a calculation where the optical thickness is equal to 0.4 instead of 1 ; but this does not change the orders of magnitude.

10.2.3. Impact on the Infrared Radiation "at the Bottom of the CO_2", from Air to the Surface.

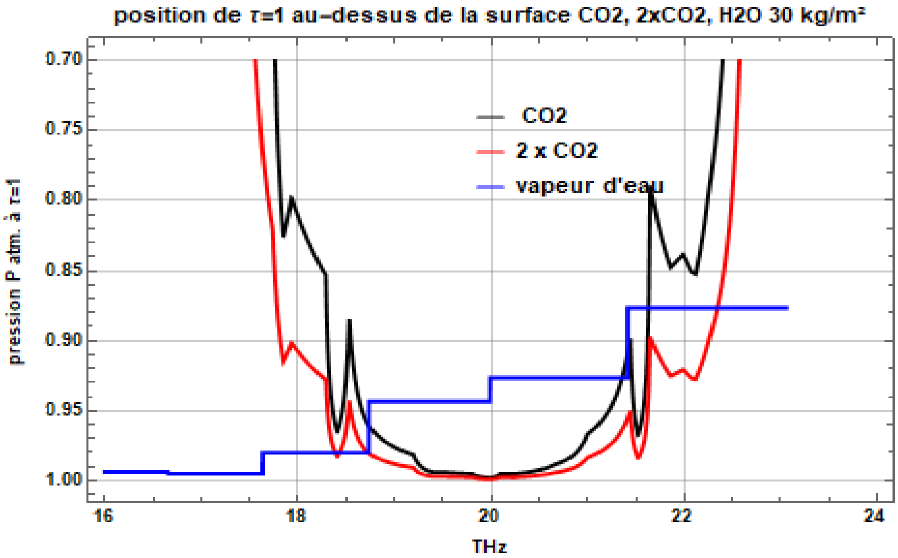
We saw in Chapter 8 that the thermal radiation Air <-> Surface was balanced, both being statistically at the same temperature.

The air radiates from an altitude where its optical thickness, seen from the ground, is equal to 1, defining in a way the lower boundary of the opacity of the atmosphere.

[3] Planck Law (reminder) : radiated power on a frequency interval df by a black body surface :
$R(f, T) = 0.0463\ f^3 / (e^{(48\ f\ /\ T)} - 1)$ where (f in THz, T in K)

The graph below illustrates this boundary : in blue for water vapour, in black and red (after doubling) for CO_2 : it is the counterpart, at the bottom of the troposphere, of the previous graph at the top : it is from these altitudes that the atmosphere radiates towards the surface (or blocks the radiation from the surface, which is the same).

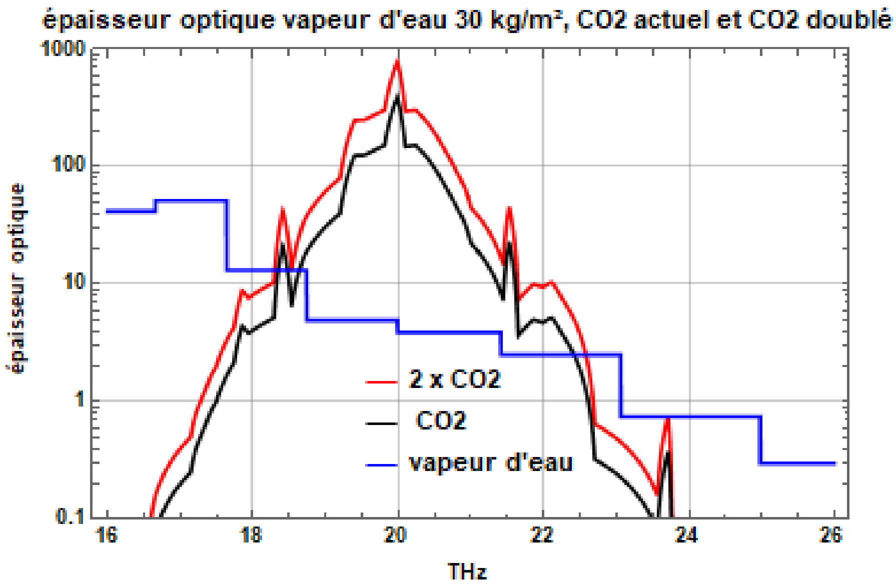
If the CO_2 concentration increases, the "dewclaw" of the CO_2 at 22 THz passes under the water vapour, and will therefore radiate towards the surface from below (red against blue of the water vapour), ... and therefore warmer (by applying the Lapse Rate) (the other dewclaw (18 THz), being masked by the water vapour, has no incidence).



The same calculation as in the previous paragraph gives an evaluation of 1.1 W/m^2.

Following a doubling (CO_2 only), the surface receives an additional 1.1 W/m^2.

10.2.4. Impact on Radiation in the Atmospheric Window.



Around 23 to 24 THz (far left of the atmospheric window), the CO_2 absorption band, as it widens, closes part of the atmospheric Window, blocking part of the 22 W/m^2 of direct radiation to the cosmos emitted by the ground surface in this Window : about 0.8 W/m^2 per clear cloudless sky, or 0.3 W/m^2 (taking into account clouds).

Following a doubling (CO_2 only), due to the partial closure of the atmospheric window, the soil surface retains 0.3 W/m^2.

10.2.5. Globally

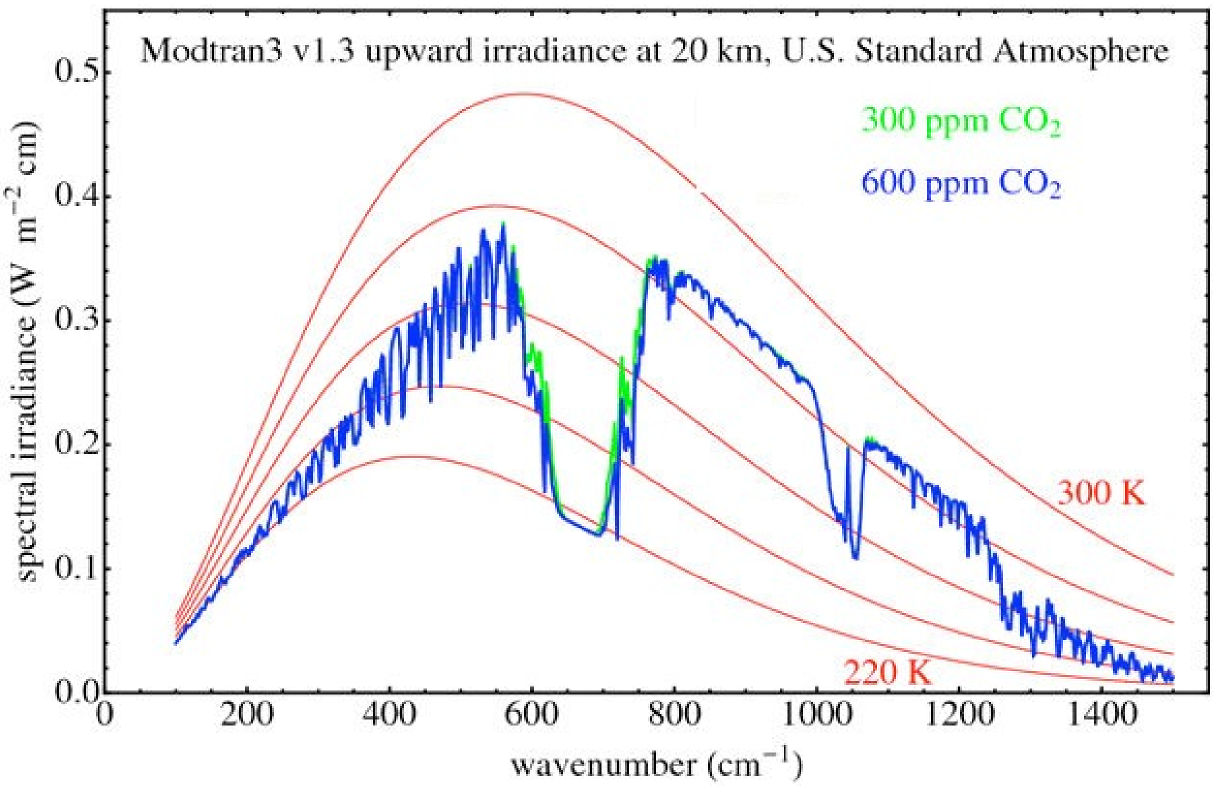
To balance a doubling of CO_2 as the only incident factor :

- The surface will have to evacuate an additional :
  - 1.1 W/m^2 (IR radiation from CO_2 to the ground)
  - 0.3 W/m^2 (partial closure of the atmospheric window)
  - - 0.4 W/m^2 (solar radiation absorbed by stratospheric CO_2 and with no surface area)
  - **thus a total of 1 W/m^2**
- The (upper) troposphere will have to evacuate an additional :
  - 2.1 W/m^2 (decrease in IR radiation at the top of the CO_2 to the cosmos)
  - the 1 W/m^2 (evacuated from the ground and recovered by the troposphere, provided the ground can balance them)
  - **thus a total of 3.1 W/m^2**

Note : in fact, the exact values do not matter, and different values can be found in the literature : but the orders of magnitude are there, and the reasoning we will follow applies to any values.

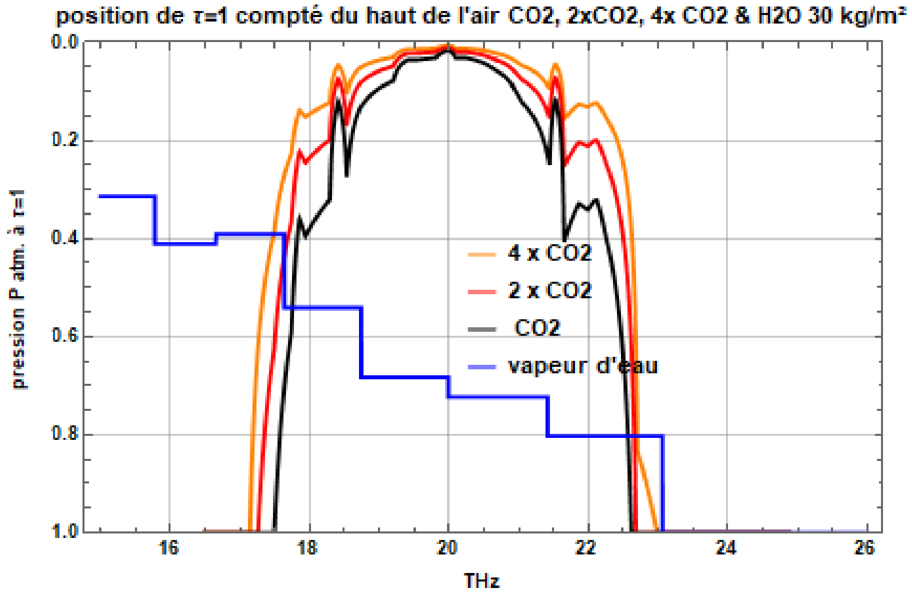
To illustrate the incidence of CO_2, the OLR (Outgoing Long-wave Radiation) is affected as follows (graph below, blue versus green) : we see in particular the incidence of the two small CO_2 dewclaws discussed above.

