1

A Description of the Main Constraints Regulating the Earth Climate

1.1. Generalities about the atmosphere and the ocean

The general objective of this introductory material is to provide a description of the main constraints regulating the Earth climate, which come from the laws of energy conservation and from the rotation of the Earth, by moving from the global picture of the Earth to more detailed processes.

The word “climate” comes from the ancient Greek “Klima” which literally means “inclination of the Earth towards the pole”. During the third century BCE, the polymath and former library of Alexandria’s director, Eratosthenes of Cyrene, calculated with a negligible error the obliquity of the ecliptic, i.e. the tilt of the Earth axis comparing to its axis of rotation around the Sun. Eratosthenes’ eclectic work, going from science to philosophy and poetry, is still partially available.

Therefore, the Ancient Greeks already knew that the Earth was a sphere and that it would be warmer near the equator and colder at the poles. From this, they also deduced the existence of another livable “unknown” world at mid-latitudes on the other side of the equator.

For a color version of all of the figures in this chapter, see www.iste.co.uk/letreut/energetics.zip.

Energetics of the Climate System,
by Hervé LE TREUT and Mounia MOSTEFAOUI.

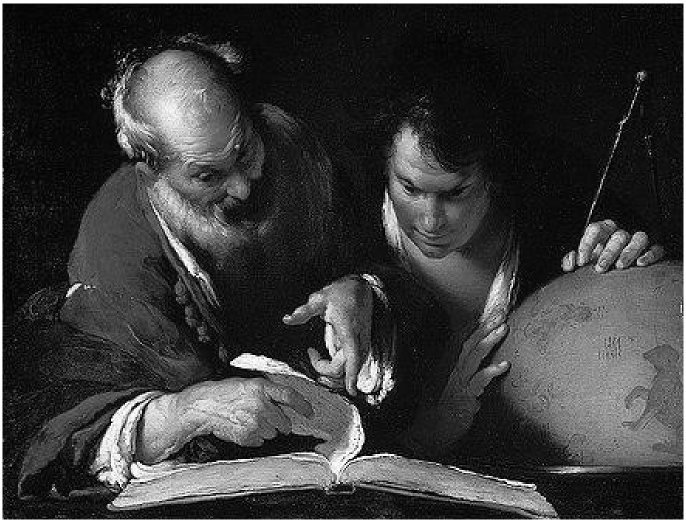


Figure 1.1. *Eratosthenes teaching in Alexandria (Source: Bernardo Strozzi (1635))*

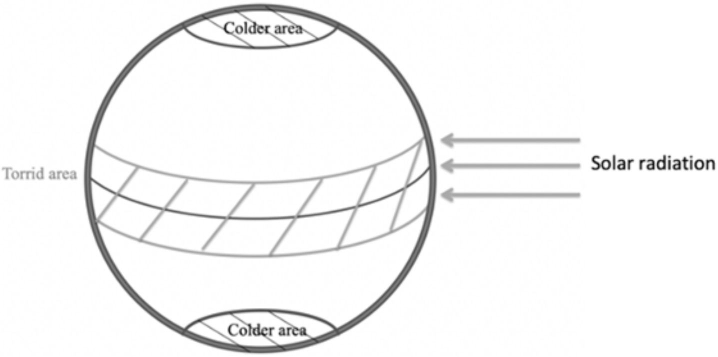


Figure 1.2. *A simplified scheme of the conception of the Earth by Eratosthenes of Cyrene*

Later, by 150 CE, Claudius Ptolemy wrote a summary of the state of knowledge in geography in his opus named *Geographia*.

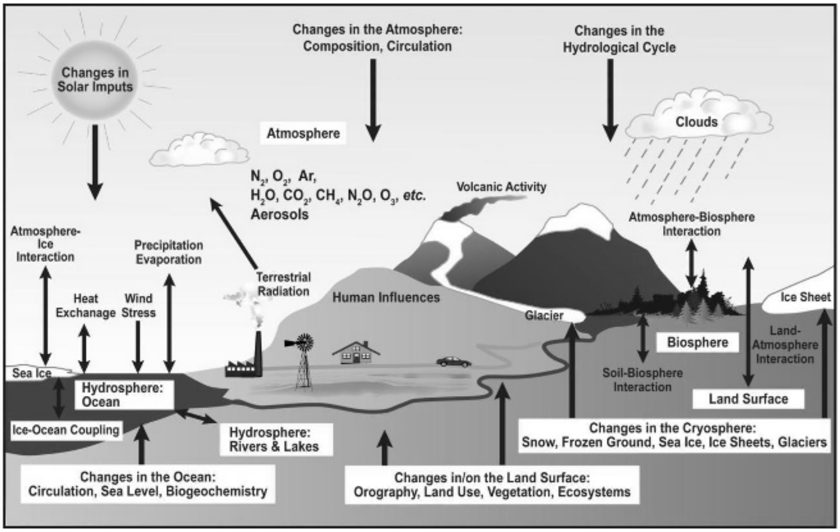


Figure 1.3. *Schematic view of the components of the climate system, their processes and interactions (Le Treut et al. 2007)*

Figure 1.3 represents a modern scheme of the ancient idea of a climate system organized in a large number of subcomponents and different "spheres" linked by different processes, among which the energy exchanges play an essential role.

"Atmo-sphere" stands for the sphere of the Earth, "hydro-sphere" stands for the sphere of water, "cryo-sphere" stands for the sphere of ice and "geo-sphere" stands for the sphere of the land beyond the surface that can be compressed. As for the word "biosphere", it was invented in the 20th century by the Ukrainian–Russian scientist Vladimir Vernadsky at Sorbonne University and stands for the sphere of life.

Figure 1.3 also illustrates the Earth complex system characterized by exchanges of energy, which represent the guiding thread of this book. No other types of exchanges such as water or momentum will be discussed in detail in this opus.

Beyond its etymological significance, we can define the word "climate" as the ensemble of statistics that describe the state of the climate system in a given location and over a given period of time (some decades). It is important to note that "statistical" does not only mean average. Moreover, the concept of risk is intimately associated with the climate definition, and it can be defined as an outcome that has a chance to happen, meaning a non-zero probability. Furthermore, we would like to underline that the notion of scale of time is absolutely key for this complex topic, which is highly dependent on a given contingency’s context.

Due to the complexity at stake, the science studying climate has no one defined name. It is usually alternatively referred to as “physics of climate change”, “climatology”, “sciences of the environment”, “geosciences”, “earth, atmospheric and planetary sciences”, etc.

1.1.1. *The atmosphere*

The Earth’s atmosphere is 100 km thick, but 99% of its mass lies in its first 21 kilometers.

Figure 1.4. *A side view of the atmosphere from a balloon (Source: François Danis – LMD 2000)*

In this chapter, we will focus on the lower part of the stratosphere, below 20 km, where the atmosphere has a mass. In Figure 1.4, we can also distinguish the ionosphere layer.

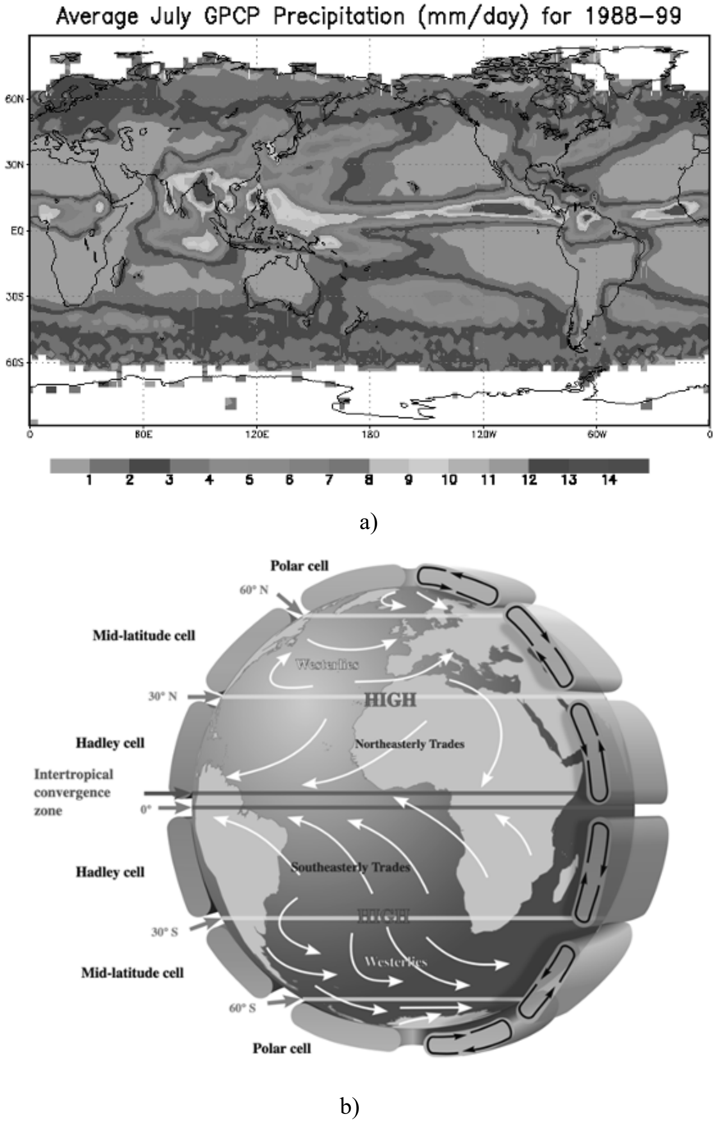


Figure 1.5. *a) Map of average July GCP precipitation for 1988–1999 (Source: World Climate Research Program); b) Scheme of Hadley cells*