Note 1 : The US Standard Atmosphere, to which this graph refers, is relatively less humid than the average.



Note 2 : this (rather old) graph refers to a doubling of 300 to 600 ppmv, but, as we have seen, any doubling produces the same effect proportionally, ...

... although a new doubling would have a partially opposite effect, because the radiation emitted "higher" would then occur in the stratosphere (altitude above 0.2 atm.), which is warmer than the top of the troposphere : it would therefore be warmer (and not colder), and therefore more powerful.

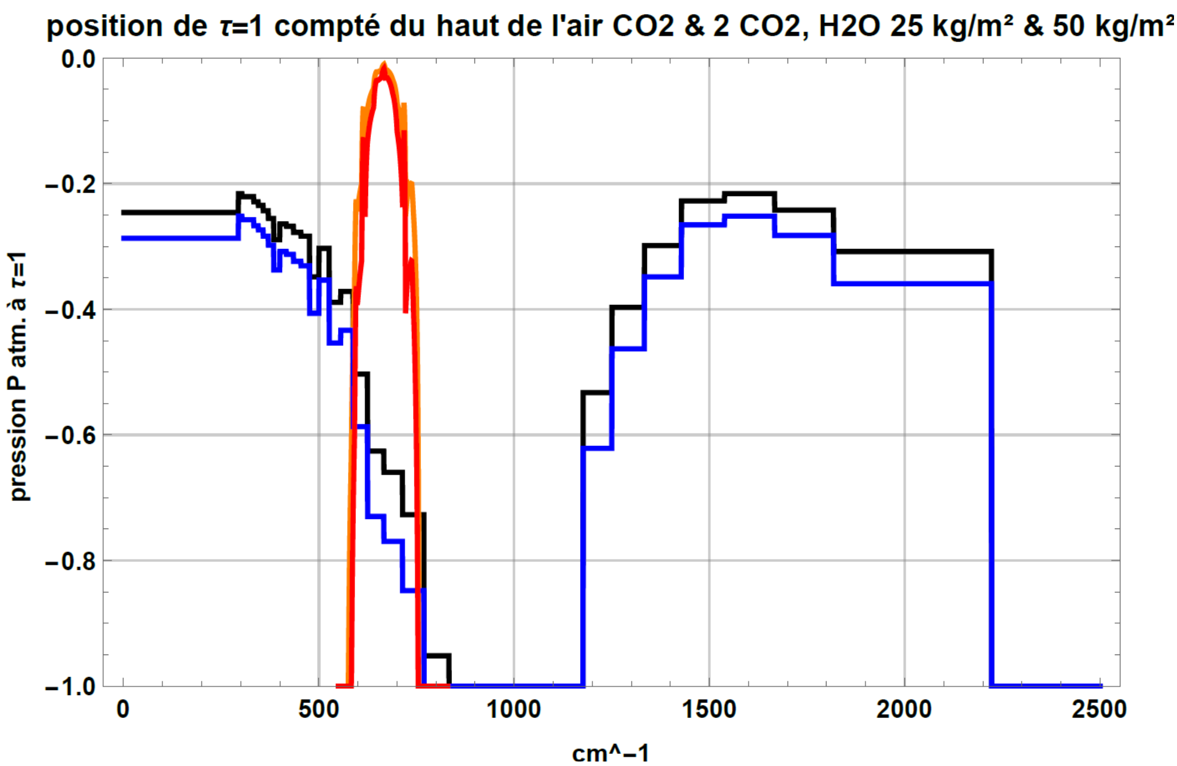


Subsequently, **as a (very) conservative measure**, we will consider that the 2.1 W/m^2 retained at altitude (the two lateral dewclaws of the CO_2 band) can only be evacuated by a temperature increase in the troposphere, which would then be reflected on the ground, due to the Lapse Rate, which would then make a **total on the surface of 3.1 W/m^2**, producing a temperature increase of :

$$\mathbf{dT = dM / (4\ \varepsilon\ \sigma\ T^3) = 3.1 / (0.204\ (288/100)^3) = \underline{0.64°C}}$$

10.3. Impact of Water Vapour : the Controversy

As soon as the ground temperature increases, due to the doubling of the CO_2 concentration, evaporation increases accordingly (7% per °C), and the same consequences can be expected as for CO_2 (black curve : radiation emitted higher, therefore at colder temperature), but over a much wider spectrum width, ... thus causing additional warming :



But :

- on the one hand, evaporation cools the soil surface very effectively, and that is still what we humans are most interested in,
- on the other hand, unlike CO_2, whose concentration does not vary with altitude, the concentration of water vapour decreases as altitude increases, due to its condensation, and therefore, intuitively, the "higher => colder" of water vapour radiation probably has a limit (at least in the stratosphere where the temperature rises).

This complexity gives rise to controversy, which is the main source of opposition between :

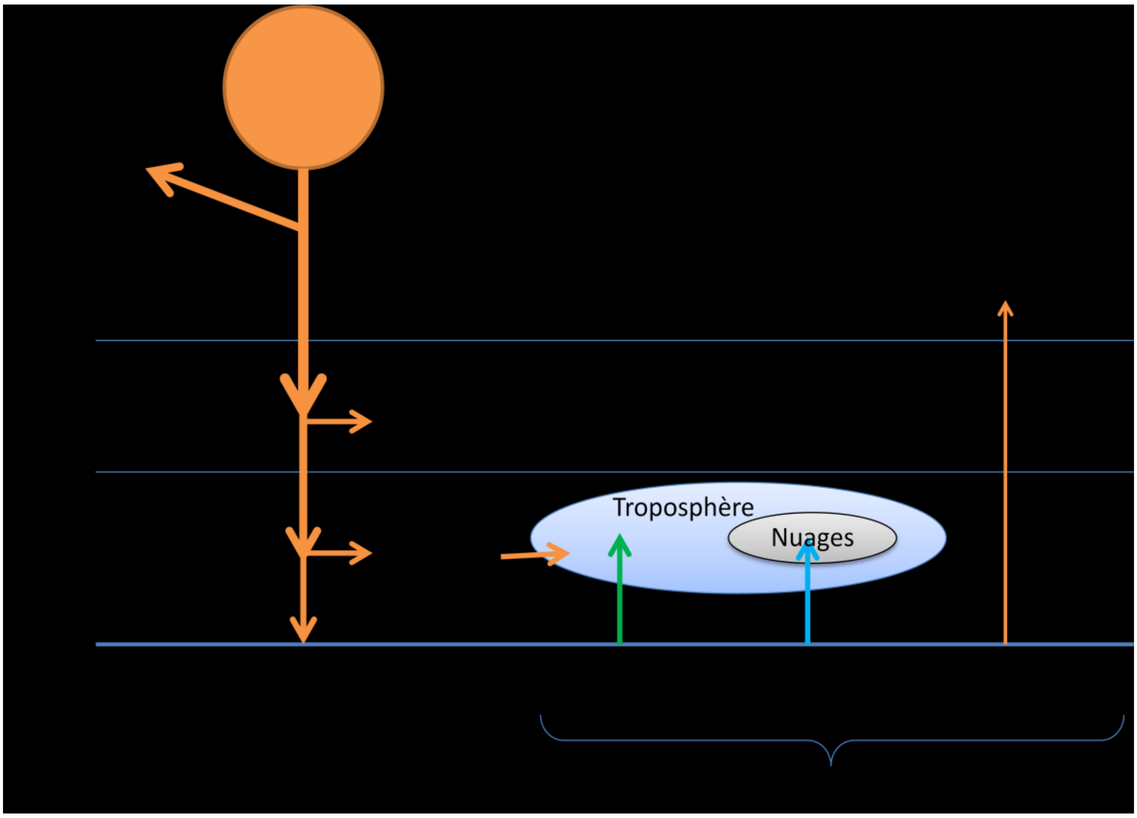
- on the one hand, "alarmists" (including the IPCC), for whom water vapour is an amplifier of global warming (the IPCC refers to "positive feedback"),
- on the other hand, the "skeptics" who, in the absence of evidence, question this IPCC position, and even think that water vapour has a compensatory and regulatory effect (stabilizing "negative feedback").

We will try to resolve this controversy by analysing the phenomena one after the other, as follows :

1. evaporation resulting from ground heating,
2. effect of this increase in evaporation on the OLR.

10.4. At the Ground Surface

Reminder :



10.4.1. Impact on Evaporation

The first question to ask is : does the cooling associated with an evaporation supplement compensate for the warming induced by the doubling of the CO_2 concentration?

We have seen (conservative hypothesis) that in the absence of water vapour, of 15°C (288 K), the average surface temperature would rise by **0.64°C**, corresponding to a radiation retention of **3.1 W/m^2**.

As also mentioned above, terrestrial evaporation evacuates on average 96 W/m^2. And each additional degree increases this evaporation by 7%.

So, if the ground surface heats up by 1°C, the additional evaporation will allow the evacuation of :

96 x 7% x 0.64 = 4.27 W/m^2, so higher than what has to be evacuated (3.1 W/m^2).

And since each °C causes 7% additional evaporation, to remove 1 W/m^2, this compensation only requires 7% x 3.1/4.27 = 4.92% additional evaporation, and the temperature would finally only rise by 0.64 x 3.1/4.27 = 0.45°C.

The same reasoning would apply if the flow to be evacuated were higher : it would always remain lower than the flow generated by the evaporation it would cause.

10.4.2. Impact on direct Radiation through the Atmospheric Window

However, there is a perverse effect : if the ground temperature increases, the water vapour concentration also increases, and its optical thickness follows, including in the continuum : thus, the Atmospheric Window undergoes two cumulative shrinkages :

- the 0.3 W/m^2 previously seen, due to the doubling of CO_2 concentration, and already counted, and which reduces the direct radiation Surface to Cosmos to 21.7 W/m^2 instead of 22,
- a new shrinkage due this time to the resulting increase in water vapour concentration.

Indeed, an increase of 0.45°C, resulting in an additional evaporation rate of 3.22% (7% per °C), would increase the optical thickness of the water vapour share in the Atmospheric Window by the same proportion, from 0.5 to 0.516.

The overall (statistical) optical thickness of the Atmospheric Window would then increase from 1 to 1.016 (the proportion of clouds being assumed to be unchanged).

However, $\mathbf{M/M_0 = e^{-t}}$, therefore dM = -t M_0 and dt= - M_0 / e = -22 x 0.016 / 2.71828 = - 0.13 W/m^2

And so, for an initial overload of 3.1 W/m^2 due to the doubling of the CO_2 concentration, it is therefore necessary, because of the Atmospheric Window, to finally evacuate 3.23 W/m^2.

But then, the evaporation increases accordingly, no longer by 3.22%, but by 3.22 x (3.23/3.1) = 3.22 x (1+0.04), which leads to a further narrowing of the atmospheric window, ... and so on : the calculation should be repeated on the basis of a 4% increase with each iteration.

However, the series 1 + 0.04 + 0.04^2 +... converges towards 1/(1-0.04) = 1.04

Finally, for 3.1 W/m^2 due to the doubling of the CO_2 concentration, it is finally 3.1 x 1.04 = 3.23 W/m^2 that the evaporation must evacuate.