In Figure 1.5, which shows a map of average July GCP precipitation in Bonn for 1988–1999, monthly means show an extremely organized atmospheric circulation, with a moving system from West to East. This is very different from the situation on other planets, with a complex organization. The scheme on the right in Figure 1.5 also shows Hadley cells that are defined below, with warm air climbing at the equator where they lose their water and descending cooler air, as well as a desert belt over continents.

The Hadley cells correspond to a relatively slow movement of the atmosphere in a mean meridian plane: with ascendance near the equator and descending air near the subtropical regions. On an annual mean, this circulation is fed by a convergence of air in the low layers around the equatorial region and a divergence higher in the atmosphere from this same area.

The fuel of this circulation comes from the more intense heating of equatorial regions compared to the other regions, getting more solar energy. This more intense heating creates a dilatation of the atmosphere at low latitudes, whose accumulated effect induces a gradient of pressure which is accentuated in the high layers of the atmosphere.

If we consider the atmosphere in its meridian plane, we can also diagnose this situation as a generator of vorticity because the gradients of pressure and density will not be aligned anymore: the air density varies not only with altitude, but also in latitude.

Despite the weak speed of this meridional flow (the winds are much more violent in the West–East direction), the Hadley cells play an essential role in the climatology of intertropical regions.

Ascending air zones are precipitating zones because of the very rapid decrease of the level of saturation of atmospheric water vapor upper in a troposphere, which gets colder with altitude. The seasonal movements of Hadley cells come together with the interplay between dry seasons or wet monsoons in the equatorial regions.

The Hadley cells play a main role in the climate system, as they transport the surplus of energy from equatorial regions to the Poles. The latitudes which limit the domain of Hadley cells in the North and in the South are therefore main indicators of the climate zones on the Earth surface.

Figure 1.6 is a representation of Hadley cells. On the y-axis on the left, the height is given in decibars; in the center, the lines are a representation of the mass of the troposphere; and the y-axis on the right, the vision is given in latitudes for three different scales of time: annual mean, winter (December/January/February) and summer (June/July/August). The horizontal lines indicate the latitudes.

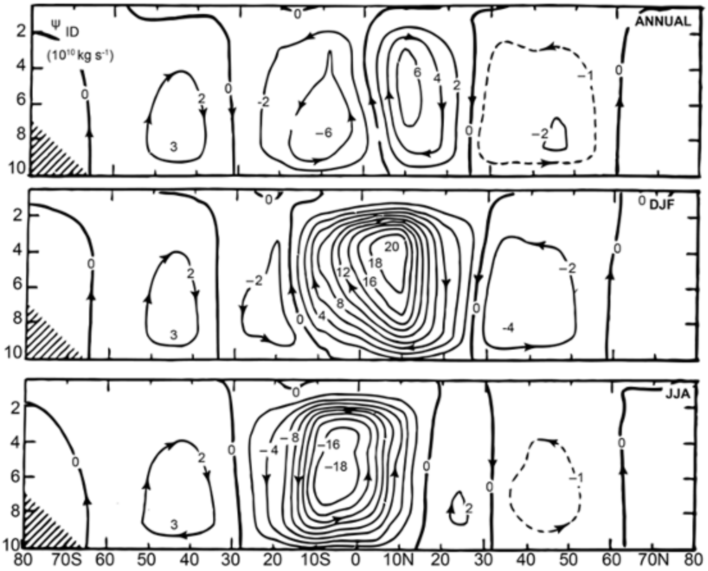


Figure 1.6. *A representation of Hadley cells (Source: Peixoto and Oort (1992))*

The stream function of meridian flow (flow averaged over longitudes and the time) is represented on a diagram of altitude/latitude. The abscissas are expressed in degrees of latitude. The lines of stream "iso-function" are by definition parallel to the flow. In the case of a stationary mean flow, we can consider that the flow is between the isolines. The values of stream functions are expressed in mass flow rate (the unity is 1010 kg/s): between two separated isolines of 1010 kg/s and 1010 kg of air every second. The diagram shows from the top to bottom in three situations: (1) the yearly mean of the flow, characterized by an approximate symmetry relatively to the equator; (2) the mean for boreal winter (December/January/February), where the main ascend is displaced from the equator toward the southern hemisphere; and (3) the mean for the boreal summer (June/July/August), where the main ascent is displaced from the equator toward the north hemisphere.

Figure 1.7 represents the atmospheric circulation viewed by the satellite radar TRMM, providing an instantaneous view of the Earth (synthesis image for demonstration by NASA). The radar echoes provoked by the presence of condensed water show ascending air. We can note, even on this instantaneous image corresponding to the month of July, an opposition between intertropical and extratropical regions. The intertropical zones are characterized by zones of ascending air essentially near the equator, and zones of air ascent more frequent approximately 30°N or 30°S. The extratropical regions are characterized by disturbances where the air ascends progressively all along “spirals” structures of several thousands of kilometers.

Figure 1.7. *Atmospheric circulation viewed by the satellite radar TRMM (Source: NASA Project TRMM)*

Figure 1.8. *Perhaps the world’s first thematic map: Edmund Halley’s map of trade winds (Source: Halley, Philosophical Transactions (1686))*

To mention some elements of history, part of this organization was already known by Halley (17th century) and Hadley (18th century). The map presented in Figure 1.8 was the result of important efforts at that time. Halley was the captain of a military boat; he was also a specialist in Earth Sciences and an astronomer well-known for comets. After his death, a comet came at the exact moment that he foresaw through his calculations.

1.1.2. *A brief comparison between some oceans and the atmosphere's main orders of magnitude*

Atmosphere	Oceans
Height ≈ 20 km	Depth ≈ 3.8 km
Average wind velocity ≈ 10 ms^{-1}	Average surface velocity ≈ 0.01 $m.s^{-1}$
Heat capacity: $C_p = 1{,}004$ J kg^{-1} K^{-1}	$C = 4{,}180$ J kg^{-1} K^{-1}
$r = P/RT \approx 1$ kg m^{-3}	$r = 10^3$ kg m^{-3}
m (column) = 10^4 kg m^{-2}	m (column) ≈ 3.8 10^6 kg m^{-2}

Table 1.1. *Atmosphere and oceans: some figures*

For the atmosphere, the height of 20 km is a very small cover around the Earth. The heat capacity is linked to the mass; it represents the capacity of energy to absorb per kilogram to change the temperature by 1°C. We also note that the density of the atmosphere is not particularly light for a fluid: 1 $kg.m^{-3}$ is indeed not negligible.

The ocean is the timekeeper of the climate occurring now and stores about 90% of the greenhouse gases. Its depth (3.8 km) is much less than the radius of the Earth (6,371 km).

The atmosphere is responsible for the geography of the Earth. It transports very fast (with an average wind velocity of 10 $m.s^{-1}$) a lower amount of energy than the ocean, which, on the contrary, transports slowly, with an average surface velocity of 0.01 $m.s^{-1}$, a larger amount of energy.

1.2. A global view of radiative processes

Figure 1.9 shows the sunspots that characterize a situation where the emissions of the Sun are cooler on average, as well as the convective motion of the magma. Every day, a scientist scrutinizes the Sun to look for sunspots, and it has been the case for centuries from the Paris Observatory. The observation of the sunspots/changes in the solar radiation started under the impulsion of the French Academy of Sciences during the reign of Louis XIV, who was at the origins of the creation of the Paris Observatory in 1667.

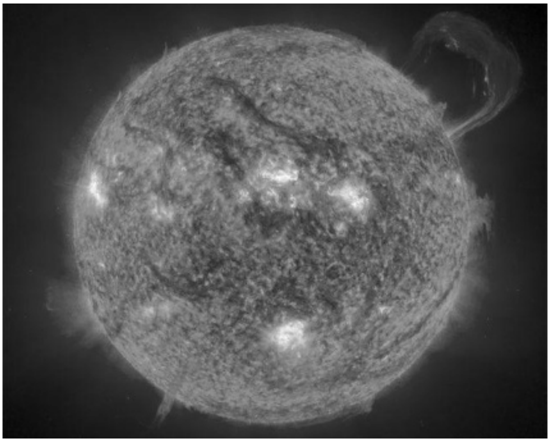


Figure 1.9. *The Sun. Source: nasa.gov.*

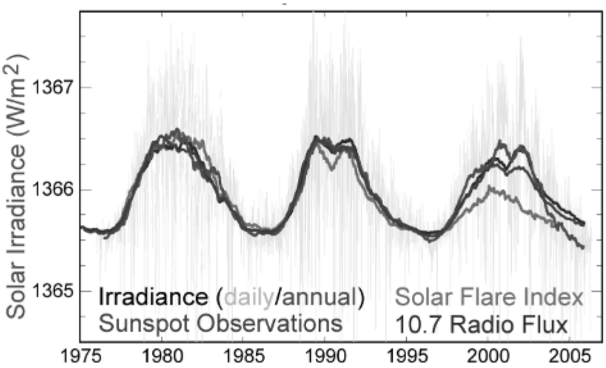


Figure 1.10. *Solar cycle variations and sunspot observation between 1975 and 2005 (Source: http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant, International Sunspot number: http://www.ngdc.noaa.gov/stp/SOLAR/ftpSunspot number.html, Flare index: http://www.koeri.boun.edu.tr/astronomy/readme.html, 10.7 cm radio flux: http://www.drao-ofr.hia-iha.nrc-cnrc.gc.ca/icarus/www/sol_home.shtml, https://en.wikipedia.org/wiki/Solar_cycle)*

What we call the solar constant is actually not constant, and a satellite can measure the variations of solar irradiance. The internal motion in the Sun has an eleven-year cycle.

In Figure 1.10, the blue line corresponds to sunspot observations. The surface temperature of the Sun is 6,000 K. At 1,366 Wm^{-2}, we see what is captured by the Earth. The solar constant gives the amount of energy that crosses the Earth.

As for sunspot observations, there are moments during which the Sun surface is cooler and emits a bit less.

NOTE.– The Earth is visible from space because it reflects the light of the Sun.

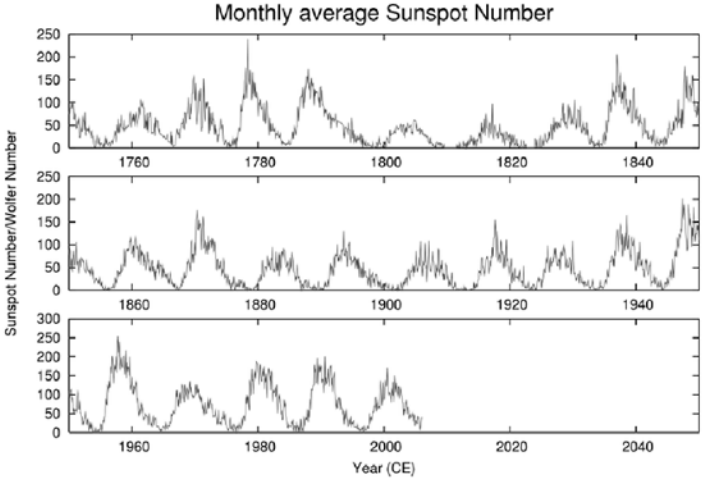


Figure 1.11. *Monthly average sunspot numbers observed since the 18th century. Source: this figure was produced by Leland McInnes using gnu plot (all data is from publicly available sources)*

Figure 1.11 shows monthly average sunspot numbers observed since the 18th century (they were measured then by looking at emission in the visible). On the upper scheme of Figure 1.11, between 1,800 and 1,820, we can see a tendency of reduction for the sunspot number: the Sun was a bit cooler due to changes in sunspots, but a volcanic eruption happening at the same time also makes things more complex to interpret.

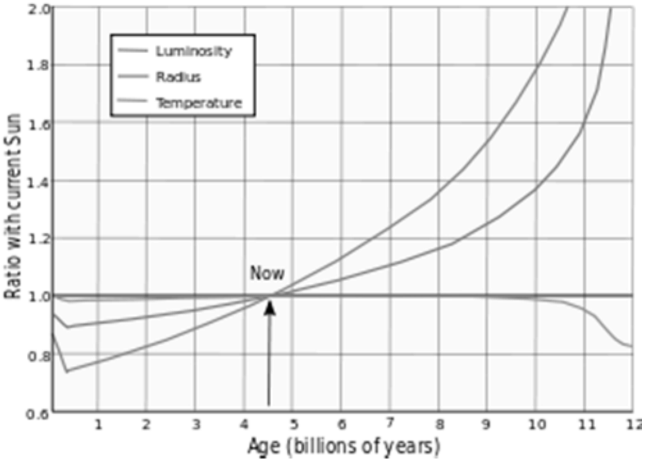


Figure 1.12. *The long term changes of the Sun "engine". Ratio with current Sun of solar luminosity, radius and temperature as a function of time (after Ribas 2010)*

Let us now consider another interesting phenomenon: 4.5 billion years ago, the Sun was younger; it had less energy. Would it have been possible to have an Earth covered with ice? We think maybe now. "The faint young Sun paradox" is the name sometimes given to the contradiction that we may find at first when considering the observations of water (in a liquid state) in the early history of our planet and the fact that the Sun's output would be 70% of the recent output at the time.

Figure 1.12 shows the luminosity, radius, and temperature depending on the age of the Sun expressed in billions of years. We can note that at around 4.5 billion years of age in the history of the Earth, the amount of radiation from the Sun increases with time.

We note a decrease of 5% in temperature from 10 to 12 billion years, while it has been stable over a period of 10 billion years.

NOTE.– A modification of solar insolation is enough to have an important impact and to disturb the system because of the form of the equilibrium. For instance, extinctions are a feature of that, a disequilibrium may raise from some cause, and if it is stable, it can have huge impacts.

Stable means, here to a first approximation, that a phenomenon lasts "long". The paradox of the young Sun asks how, if a planet was frozen, we could have gotten out of this state: one of the explanations is that, under the ice, there were submarine phenomena. We will come back to this later on.

The solar radiation is emitted in the ultraviolet (UV)/Visible/infrared (IR) domain (10–15 μ), while the terrestrial radiation is entirely in the IR domain (0–0.5 μm).

A blackbody absorbs all of the radiation it receives and re-emits it. This phenomenon can be expressed as a function of temperature:

$$E = \pi B \ = \sigma T^4 \qquad [1.1]$$

The term on the right side of this formalism that we call the Boltzmann equation represents the energy emitted per square meter summed up over all wavelengths; it is expressed in $W.m^{-2}$.

This phenomenon can be represented graphically as a function of wavelength in Figure 1.4, which shows the existence of two different domains of energy with the normalized blackbody curves.

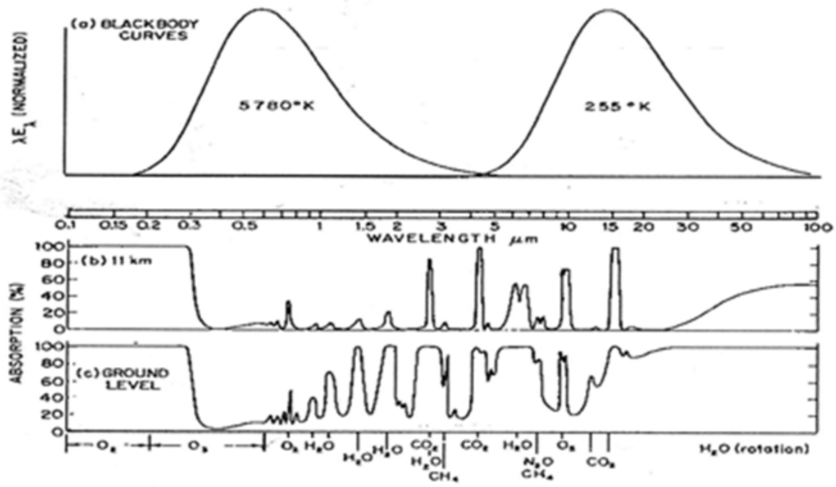


Figure 1.13. *Normalized blackbody curves for the Sun and for the Earth (Source: Brunetti and Prodi (2015)*

The Sun emits a radiation:

$$E_{Sun} = \sigma T_{Sun}^4 \qquad [1.2]$$

with T being the temperature of the Sun near the Surface, with σ = 5,67 10-8 W m^{-2} K^{-4}.