... corresponding to a **temperature increase** of : 0.46 x 1.04 = **0.48°C**.

We have here an extremely effective regulation system : except locally or temporarily, **on the ground (and this is what interests us humans most), the system is stable : globally, evaporation compensates for the increase in radiance due to the doubling of CO_2 concentration with a very small temperature increase : less than 0.5°C**.

10.4.3. By Convection

If the temperature at the ground surface rises, convection also increases, in proportion to the temperature (increase in the Archimedes' thrust of the gas due to its expansion), according to PV = RT (law of perfect gases).

If the ground temperature increases by 0.5°C, the convection evacuation increases by 0.5 / 288 = **0.17%**.

As a precautionary measure, we will neglect this influence.

10.4.4. Balance at the Ground Surface

We are facing a kind of vicious circle : the higher the temperature rises, the more evaporation there is to compensate for it ; but the more evaporation there is, the less the atmospheric window radiates from the ground towards the cosmos, which raises the temperature.

But it is a false vicious circle : physically, at a temperature T, any increase in temperature causes :

- an increase in radiative flux proportional to the cube of temperature : **$4\ \varepsilon\ \sigma\ T^3 = 20.4 \times 10^{-8} \times T^3$**
- additional evaporation proportional to temperature (7% / °C) compensating for a radiative flux of **96 x 7% = 6.72 W/m^2/°C**

As long as **$20.4 \times 10^{-8} \times T^3$** remains below **6.72 W/m^2/°C**, evaporation is able to remove any increase in radiative flux ; the limit corresponds to T3 = 6.72 x 108 / 20.4, i.e. a soil surface temperature of 329 K or 56°C :

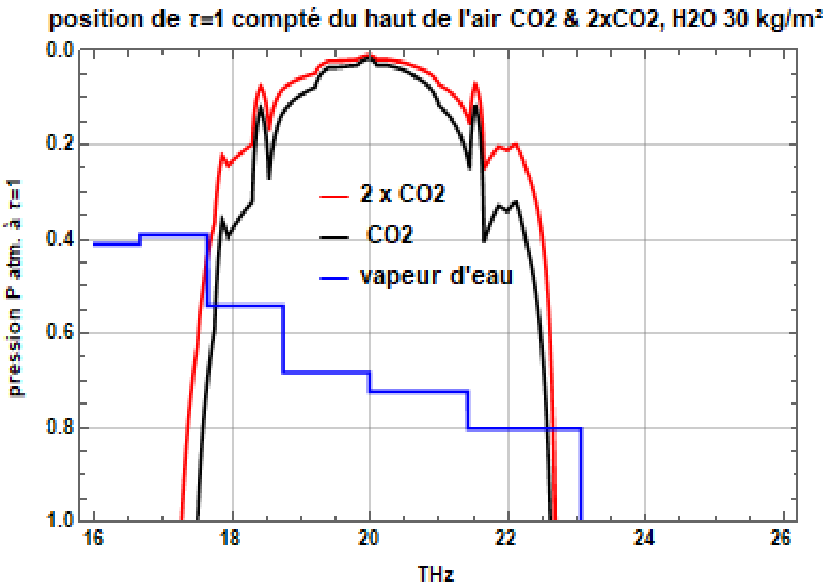
In other words, as long as the ground temperature does not exceed 56°C (on average), evaporation compensates for any increase in radiative flux, and therefore in temperature related to such an increase, whatever the cause.

Fortunately, all oceans are below 56°C, and the higher temperature land areas are mostly desert, therefore dry, and therefore the radiation from the Atmospheric Window is very little blocked.

10.5. On Top of the Water Vapor

But this ground equilibrium could not be maintained if, at the top of the atmosphere, this additional water vapour blocked the evacuation of the 3.1 W/m^2 : the temperature at altitude would rise and would be reflected on the ground via the Lapse Rate.

Note : of these 3.1 W/m^2, only the 1 W/m^2 from the ground is concerned : indeed, the 2.1 W/m^2 of the two CO_2 dewclaws, which, as a precautionary measure, we have included in what the ground had to release (due to the Gradient Gradient), are both above the radiation altitude of the water vapour.



And so, these 2.1 W/m^2 should simply be balanced by a temperature rise at the top of these dewclaws, at an altitude of about 0.2 atm. near the tropopause.

For the rest (1 W/m^2) :

10.5.1. Simplifying Hypothesis : upper Atmosphere saturated with Water Vapor

We will see later that this hypothesis is purely theoretical, and that this is not the case in reality, but it has a pedagogical interest.

The **saturated vapour pressure** is given by the Clapeyron formula (which we will not give here for simplification purposes) ; **it depends only on the temperature**.

Likewise :

1. the **radiative altitude** of the water vapour, linked to its transparency, depends only on its concentration, and therefore on its partial pressure, which, in a saturated atmosphere, is equal to the saturated vapour pressure ; which also **depends only on temperature**.
2. **the radiative flux ($M = \varepsilon \sigma T^4$) also depends only on the (emission) temperature**.

As a result, if the atmosphere is saturated with humidity, the emission altitude and radiative flux are both attached to each other via temperature : if the temperature shifts upwards or downwards, the emission altitude follows, and the flux remains unchanged.

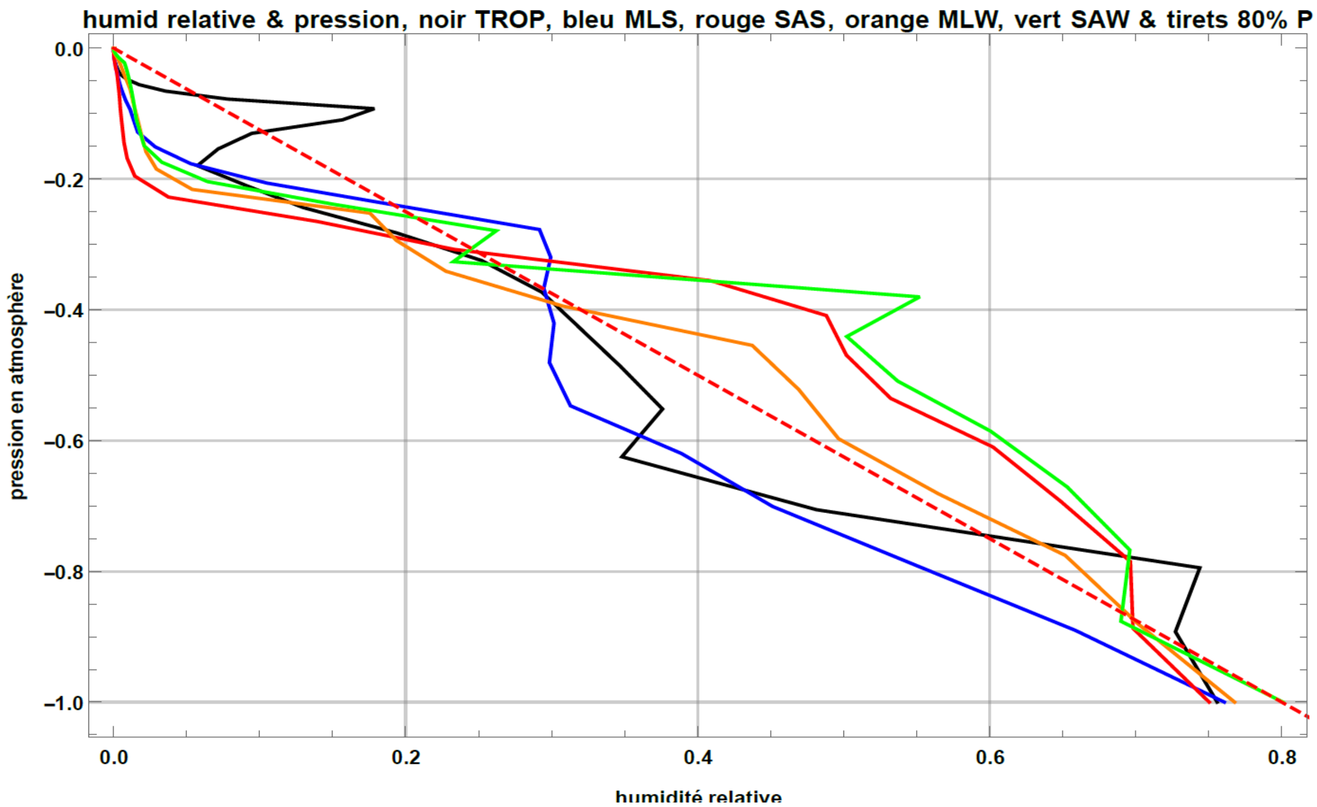
Even higher, the radiation of water vapour would still have the same power, and therefore could not compensate for an increase in tropospheric temperature.

... with a limit : the tropopause : because above, the temperature rises, without the air being saturated with humidity since there is no convection, and therefore, the top of the water vapour can radiate more strongly.

10.5.2. The Reality of Water Vapour : relative Humidity decreases with Altitude

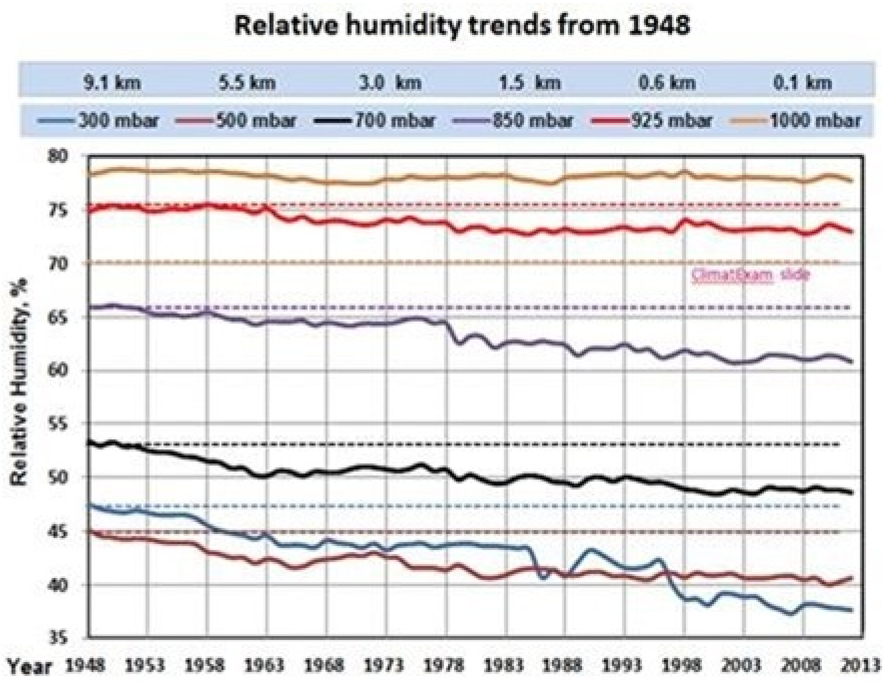
Physically, the saturated vapour pressure, and therefore the maximum vapour concentration (theoretical, excluding oversaturation), decreases as a function of temperature, and therefore of altitude.