Neither the Sun nor the Earth are actually perfect black bodies, but we can do the approximation that the Earth emits a radiation that we can note:

$$E_{\text{Earth}} = \sigma T_{\text{Earth}}^{4} \qquad [1.3]$$

On Earth, we receive only a small part of the incident solar radiation (caption of a very small part of the solar energy coming from the Sun). The method to make the measurements can be simplified as follows.

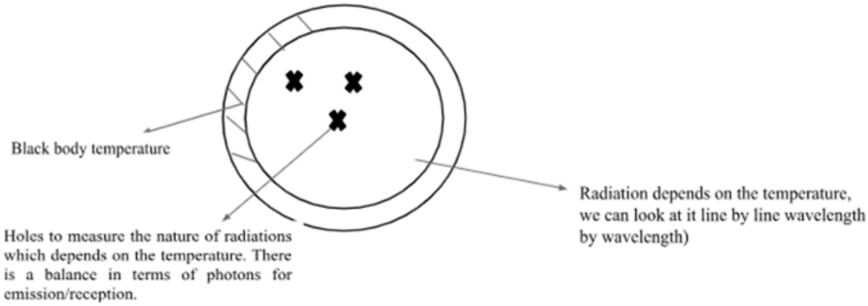


Figure 1.14. *Simplified scheme for the measurement of blackbody radiations*

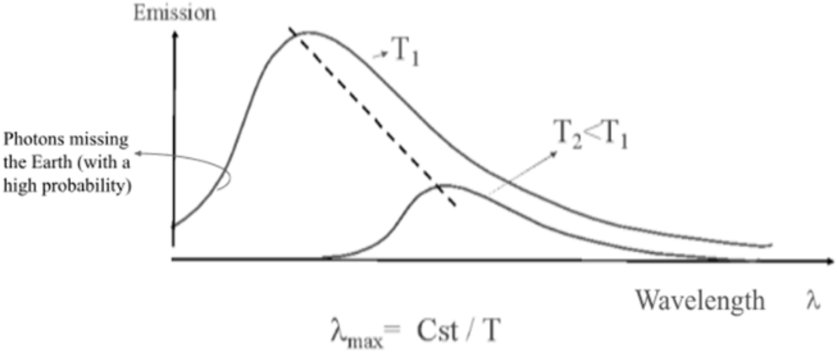


Figure 1.15. *Scheme comparing the emission of a blackbody as a function of wavelength for a given body of temperature T_1 and a cooler one with a temperature $T_2 < T_1$ (Source: adapted from Young and Freedman (2012))*

A blackbody behavior can be studied thanks to the simplified model of a black cavity with a hole and walls opaque to radiation. If the cavity is kept at a temperature fixed T, the radiation trapped inside the cavity is at thermal equilibrium with the enclosure.

Both the Earth and the Sun emit electromagnetic radiation in rather different wavelengths. Only a very small part of the solar energy is captured by the Earth, and the Earth emits energy in another domain at longer wavelengths. A radiative equilibrium is reached at different wavelengths. We can make a budget as they represent different sorts of radiations. Figure 1.15 shows the different shapes of emission curves for the energy emitted at different wavelengths. We note that for a cooler body, the maximum is a longer wavelength and the energy at a longer wavelength is less than the energy of a body that is a bit warmer. This is the principle for the Wien’s displacement law.

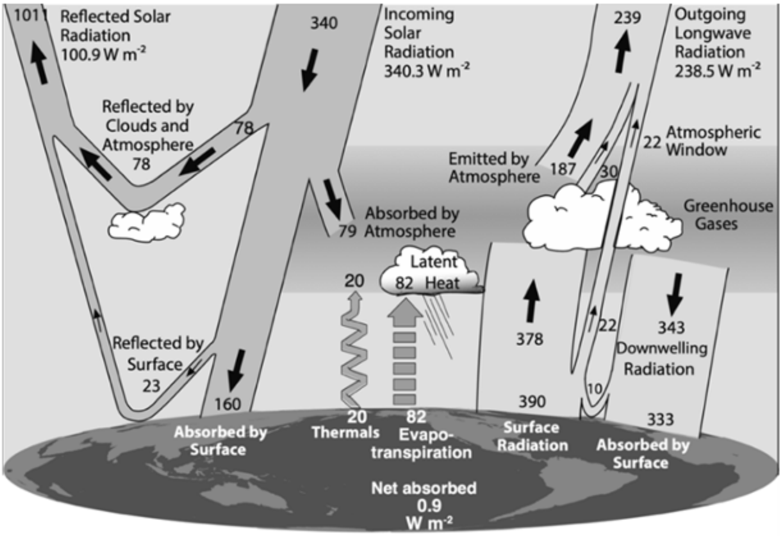


Figure 1.16. *Earth Global Radiation Budget (Trenberth and Cheng 2022)*

The Earth Global Radiation Budget depends on temperature. The unit of radiation is in W.m^{-2}. We can write the following equation:

Solar radiation incident = Reflected solar radiation + Radiation emitted in the infrared

$$340 = 101 + 239 \qquad [1.4]$$

with:

Reflected solar radiation = Albedo + Outgoing reflected longwave radiation

$$107 = 77 + 30 \quad [1.5]$$

What arrives on Earth is not 1,366 W.m^{-2} because the Earth is a sphere and the Earth surface that captures the solar energy is a disk; therefore, it is necessary to apply a division of this incoming energy by a factor of 4 as described in the following:

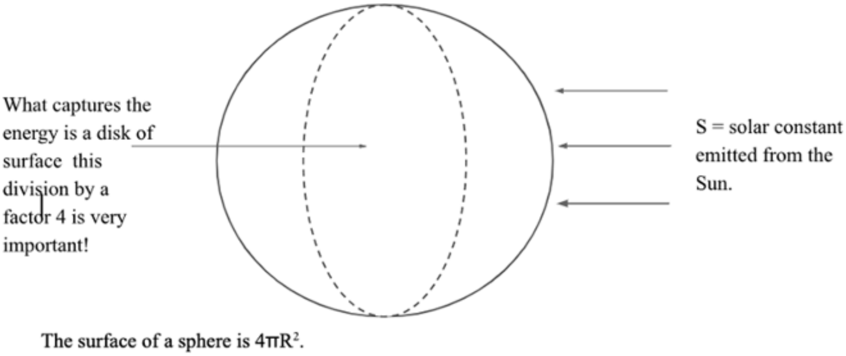


Figure 1.17. *A simplified scheme of the capture of the Sun energy by the Earth surface*

The surface of the Earth sphere can be written as follows:

$$S_{earth} = 4\pi R_{earth}^2 \quad [1.6]$$

Therefore, if we note R_s, the solar incoming radiation captured at the Earth's surface, we have:

$$R_s = \frac{S_{earth}}{4} \quad [1.7]$$

We must be careful: the solar cycle is often misused by the climate-skeptical community members, who often forget this division by a factor of 4 parameter.

A simplified global equation can be written as follows:

$$C_t \frac{dT}{dt} = R_S (1 - \alpha) - R_t(T) \quad [1.8]$$

with T being the global earth temperature (of the largest heat storage component: the ocean), C_t being the global heat capacity, R_S being the solar incoming radiation, R_t being the outgoing terrestrial radiation, and α being the albedo.

The simplified global equation [1.7] contains much information about the complexity at stakes.

The left side of the equation represents the energy stocked in the ocean and is almost always at equilibrium. In what sense is this equilibrium stable? With an albedo of 0.3 generally, but this changed with past climates, what is absorbed is not exactly equal to what is reemitted: locally, we are not at equilibrium.