But, what is more unexpected, in the observed reality, the relative humidity, i.e. the proportion of steam in relation to this maximum value, also decreases, from 75% on average on the ground, to less than 10% at the tropopause level : this is what the "typical profiles" (i.e. the compilation of a very large quantity of observations) show :



TROP = intertropical zone ; MLW and MLS = Mid Latitude Winter and Subarctic ; SAW et SAS = Subarctic Winter and Summer.

Confirmation NOAA : source : http ://www.esrl.noaa.gov/gmd/aggi/ :



In other words, with altitude, the actual water vapour concentration decreases faster than its saturated vapour pressure.

This observation is totally counter-intuitive : one would rather expect that the warm air, as it cools as it rises to altitude (convection), would become more and more saturated, to the point of forming clouds... until the tropopause.

But convection works in both directions : by mixing as it descends, cold air, which, even saturated, contains little water vapour, mixes with lower, therefore warmer, air, lowering its relative humidity ; ... and so on.

There is probably another additional explanation : at very high altitude and very low temperature, the concentration of water vapour does not saturate in relation to liquid water (absent at this altitude where supersaturated vapour is transformed directly into ice), but in relation to ice (omni-present in tiny particles that coalesce water directly from the gaseous state (vapour) to the solid state (ice), without passing through the liquid state.

However, the saturated vapour pressure in relation to ice is much lower than that in relation to water, in the report :

$$P_{sat/ice} / P_{sat/water} = (T / 273)^{2.45}$$

e.g. at 233K (or -40°C), $\mathbf{P_{sat/ice} = 68\%\ P_{sat/water}}$

And this gap increases until the tropopause : this reinforces the first explanation above.

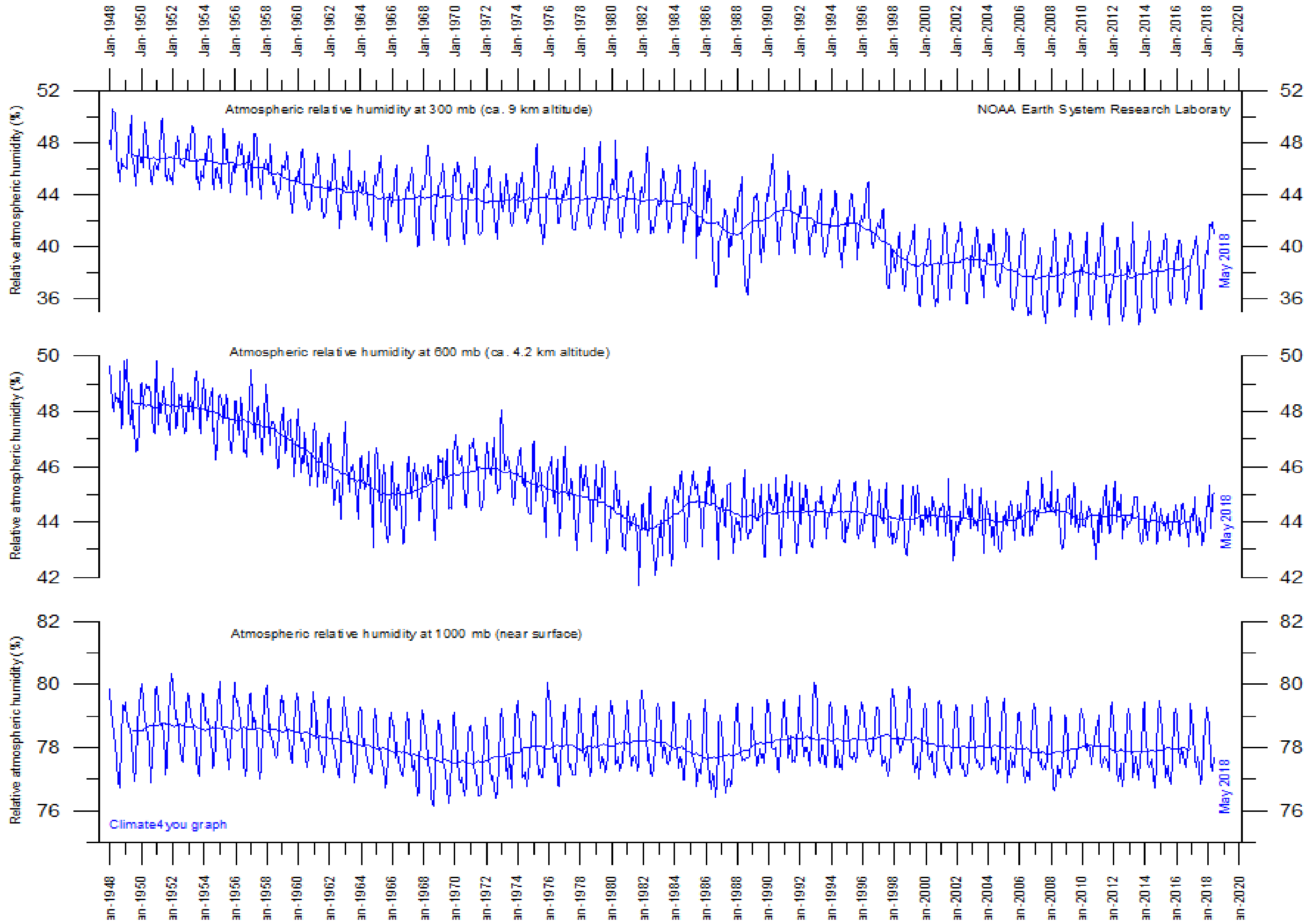
The average value of relative humidity has an almost continuous decrease profile as a function of altitude (the "about" is related to the dispersion of the measurements, and in particular to clouds, which introduce discontinuities in the slope of the above Typical Profiles).

As a result, if the atmosphere is more humid, the temperature at the emission altitude is higher, allowing the excess energy associated with this more humid atmosphere to be removed.

Although it is higher, the radiation of water vapour has more power, and can therefore compensate for an increase in tropospheric temperature. Water vapour therefore has a moderating (not an amplifying, as some alarmists claim) effect on global warming.

10.5.3. ... and even beyond, in time

While the concentration of vapour at ground level has increased (from 1948 to August 2017) (which is also consistent with this increase in temperature : 7% per additional °C),... at altitude, it has decreased, even in terms of relative humidity (upper curve below), which is a priori unexpected, but which allows water vapour to radiate from lower, and therefore even hotter :



10.6. Summary

If the atmospheric concentration of CO_2 were to double (which would take about 200 years at the current rate of 2 ppmv/year), overall, the atmosphere would retain about 3.5 W/m^2 :

- 0.4 W/m^2 in the stratosphere, which would be directly released by direct radiation,
- 3.1 W/m^2 by the troposphere.

At ground level, these 3.1 W/m^2 would, at worst, result in additional evaporation, and a new equilibrium would be established with a maximum temperature increase of less than 0.5°C.

At altitude, these 3.1 W/m^2 should also result in a higher temperature increase (more than 1 °C towards the "top" of the water vapour, according to Stefan Boltzmann's law), but because :

1. the water vapour concentration decreases faster than the temperature when the altitude increases,
2. it also decreases over time at the same altitude,

... these two effects combine to make the water vapour radiate "warmer", and therefore stronger, this additional flow to the cosmos.

And so :

1. **the climatic sensitivity to CO_2 is at most around 0.5°C,**
2. **water vapour has an overall regulating (and not aggravating) effect.**

11. The Reality

Since 1950, the CO_2 concentration has increased from 300 to 400 ppm, an increase of 33%, whose radiative effect is 41% of a doubling (the radiative effect is proportional to the logarithm of the concentration), corresponding to a temperature increase of 0.2°C.

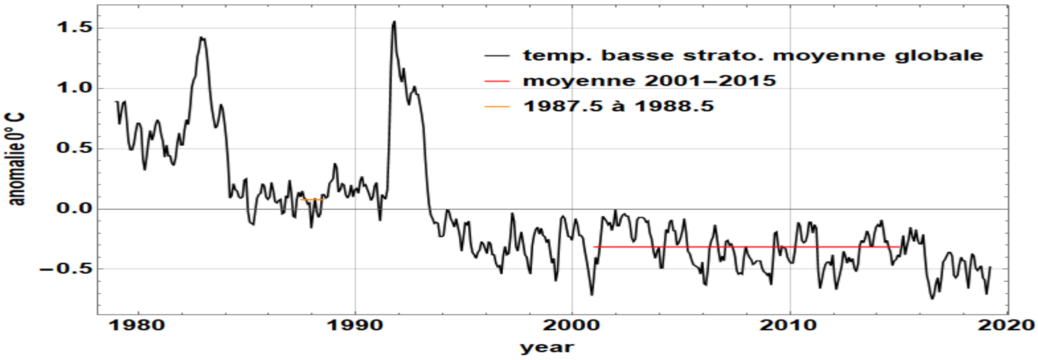
And so, if the temperature has risen by about 0.5°C since then, the increase in CO_2 concentration cannot be the cause (or at least the only cause).

And so, this rise in temperature has other causes. And so we have to go back to the observations :

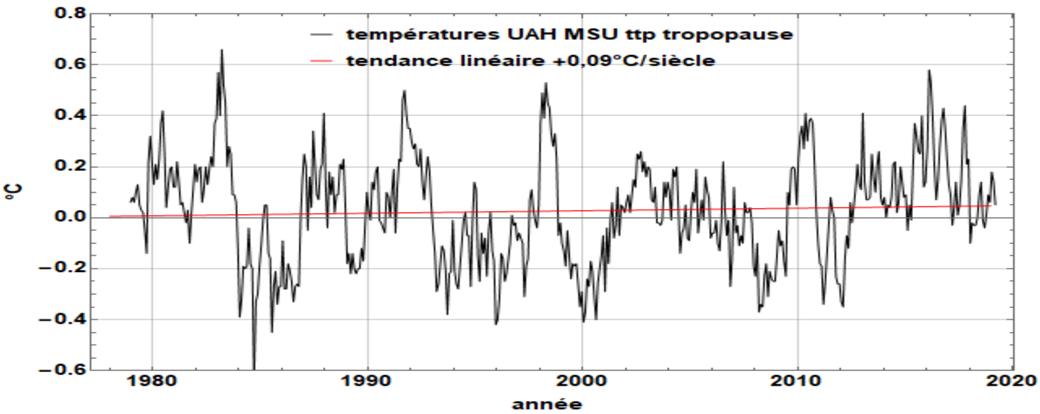
11.1. Temperatures rise faster at Ground Level than at Altitude

Low stratosphere :