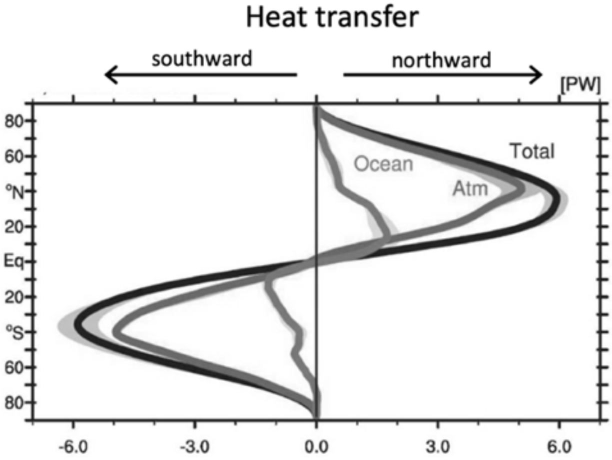


Figure 1.18. *Required heat transfer (in PW, i.e. 10^{15} W) to balance the differences of net radiation at the top of the atmosphere (black curve) and distribution of this transport among oceanic contributions (in blue) and atmospheric ones (in red). A strictly positive value on the x-axis refers to a northward transport (Source: Fasullo and Trenberth (2008))*

In Figure 1.18, we can see the dynamics of the ocean and of the atmosphere. The fact that temperatures are not warm enough in the poles is balanced because some excess heat is being brought away by the dynamics of the ocean and of the atmosphere, which take extra heat toward the poles.

1.3. Past climate history

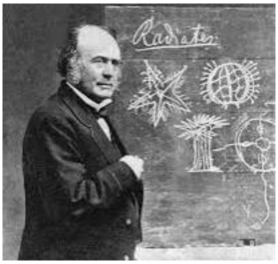


Figure 1.19. *Picture of Louis Agassiz, first scientific proposal of past ice ages (1837), from an unknown author (public domain)*

Louis Agassiz was a paleontologist; he studied glaciers in the Alps. He found rocks named “Moraines”, organized by layers in rivers; they gave names of rivers to these past ages, and they are extremely difficult to date. Those blocks are easily recognized by geologists, as they were present very far from the glaciers. Agassiz’ first scientific proposal of past ice ages was made in 1837 at Neufchâtel. He notably stated that ancient glaciers also notably covered Europe, Asia and North America.

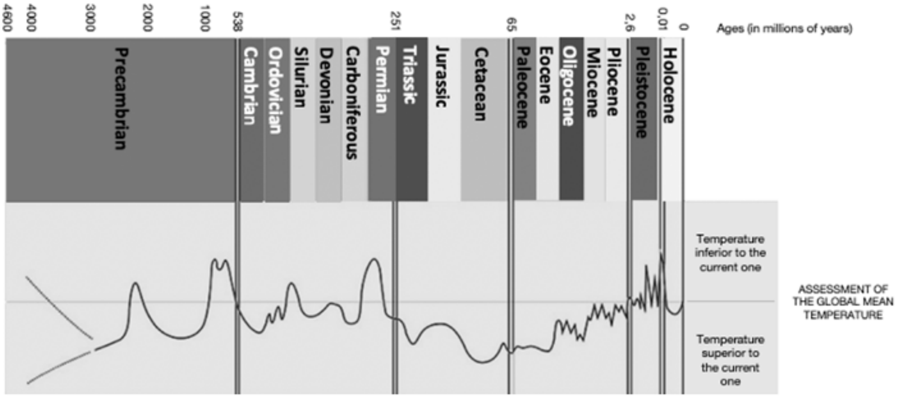


Figure 1.20. *Temperature trends over the last 4.5 billion years before present (Source: Le Treut (2013))*

Different geological indicators allow us to reproduce the global shape for the curve of temperature changes of the earth since its origins, 4.6 billion years ago. They point to a climate that is generally warmer than the one of the most recent two million years.

We are essentially interested in the Holocene represented in Figure 1.23, the period during which our human ancestors started to develop in terms of civilization.

In Figure 1.20, we can note that the evolution of the temperatures over time is not linear. The oceans were formed during the Precambrian, and the atmosphere changed its composition then. The Pleistocene is featured by cold temperatures, with oscillations.

The Cretaceous, the Jurassic and the Triassic represent a warm era compared to the Primary era.

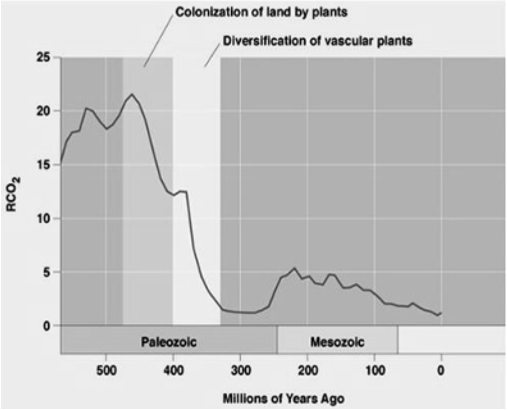


Figure 1.21. *Global temperature trends over the last 4.5 billion years before present, from an unknown author (Le Treut 2013)*

The Sun continuously brings energy to the Earth, so why is the Earth not getting indefinitely warmer and warmer? In 1824, Joseph Fourier answered with this explanation: because it emits some “Chaleur Obscure” (Invisible Energy). That is how the greenhouse effect was discovered by Fourier, who explored the heat transfers in a body. Fourier realized that for balance, the Earth has to get rid of what he called an “obscure heat”, invisible to the human eyes, which must exist for equilibrium.

According to the scientist James Lovelock, a member of the British Royal Society during the 20th century, the Gaia Theory can be defined as follows: the climate of the Earth is regulated by life, which ensures an equilibrium between the increasing solar emissions, and the decreasing greenhouse effect. This theory is valid at the scale of (hundreds of) millions of years.

The RCO_2 parameter is defined as the ratio between the atmospheric CO_2 mass at a given time in the past over the current value of the atmospheric CO_2 mass. In Figure 1.21, we note that RCO_2 decreased of CO_2 since around 459 million years before present; it is very much because of the appearance of life. For Lovelock, if the Earth has been stable for such a long time compared to Mars or Venus, for instance, it is because of life maintaining life. However, it is important to note the scale of time, which is very important: it works at the scale of millions of years.

Therefore, it would not be realistic to count on that effect, as human beings would be replaced in the meantime! This time scale is so long that this phenomenon cannot be considered as a solution to avoid acting on tackling global warming, a topic that will be discussed in more detail in Chapters 4 and 5.

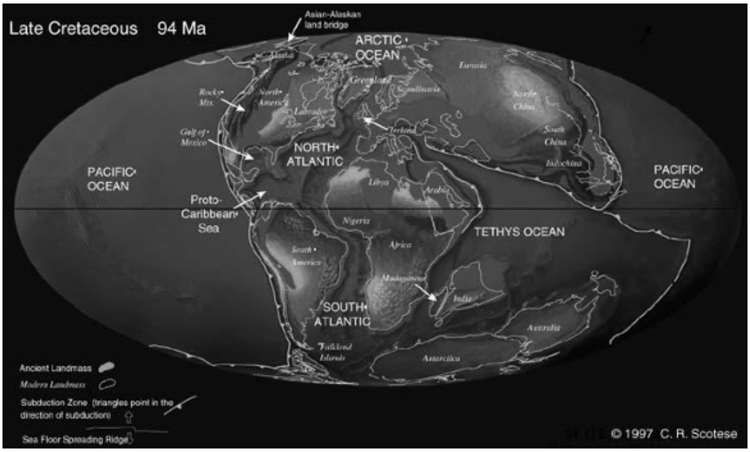


Figure 1.22. *The breaking up of the Pangea: more than 100 million years ago (Source: Scotese (1997))*

Figure 1.22 illustrates another feature: the continental drift, which produces an acceleration of the cooling. This phenomenon occurred at the same scale of time as the cooling during the Quaternary era.

The South pole was then covered with ice and the albedo participated in the cooling.

If we name α the albedo, we can ask ourselves how the climate is changed when we affect the albedo and if the effects of solar inputs are direct or indirect.

A first example of the complexity is the demonstrated dependence of the albedo α on the temperature T, which we already discussed with the following equation:

$$C_t \frac{dT}{dt} = R_S\,(1 - \alpha) - R_t\,(T) \qquad [1.9]$$

The cryosphere modulates α and takes three forms:

– snow cover (quick response, from days to seasons);

– sea ice (quick response, seasonal time scale);

– continental glaciers (very slow response).

When considering those cycles, there are things that cannot be explained solely by the solar input. Let us work very briefly with a few equations, even though it is not possible to solve those equations until the end.

However, those types of equations have been used to try to show why this is more complex than a simple dependence on solar input. Also, this has implications for the future climate. The equation we will consider first is equation [1.9]: if α varies in a simple way, we have three equilibrium states (see Figure 1.23):

– one is unstable;

– two are stable.