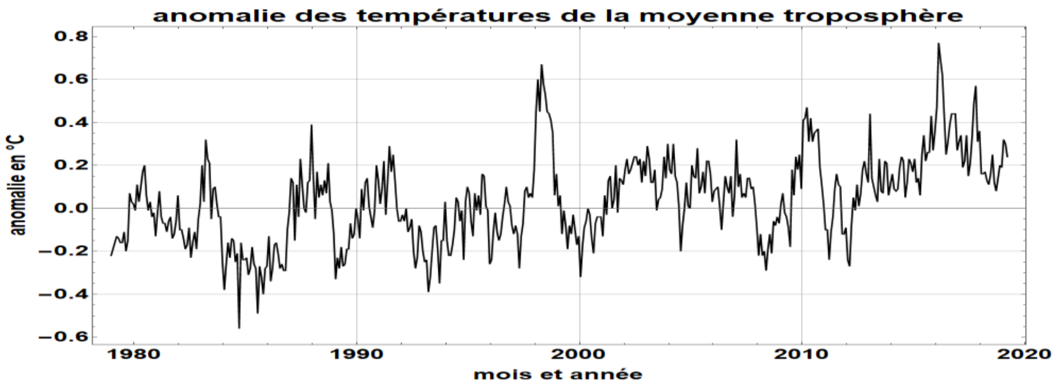
Reflects volcanic eruptions



Tropopause :

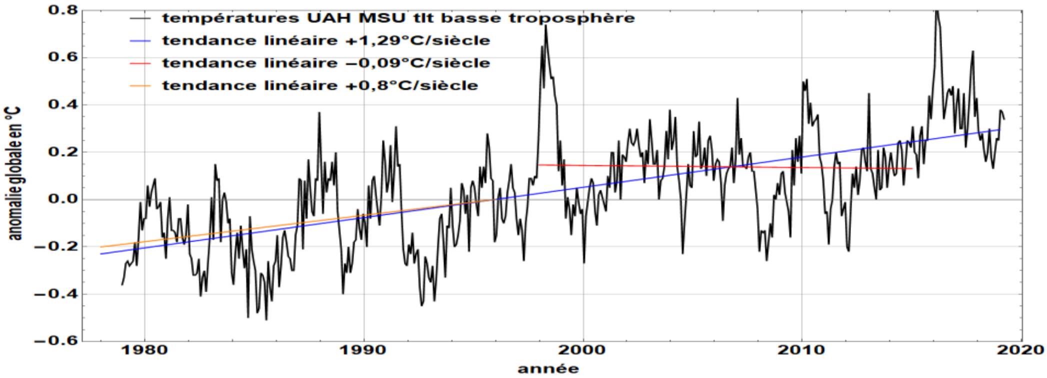


Mean Troposphère :



Low Troposphère :

Reflects El Niños (1998 and 2016)

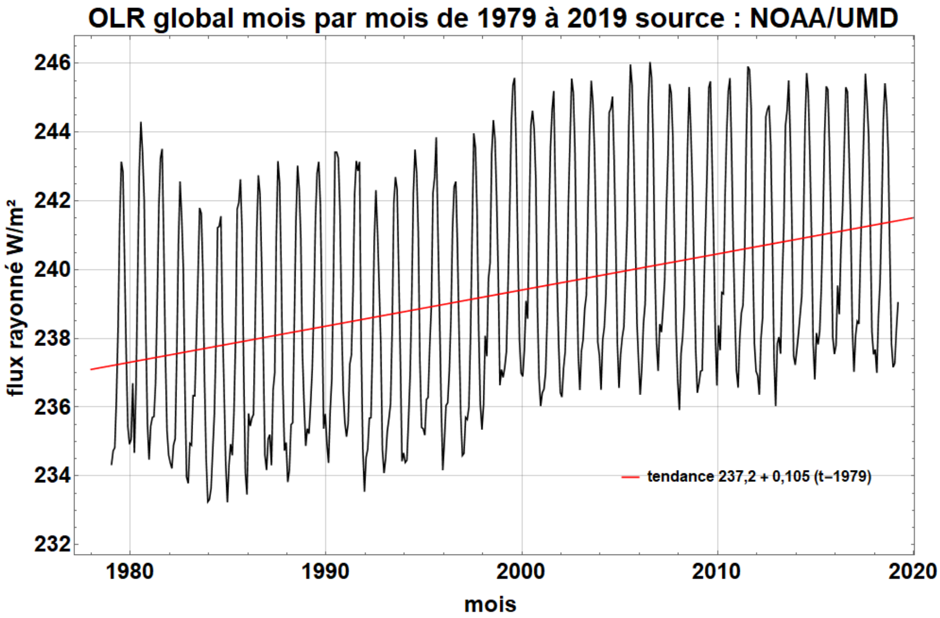


Sources : satellite observations : https ://www.nsstc.uah.edu/data/msu/v6.0/xxx/uahncdc_ls_6.0.txt
where xxx= tls (low stratosphere), ttp (tropopause), tmt (mean troposphère), tlt (low troposphère).

These observations run counter to a "top-down" warming, as it should result from an increase in the concentration of CO_2 (the two lateral dewclaws) and water vapour : these observations show that the warming comes from below.

As a reminder, an increase of 0.5°C (since 1980) at ground level corresponds to an increase in radiance of 2.5 W/m^2 (while the CO_2 concentration has increased by less than 25% over the same period).

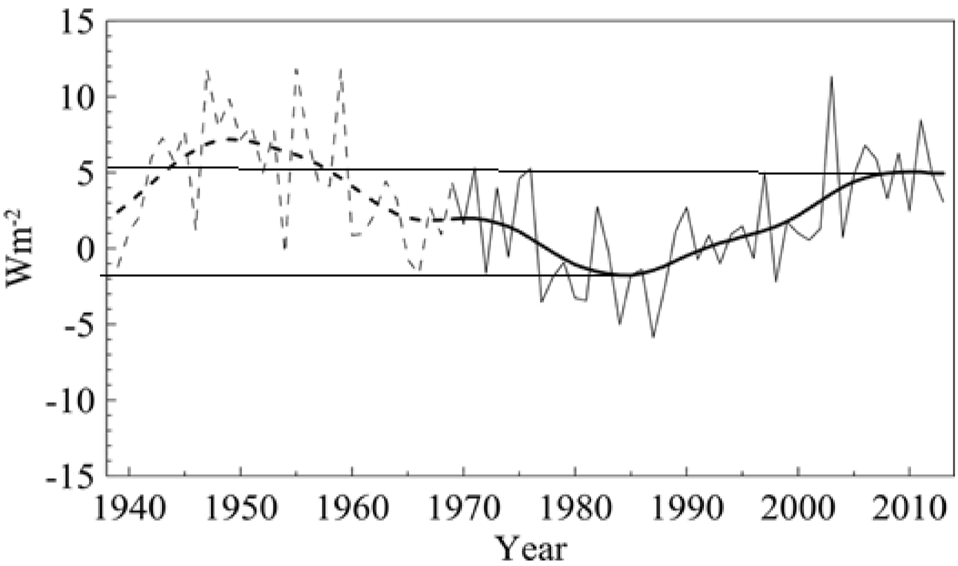
11.2. The OLR has increased significantly : 4 W/m^2 since 1980



However, under established conditions, if the OLR increases, it is because the Earth, below its emission altitude, receives the equivalent energy (otherwise, the imbalance would cause the Earth to cool down).

11.3. Ground Level Insolation has been increasing since the 1980s : 7 W/m^2

... which corroborates the increase in OLR.

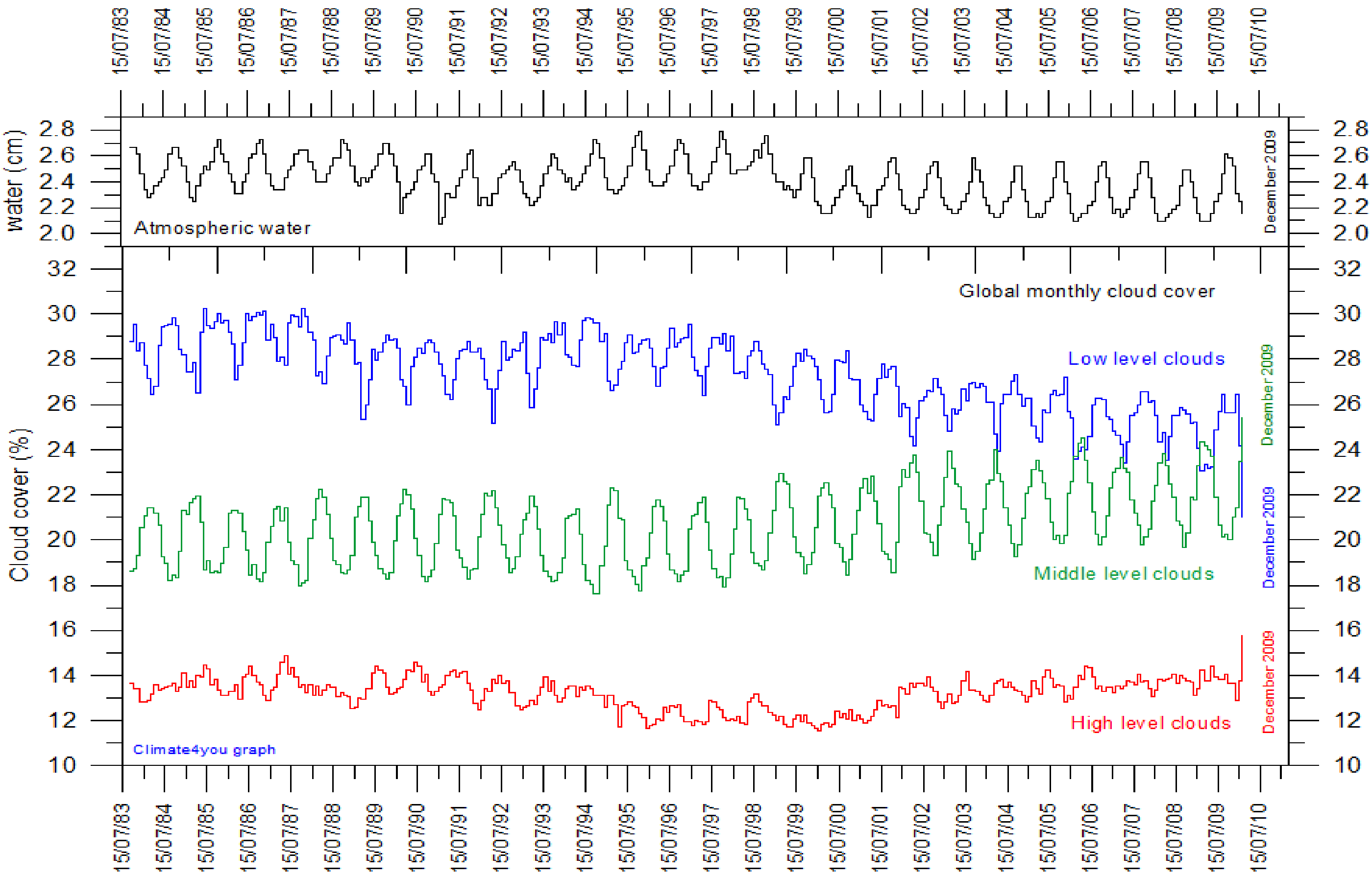


Source : Wild, M. The Global Energy Balance Archive (GEBA) version 2017 : A database for worldwide measured surface energy fluxes [*https ://www.researchgate.net/figure/Composite-of-56-European-GEBA-time-series-of-annual-surface-downward-shortwave-radiation_fig5_319251713*](https://www.researchgate.net/figure/Composite-of-56-European-GEBA-time-series-of-annual-surface-downward-shortwave-radiation_fig5_319251713)

... But solar cycles have too little impact to justify (directly) such amplitudes of variation.