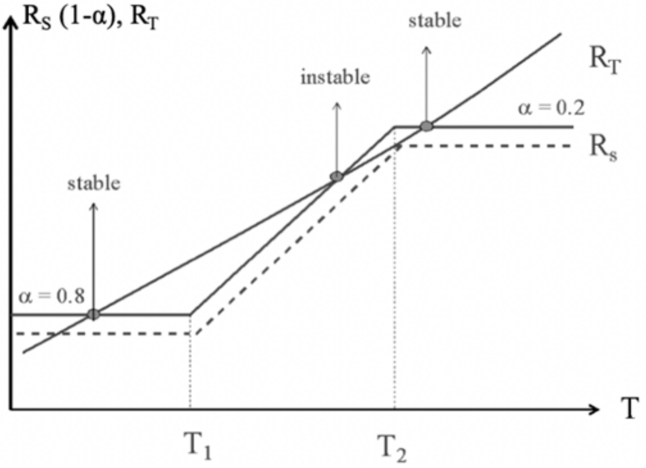


Figure 1.23. *Representation of R_S (1-α), R_T as a function of temperature*

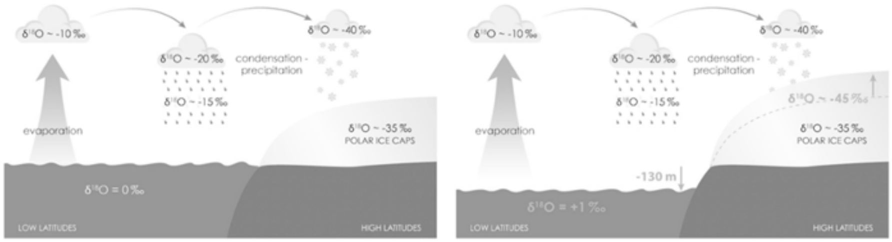
In Figure 1.23, we can observe three points of equilibrium represented in green. Those points are either stable or unstable, found by using the equation detailed previously and by applying stability conditions (the aim here is not to deliver calculus details).

Graphically, a point of equilibrium is observed when the red curve representing the solar radiation crosses the blue curve representing the terrestrial radiation.

For the unstable point of equilibrium, it corresponds to the situation where the absorbed Sun energy brings it to a higher level: it gets out of range, and therefore, it goes out of equilibrium. This simplified model provides us with precious information about the complexity of the system.

A simplified explanation of the methods used to study past climates and oscillations between glacial and interglacial ages can be proposed as follows.

Water isotopes are essential tools to reconstruct the sequence of glacial–interglacial ages, as there is a link between the temperature for snow formation and its isotopic composition.



Current period (interglacial) Last Glacial Maximum

Figure 1.24. *Simplified scheme illustrating the principle at the origins of the isotopic thermometer (Source: e-CalPSu (Jouzel 2018))*

The number of isotopes indeed diminishes as the evaporating water from the poles loses temperature: we speak about an “isotopic thermometer”, which is a precious tool to reconstitute climates from the past.

In the ice cap, there is a low isotopic content (low amount of O^{18}). This method was notably used by Lorius et al. (1985).

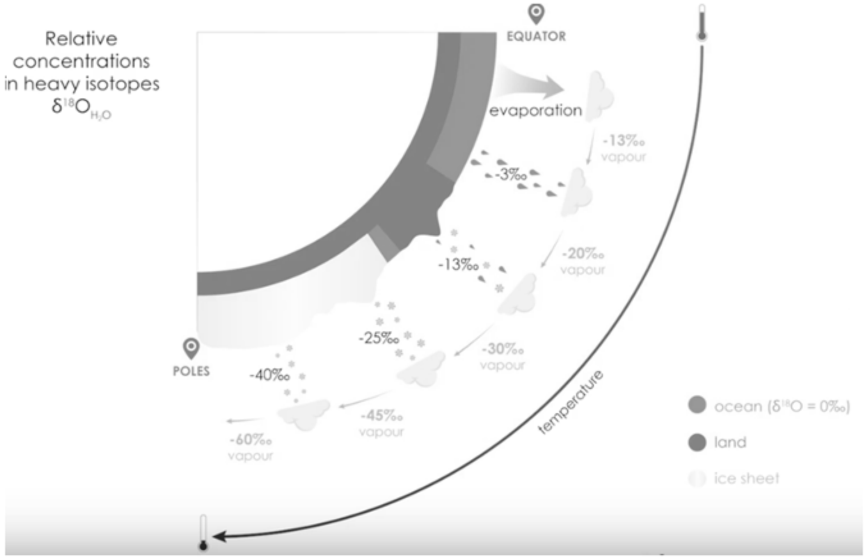


Figure 1.25. *Scheme showing the decrease of isotopes $\delta^{18}O$ as the evaporating water from the poles loses temperature (Source: e-CalPSuL, Jouzel (2018))*

More in detail, the fluctuations of the isotopic content that we can note δO^{18} at a given level *i* can be obtained thanks to the following relation:

$$\delta^{18}O = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{\text{sample}}}{\left(\frac{^{18}O}{^{16}O}\right)_{\text{standard}}} - 1 \right) \times 1{,}000\ ‰ \qquad [1.10]$$

with the standard $\delta^{18}O$ featured with a known isotopic composition (Vienna Standard Mean Ocean Water (VSMOW)).

Therefore, we consider the changes compared to the difference in the ocean. The method consists of assessing among O^{16}, O^{17}, O^{18}, whether the latter is more or less present. The ice caps were created by the water evaporating from the ocean (which is dense) that loses a given quantity of δO^{18}, and that is then transported in the atmosphere (less dense than the ocean) and precipitated all along its way.

By measuring the amount of O^{18} in the ocean, we can deduce the amount of ice it contains.

The level of O^{18} in the past, at the bottom of the ocean, is set at 0 when animals die: time zero is set at the time at which those animals started to sediment. The sediments correspond to past ages composed of skulls of animals containing $CaCO_3$.

The calcite shells on Figure 1.26 of the foraminifera give access to ocean water composition at the time they were living.

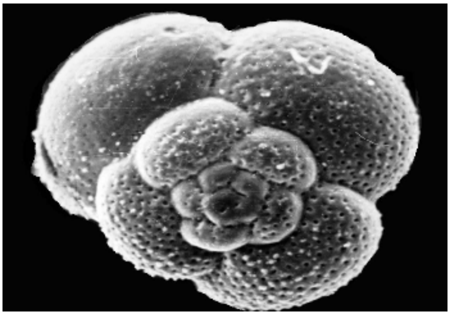


Figure 1.26. *The calcite shell of a foraminifera (Source: UCL Collection)*

It has taken decades of work in order to map out how climate has changed and compute these results in models. Different researchers made holes in the ocean floor in order to assess the variations in the volume of continental glaciers over the past 10^6 years.

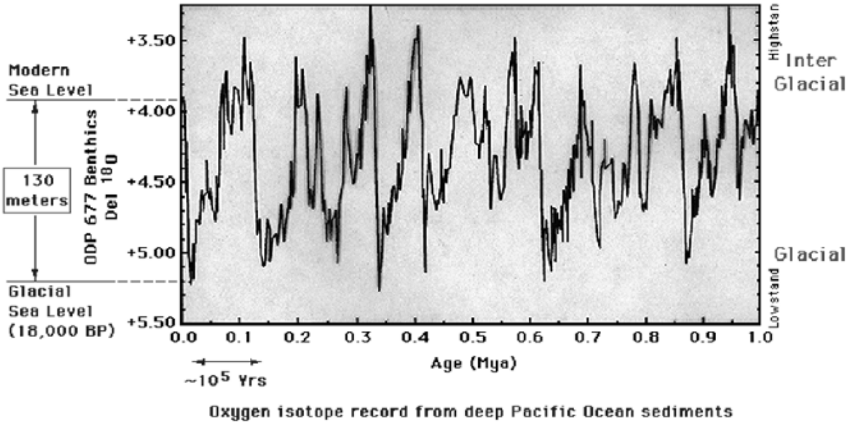


Figure 1.27. *Variation of Volume of Continental Glaciers over the past 10^6 years (Source: Denton et al. (2010))*

The accumulated ice is also able to provide climate records over almost a million years, as shown in Figure 1.27.

As mentioned previously, the isotopic thermometer is a very accurate way to measure the temperature. Glaciers are made of snow which have been circulating for several million years, and the gravity of ice layers is at play too. Jean Jouzel worked on this topic with Claude Lorius, among others, in the 1980s. In a recent book published in 2019, "Climats passés, climats futurs", Jouzel detailed the steps of this exceptional research journey.