11.4. The Cloud Cover has been decreasing

... especially low clouds, which condition most of the albedo.



As a reminder, 1% less albedo (from 31 to 30% for example) means 3.4 W/m^2 more at ground level.

11.5. Conclusion

If the temperature has increased by 0.5°C since 1980 (and by 1°C for a century), the increase in CO_2 concentration cannot be blamed, or at least only marginally.

Other causes have necessarily occurred, which justify an increase in insolation (and therefore OLR), and which explain that the temperature of the lower troposphere (and therefore at ground level) increases faster than the rest of the atmosphere.

To find out more, it is necessary to continue and expand the observations, without focusing on CO_2, which can only play a marginal role, and finally quite simple to evaluate.

12. Climatic Cycles

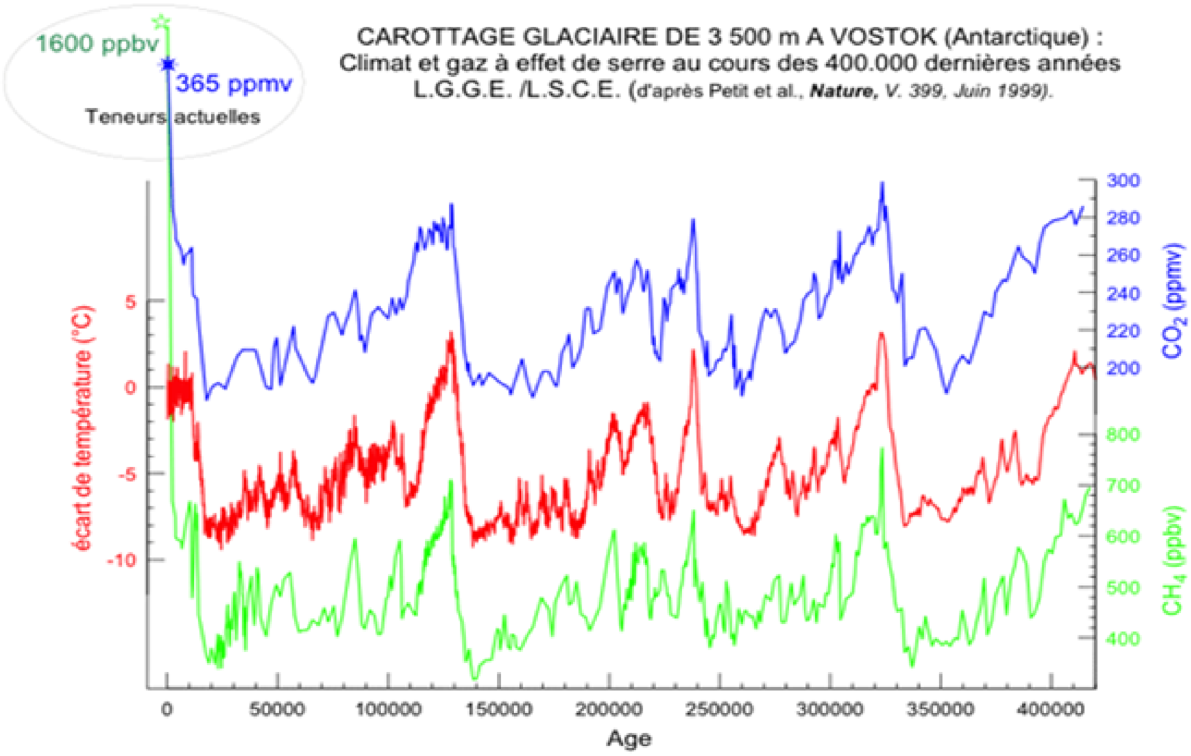
It is no secret that the climate follows cycles. In the current state, we do not know these cycles well enough, because they overlap each other, with periodicities that can be very different, even variable, which can range from a few days to a few tens of thousands of years, with amplitudes that can also be different.

We will detail some of them to show their effects.

12.1. Milankovitch Cycles

See : http ://planet-terre.ens-lyon.fr/article/milankovitch.xml

The best known and most extensive are the Milankovitch cycles, which have an average amplitude of 8 to 10°C (2°C at the equator, 30°C at the polar circle) : 20,000 years ago, there was 2 km of ice thickness above Boston, for example ; today we are at a maximum of these cycles.



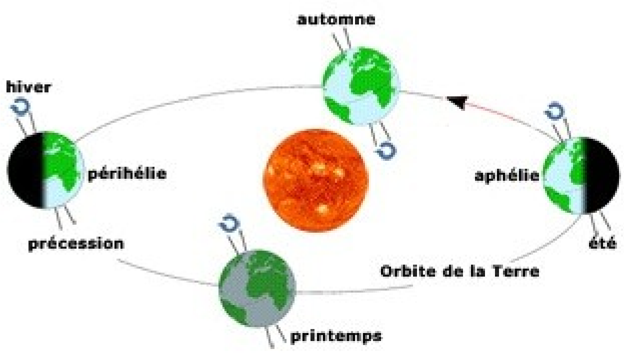
The graph above shows in particular the temperature variations (in red) related to these cycles.

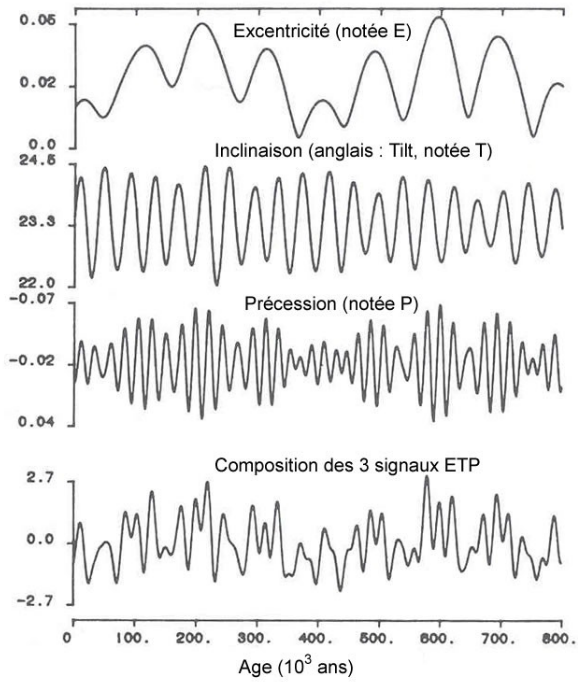
But it has also often been used as a demonstration argument for the effect of CO_2 (in blue) on temperatures (in red) : it must be said that the correlation is striking. But when we have 3 curves connected in this way, if one is the cause, the other two are probably consequences ; then, if the cause is CO_2, how can CH_4 be the consequence?

In reality, Milankovitch's cycles are caused by orbital variations of the Earth (and it is difficult to see CO_2 influencing the Earth's orbit) : in fact, when you zoom in on the graph, it appears quite clearly that it is CO_2 and CH_4 (methane) that follow temperature, and not the opposite, which is consistent with the fact that the ocean desorbs when the temperature warms.

There are three main components that reflect the orbital variability of the Earth :

- <u>Eccentricity</u> of the Earth's orbit (period of 413,000 and 100,000 years) (0 to 0.053, currently 0.016)
- <u>Inclination</u> of the pole axis (41,000 year period)
- <u>Precession</u> of the Earth's axis of rotation (23,000 and 19,000 year period)

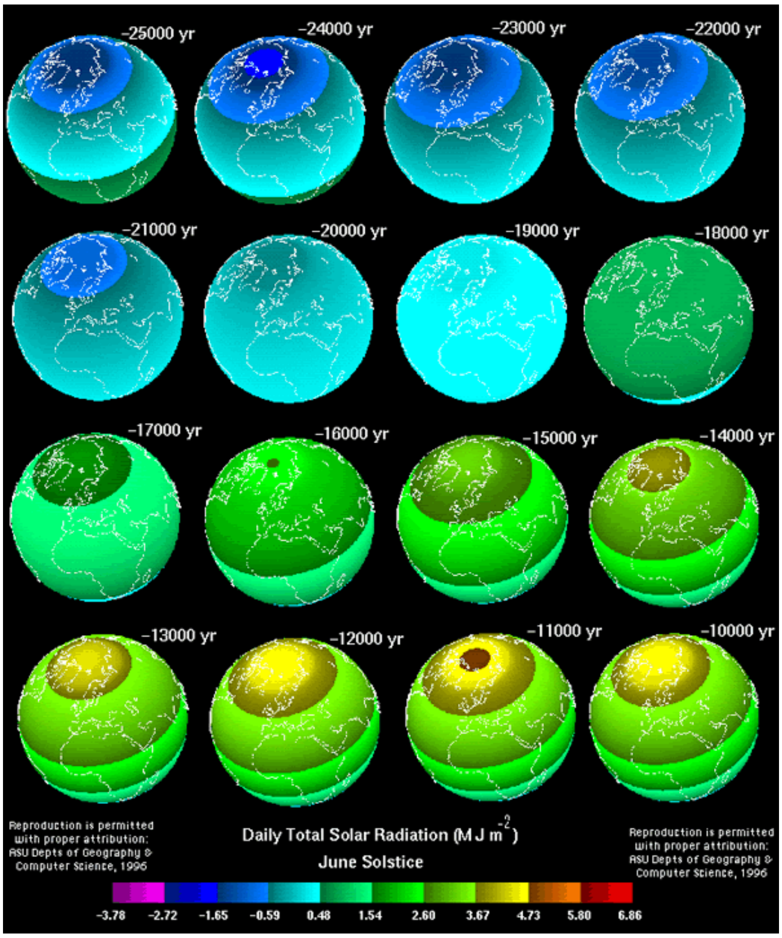




There does not seem to be a "quantified" explanation of Milankovitch cycles that can explain such amplitudes of temperature variation. But intuitively :

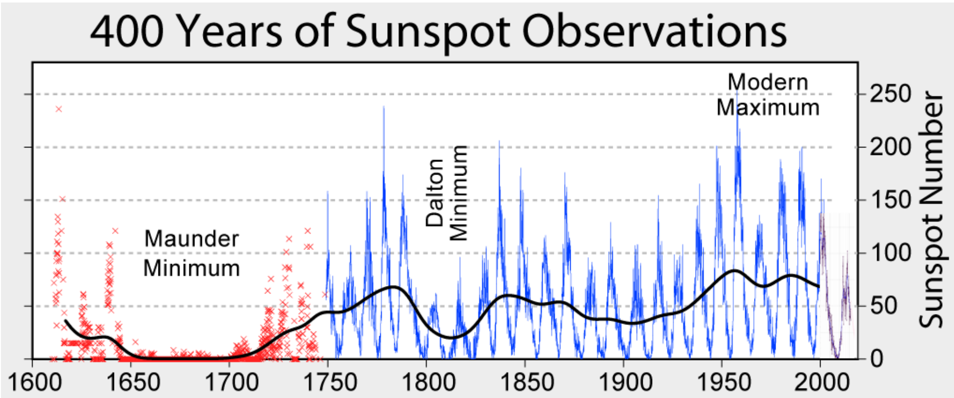
- an increase in eccentricity can cause one circumpolar area to stay in the shade longer than the other : the ice will then expand there, and when it returns to the sun, its albedo will have increased, and it will then absorb less of the Sun's radiation, so it will not lose all the ice it has gained.
- an increase in the inclination of the Earth's axis causes the polar ice to extend from the hemisphere to the shade, and thus further increases the albedo when it returns to the sun.