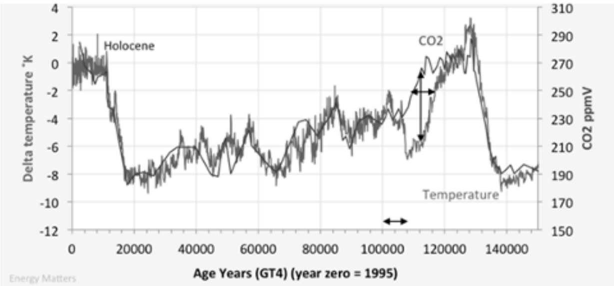


Figure 1.28. *Vostok Ice Core Temperature and CO_2 over the past 150,000 years (Source: Energy Matters, www.ncdc.gov/paleo/icecore/antartica/vostok/vostok.html)*

Figure 1.28 shows that temperatures fluctuations cannot be explained by solar fluctuations only. The most recent interglacial step was a bit warmer than now. The fluctuations that we note at around 20,000 years before present have nothing to do with the Sun. We can also note that in recent times, in less than 2,000 years, there are two temperature maxima. Without solar forcing, the system can oscillate by itself. A forced nonlinear oscillator tends to take the periodicity of the forcing. Some phenomena cannot be explained by solar effects.

Processes which can be detected from deep sea ice cores that give the isotopic content of the sea water in the past will be detailed here. We can indeed deduce the amount of ice in Antarctica, Northern Europe and North America mostly, and Greenland from deep sea cores, thanks to the isotopic contents of sea water. We can then detect carbon dioxide and methane in the bubbles of the ice.

Figure 1.29 presents carbon dioxide concentration, temperature relative to present climate expressed in thousands of years before present with time going from left to right, over the past 400,000 years. This work by Lorius et al. (1985) was pioneering for showing that carbon dioxide and methane – the two main greenhouse gases – were more or less in phase with the temperatures of Antarctica.

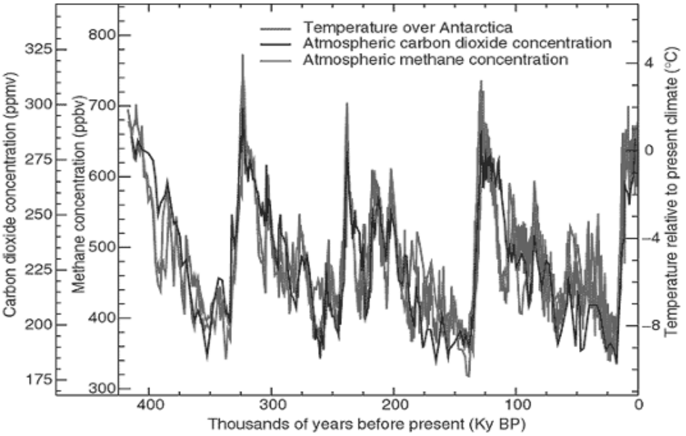


Figure 1.29. *Vostok Ice Core Temperature and CO_2 over the past 400,000 years (Source: Energy Matters; www.ncdc.gov/paleo/icecore/antartica/vostok/vostok.html)*

An interesting question is to know whether the temperature is being driven by carbon dioxide and methane or if carbon dioxide and methane are driven by temperature. This is different from the present situation: we have a climate, more or less at equilibrium, and we introduce carbon dioxide and methane in the atmosphere: therefore, we expect a direct impact of those gases over temperatures.

Instead, Figure 1.30 shows a cycle with a complex combined role of carbon dioxide and methane. Let us consider the Earth mean temperature, plus an addition of carbon dioxide and methane, like in the present situation. What existed in the past was a bit different, and we think that the solar input was probably playing a role which would be antisymmetric between the two hemispheres.

In Figure 1.30, we consider a climate more or less at equilibrium, in which two greenhouse gases, carbon dioxide and methane, are introduced: on the one hand, there is a direct impact of those two gases. On the other hand, solar input also induces temperature increase, and then CO_2 and CH_4 increase, and as a result, the temperature in the other hemisphere increases: this is probably the phenomenon occurring from one hemisphere to the other, which means that the role of CO_2 and CH_4 in the past was mainly to phase the two hemispheres, knowing that in fact the real common energy input was the change of energy from the Sun, which is itself coming from the seasonal changes.

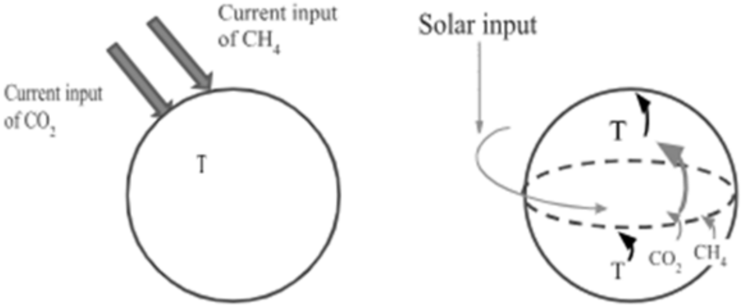


Figure 1.30. *A scheme of the combined role of carbon dioxide and methane*

There are actually three ways for modifying this energy input from the Sun at the top of the atmosphere:

1) Eccentricity, which is related to the shape of the ellipse: it changes the energy input.

2) Obliquity, which concerns the inclination of the axis of rotation of the Earth and has 40,000 years of periodicity: it does not change the total energy input.

3) Precession of equinoxes, which does not change the energy input.

This leads us to make some astronomical considerations and a short digression about the Milankovitch theory (see Figure 1.31).

Milankovitch was a Serbian climatologist who built up the theory of astronomical forcing of Quaternary era climate change in the 19th century. The discovery of Neptune by the French astronomer Le Verrier is widely regarded as a critical validation of celestial mechanics during the same century. This theory explained that 20,000 years ago, the Earth was nearer from the Sun in the summer due to the precession of solstices and equinoxes.

To come back to our considerations summarized in Figure 1.30 about the combined role of carbon dioxide and methane, it means that the way humans affect the climate through greenhouse gases in the present time and the way greenhouse gases may have played a role in the past is largely different because of the complexity of solar input going through seasonal cycles, mostly through the differences between the equator and the pole. Also, as will be detailed further in this book, the fact that CO_2 and CH_4 are well-mixed in the atmosphere creates a situation in which they play a very active role (mostly afterward).

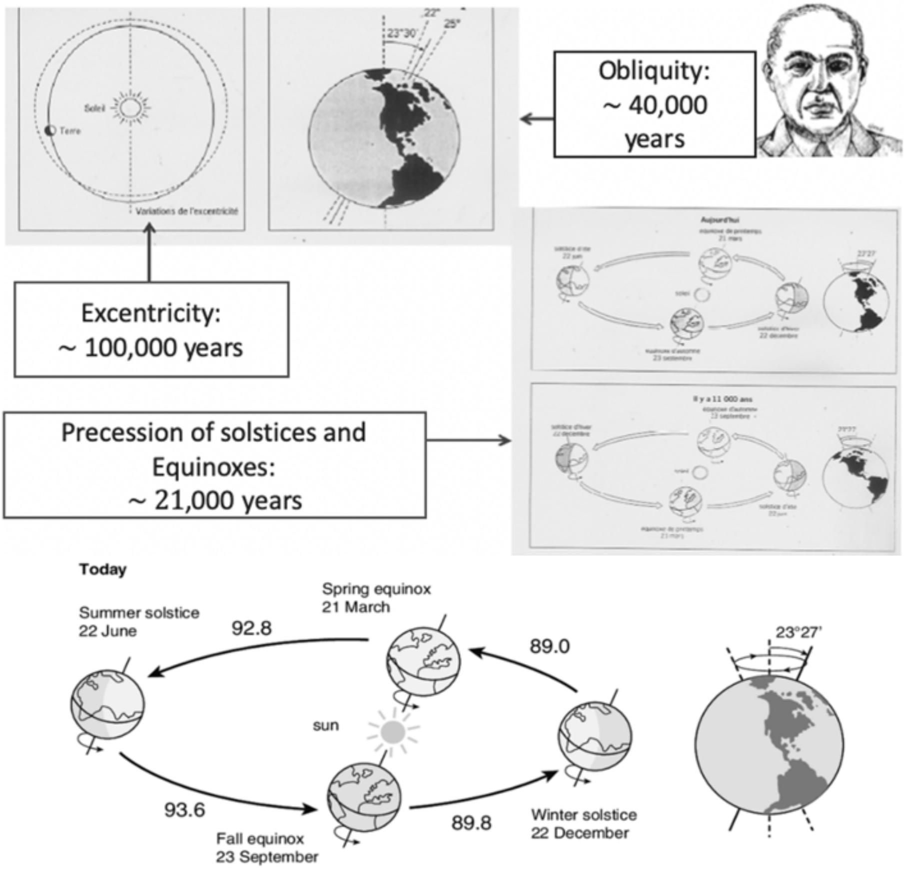


Figure 1.31. *Milankovitch theory: astronomical forcing of Quaternary era climate changes (Source: Astronomical theory and orbital forcing, Yin and Berger (2012))*

There have been a number of debates on this topic. For example, in the documentary by Al Gore "An inconvenient truth", at the time he is climbing over a ladder and shows that the greenhouse gases have been increasing, the question is raised: what will temperature do? The answer is actually not that simple: temperature will increase, but the reason why it will increase is not as obvious as it may seem. Using the past to demonstrate that temperatures will increase is not something completely correct. Beyond the simple scheme on Figure 1.30, attention must be paid.