These two phenomena are cumulative, both in themselves and on top of each other, over several tens of thousands of years :



12.2. Solar Cycles

The sun itself has cycles, materialized by the number of its tasks, and which result in variations in radiation of a few W/m^2 :



(Source wikipedia)

These variations in radiation are insufficient in themselves to justify significant differences in radiative flux and therefore temperature, but there are, however, quite striking correlations, and perhaps an explanation involving the mode of cloud formation and the impact on albedo :

12.2.1. Svensmark's Theory

Svensmark's theory (presented in his recent book FORCE MAJEURE (The Sun's Role in Climate Change), from which the figure below is extracted) is as follows (multi-band pool table) :

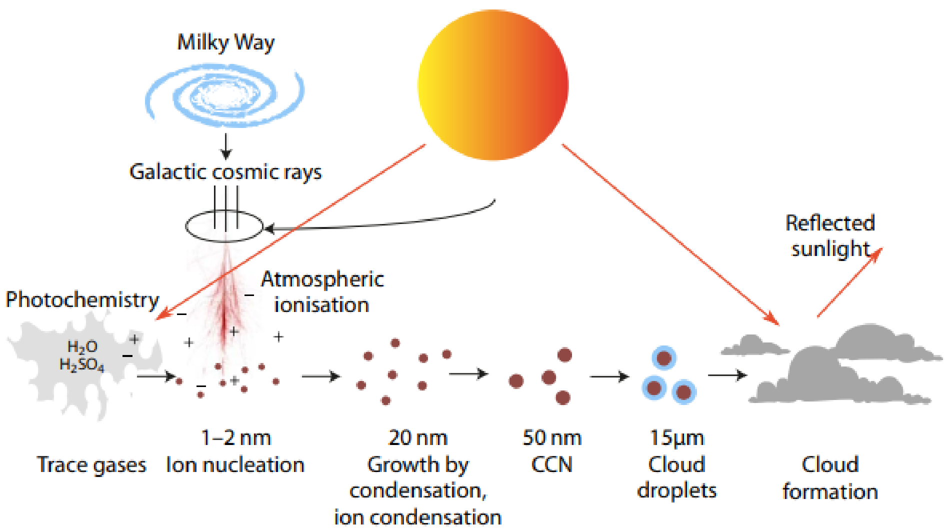


Figure 12: The physical mechanism linking solar activity variations to climate change.
In summary, the link is: (a) a more active Sun, (b) stronger solar wind, (c) fewer cosmic rays, (d) less atmospheric ionisation, (e) less nucleation and slower growth, (f) fewer CCN, (g) clouds with less droplets, (h) less reflectivity, (i) less reflection of sunlight and a warmer Earth.

A more active sun (more sunspots) leads to :

- more powerful solar winds,
- that stop cosmic rays,
- which reduces atmospheric ionization,
- which slows down the nucleation and growth mechanisms of water drops,
- ... so the formation of clouds,
- which reduces albedo,
- and therefore increases the temperature.

12.2.2. G.A. Zherebtsov's Theory

Source : [http ://www.science-climat-energie.be/2019/05/04/un-mecanisme-russe-pour-expliquer-le-rechauffement-global/](http://www.science-climat-energie.be/2019/05/04/un-mecanisme-russe-pour-expliquer-le-rechauffement-global/)

This very recent theory will be developed in a later revision of this book

12.3. Oceanic (or other) Oscillations (e.g., 60-year cycle)

All ocean cycles NAO (North Atlantic Oscillation), AMO (Atlantic Multidecadal Oscillation), PDO (Pacific Decadal Oscillation), ENSO (El Nino Southern Oscillation)... have as a rule a variation in the difference in atmospheric pressure over ocean basins (e. g. Lisbon and Iceland, or Tahiti and Darwin), and in ocean temperature.

This results in variations in winds, sea currents, formation of depressions, etc... What distinguishes these phenomena is their period (more or less variable), their amplitude (often variable), their location and their area of influence...

Some studies attribute these cycles to a "tidal" effect of the solar surface, and the eccentricity of the Sun around the centre of gravity of the solar system, under the effect of the large planets (Jupiter, Saturn).

These oscillations can have a worldwide impact.

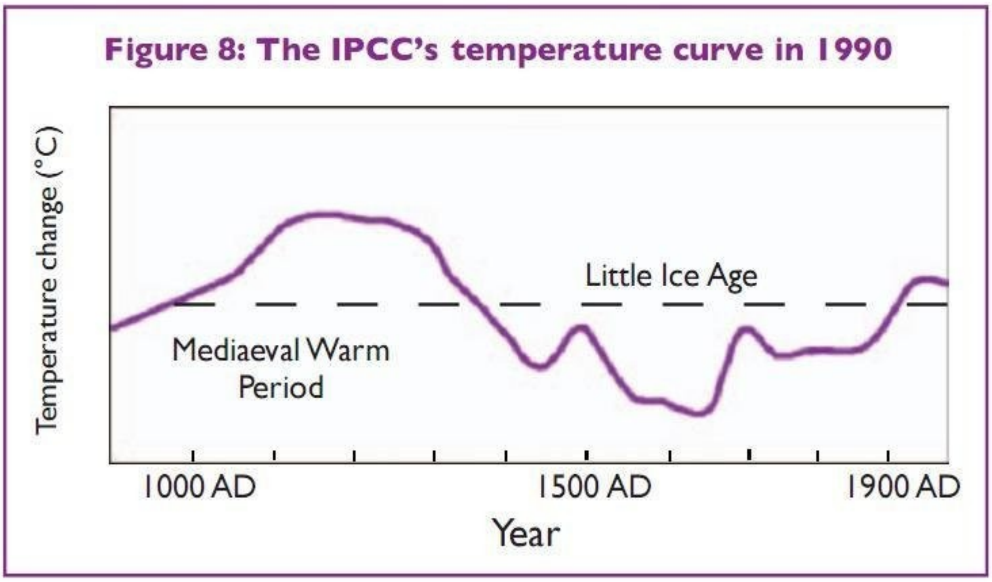
12.4. Conclusions on Cycles

Climate cycles are not well enough known, at least not enough to make reliable climate predictions.

As a result, they are being pushed under the carpet, and are not taken into account in climate models, observations or the IPCC's mission :

"The IPCC's mission is to assess,..., scientific, technical and socio-economic information... to better understand the scientific basis of the risks **associated with human-induced climate change**, to identify more precisely...".

Nevertheless, they cannot be ignored, as they are undoubtedly involved in very significant past climatic variations (in particular the Medieval Optimum and the Little Ice Age), and are nevertheless cited by the IPCC in its first report :



IPCC 1990

This graph shows that we could well be currently in a repetition of the Medieval Optimum.

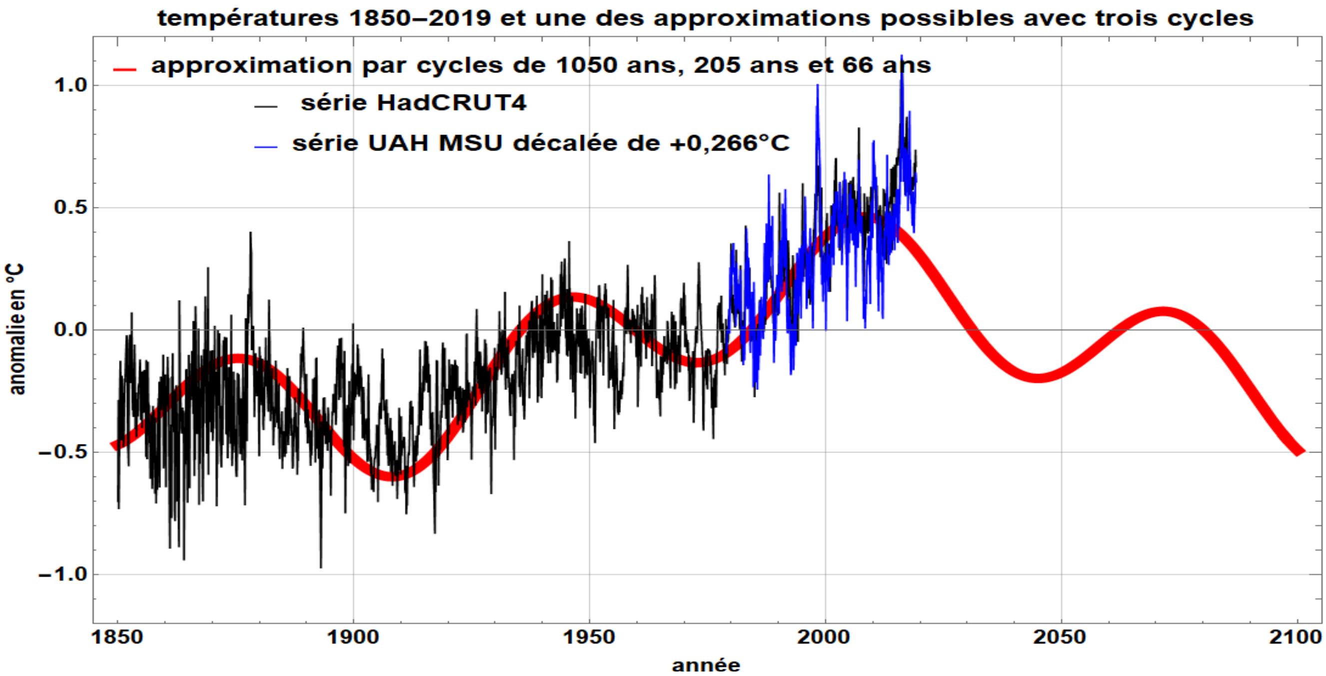
The figure below shows two temperature series that for the last 40 years do not show large differences : they are the land + sea series (black) and the satellite series of observations of the lower troposphere (blue), with an approximation test by three sinusoids :

- in black reconstitution of the CRU from measurements on land and at sea,
- in blue UAH MSU series of low tropospheric satellite observations (TLT) (offset by +0.266°C)

- in red one of the multiple "heuristic" approximations possible with a 1020-year cycle (that of the previous graph), a 215-year cycle and a 65-year cycle.

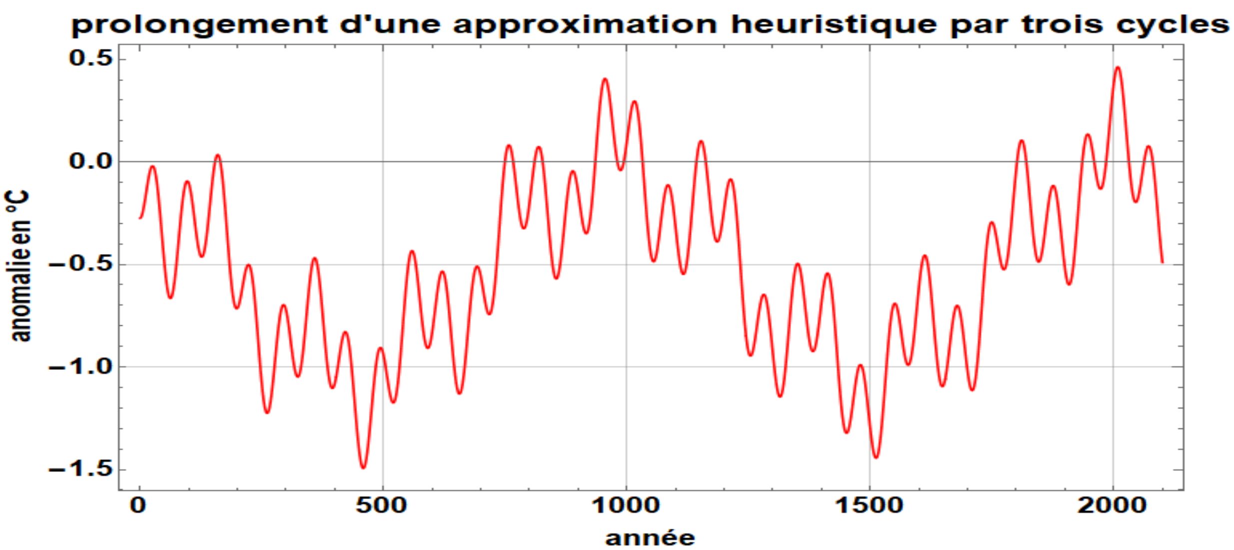
The 60-year cycle (here 65 years) is certainly very marked, but the longer cycles obviously cannot be set with only 170 years of observations.

Series of "global averages of monthly mean temperatures observed at various points on the globe" expressed as anomalies compared to the averages of the same month taken over a reference period :



As a curiosity, this too simple approximation gives back the Roman and medieval climatic optima well documented by historians... and the calamitous periods (famines, epidemics, death from cold and hunger of a significant part (up to half) of the inhabitants of some countries) of the great invasions around 260 - 500 and the small ice age from 1300 to 1700.

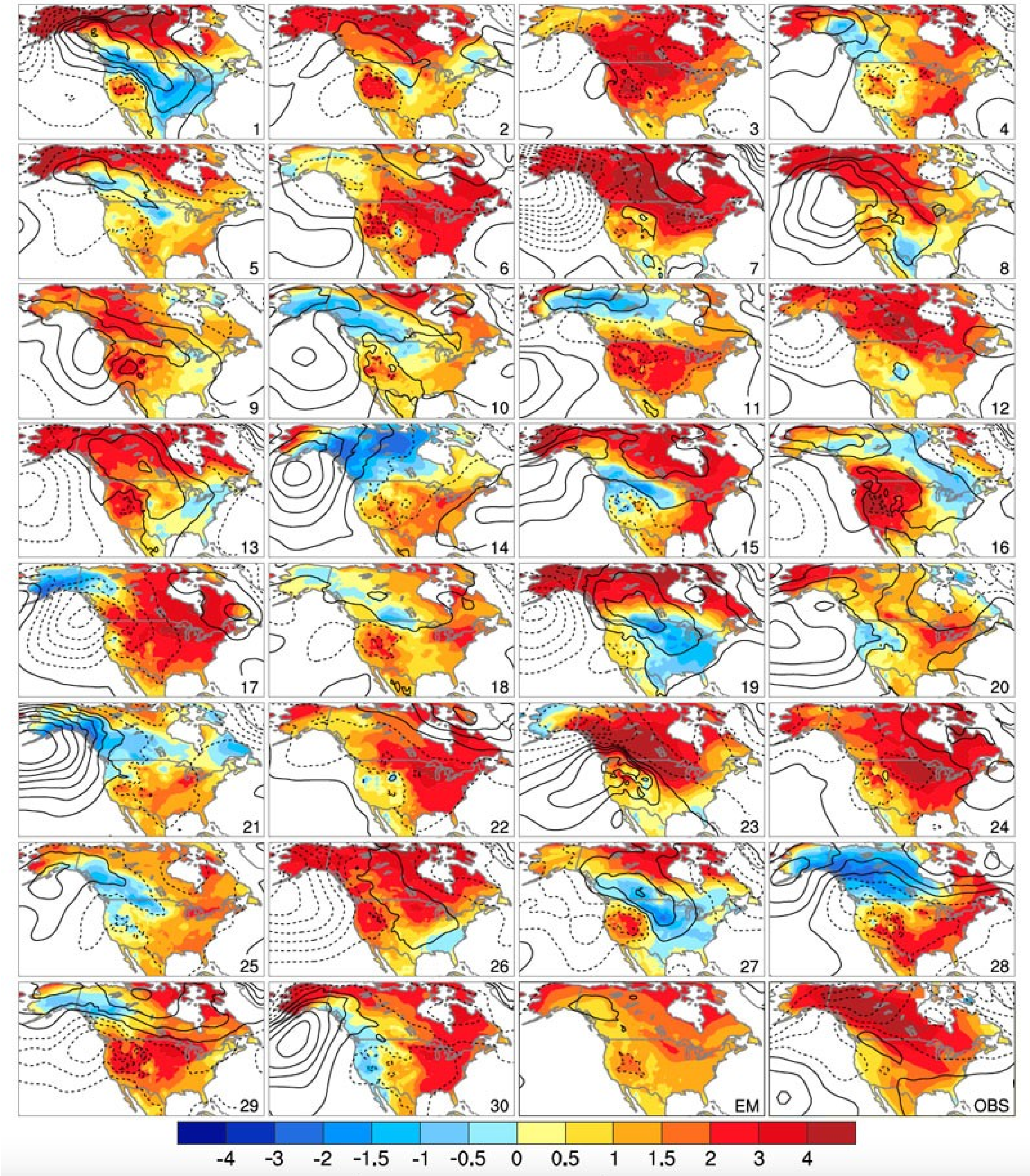
Extension on 1 - 2100 of the "heuristic" approximation of the previous figure :



13. The Climate is chaotic

The drawing below represents the temperature result of 30 Community Earth System Models (CESM), with a mesh size of 1° latitude x 1° longitude, over 50 years (exactly), between 1963 and 2012.

The difference between these models is simply due to a difference of less than one billionth of a °C under the initial conditions. The lower right figure (marked OBS) is the result of actual observations.



https://www2.ucar.edu/sites/default/files/images/2016/atmosnews/perspective/CESM%20LE%20art.png

Autre source : https ://wattsupwiththat.com/2016/10/22/chaos-climate-part-4-an-attractive-idea/

This is how Edward Lorenz highlighted Chaos Theory (or the "Butterfly Effect").

This forecast should make us humble in the face of the complexity of the climate. It may explain why all climatologists' alarmist forecasts are made on a conditional basis : "... could...".

14. Conclusions

Physics (and common sense) contradict a number of preconceived ideas, particularly those conveyed by most media.

In particular :

- The Greenhouse Effect by radiation from below upwards, then backwards from above down does not exist, either in a conventional greenhouse (which works by blocking convection), or in the atmosphere.
- The -18°C of an Earth without "greenhouse gases" is a myth : an Earth without an atmosphere would have a much lower average temperature (probably in the range of -50 to -60°C) : the average on the Moon is -80°C.
- It is the Lapse Rate, linked to the weight of the atmosphere (and not its chemical composition), which, due to an increase of 6.5°C/km from the Tropopause, explains that the temperature at the Earth's surface reaches 15°C on average.
- Evaporation is the main regulator of surface temperature (oceanic at 71%) (7%, or more than 6.5 W/m^2 per °C difference).
- If the CO_2 concentration were to double, the result would be a surface temperature increase of less than 0.5°C : this is far from the alarmist forecasts of up to 5°C and above.
- Water vapour has a regulating effect (negative feedback) and not an amplifier.
- If the temperature has risen by 1°C in a century, the causes must be found elsewhere than in the CO_2 concentration.
- The climate is subject to cycles ; the lack of knowledge of these cycles distorts all the conclusions that can be drawn from observations.
- The climate is chaotic, and it is impossible to draw localized conclusions (e. g. increase or decrease in rainfall at a particular location) (except perhaps using artificial intelligence techniques (http ://knowledgeminer.eu/)?).
- ... And generally speaking, there are still insufficient observations to draw from it an indisputable theory of global warming that justifies the warming currently observed.

Even if it is impossible in such a book to push the calculations further as simulation programs would, the orders of magnitude are there, and a simulation that would give very different results should be questioned.

"The Earth's atmosphere, which has undergone much greater transformations in the past than those envisaged, has behaved as a stable system, the biosphere has also adapted, and media catastrophism therefore appears irrational. We cannot fight a magical thought with theory, only with common sense. It is only when dogma claims to be based on science that all its shortcomings must be shown." (Lionel Fischer, proofreader).

Reviewers

The author would like to thank all the reviewers who contributed to the improvement of this book, including :

- Reynald Du Berger, Eng. FIC, Professor of Geophysics, retired from the University of Quebec, Member of the Scientific Committee of the Association des climato-réalistes :"... this text could be used to inspire the writers of the next science and technology textbooks in Quebec (SVT in France). It is time to replace the propaganda made by the tearful and sweaty polar bear on his drifting ice cube with real science, which claims to teach our young people the "science" of climate."
- Lionel Fischer, engineer ENSCMu 1993, MD, professor of Physics and Chemistry, exegete of the last IPCC report (AR5) :"..., I find this initiative of Messrs Moranne and Veyres excellent, beneficial, and I will certainly send all the students of my school back once the work is completed, hoping to have contributed my stone."
- François Gervais, Professor Emeritus at the University of Tours ; Former CNRS Research Director at the Centre de Recherche sur la Physique des Hautes Températures, Orléans ; Former Director of the UMR CNRS 6157, Member of the Scientific Committee of the Association des climato-réalistes ; Expert Reviewer of the IPCC AR5 report : "We can only encourage the reader to engage in the little intellectual gymnastics of immersing himself in this presentation and then, if we hope he has benefited as much as we would like, to make it known and spread it."
- Jean-Claude Gropeaux, Licence in Cellular Biology and Animal Physiology (Dijon), Master's Degree in Plant Science and Technology (Dijon), DEA in Behavioural Biology (Ethology) (Villetaneuse/Dijon) ; SVT Professor for 24 years, passionate about climatology : "This book is a very good initiative because it is what I would have liked to have found read 3-4 years ago when I started to be interested in this subject."
- Philippe de Larminat, engineer, 1964, PhD, 1972 ; former professor at the Institut National des Sciences Appliquées (Rennes, France) and at the Ecole Centrale (Nantes). Author of 6 books and more than 100 articles published in journals and at international conferences. His research interests include mathematical modeling, process identification, signal processing and control theory. Since 2012, he has been doing pioneering work on the identification of the Earth's climate system : "I have been a bit of an advocate of the devil, during this review, to which I would not have devoted so much time if I had not appreciated the whole text very much".
- and of course Camille Veyres, my mentor in this process : Polytechnician (1967-1970), Mining Engineer, HEC CPA, Telecom ParisTech, former professor, specialist in Radio - Radiation - Fibre optics (France-Telecom), lecturer and author of many studies.