The demonstration that CO_2 plays a role between the two hemispheres is maybe one of the most important results of Jean Jouzel.

If we go back to Figure 1.29 and observe CO_2, we may anticipate the temperature effect which we expect, and also the reverse, which was not completely expected. There were actually many debates around the following question: why does CO_2 change sometimes before, and sometimes after a temperature change? The answer is that the mechanism at play is complex. Jouzel's results show that indeed there is a link between the two and greenhouse gases are part of the problem. Temperature will increase but past reasons are not completely correct.

We already mentioned that there are two kinds of results to document past climates: the ones from the deep-sea cores, and the ones from the glaciers. We also have a lot of continental records, and the largest number by far of scientists currently working on past climate is focusing on continental records.

Palynologists (scientists studying pollen) work all around the Earth to study where different typical types of vegetation can be found, and from that, infer temperature and humidity records, as they can be linked together. The same work is also largely done for the ocean.

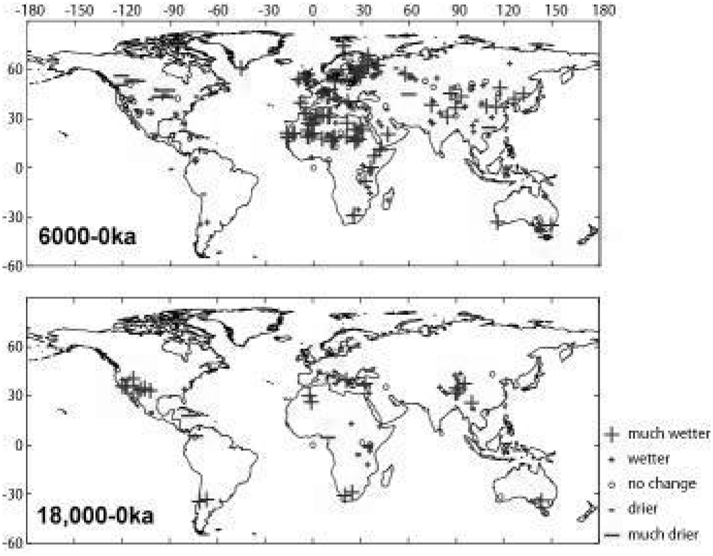
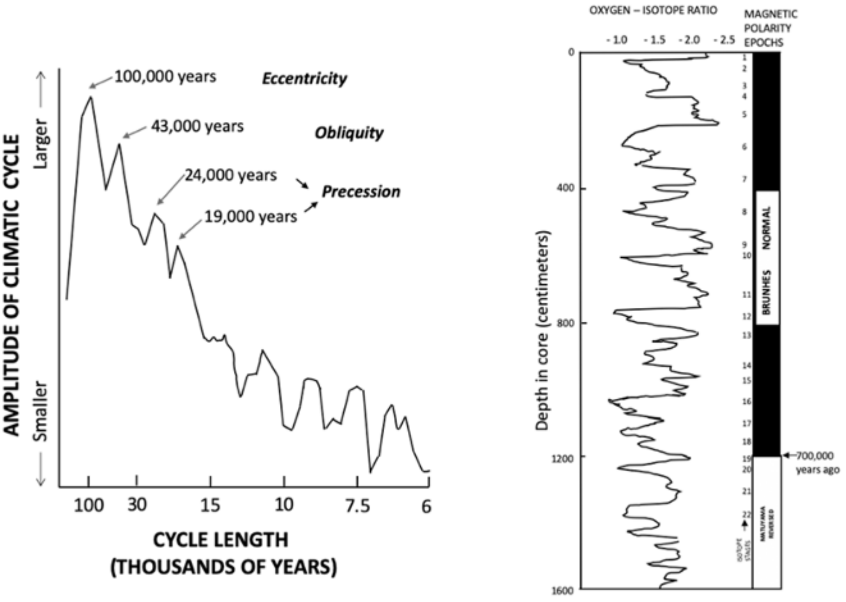


Figure 1.32. *Diagram for humidity at two different timescales based on continental records (Source: Le Treut 2018)*

Figure 1.32 shows that there was a large humidity 6,000 years ago when the North African Sahara was green. This much wetter situation is documented by a large number of records, and we know that it is due to the precession of the equinoxes.

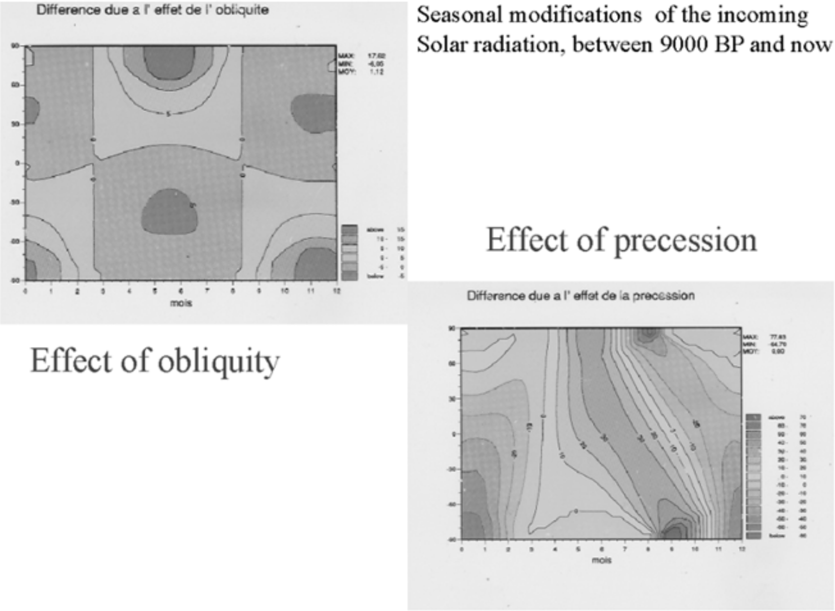


a) b)

Figure 1.33. *a) Spectrum of climatic variation of the past half-million years. This graph – showing the relative importance of different climatic cycles in the isotopic record of two Indian Ocean cores – confirmed many predictions of the Milankovitch theory; b) The “Rosetta stone” of glacial eras (Source: schemes adapted from Imbrie and Shackleton, 1974–1976)*

Figure 1.33(a) and (b) shows results by the Scottish geologist, oceanographer and military John Imbrie’s teams. Imbrie (1925–2016) was very vocal and wrote a book that he entitled the “Rosetta Stone” of the glacial eras.

This so-called “Rosetta Stone” was the first core that could be dated. For this core first, the Fourier’s transform calculations provided the same kind of fluctuations as the ones computed from astronomical forcing.



a) b)

Figure 1.34. *Seasonal modifications of the incoming solar radiation between 9000 BP and now. a) Effect of obliquity); b) Effect of precession (Source: Berger and Loutre (1991))*

The astronomical effects on the Sahara are shown in Figure 1.34, which shows the kind of seasonal modifications of the incoming solar radiation between 9000 BP and now.

The effect of obliquity (see Figure 1.34(a)) pertains to the axis of rotation of the Earth being more or less bent over the plane of the ecliptic, which is the plane of the motions of the Earth around the Sun. This obliquity is the parameter making the difference between summer and winter. When the obliquity is larger, differences between summer and winter are also larger and this configuration mostly changes the amount of energy near the poles, as shown in Figure 1.34(a).

The effect of precession (see Figure 1.34(b)) is also illustrated for one given year, and it shows the differences over this one year of rotation of the Earth around the Sun. The observation of those differences over the same period of time shows that the effects of precession induce a displacement of the warmer period during the course of the year. It is possible to impose this behavior to a numerical model and compute the climate of the past.

Such simulations were done many years ago. The results presented in Figure 1.35 show the differences between the past climate (9000 BP) and present climate in terms of summer temperatures.

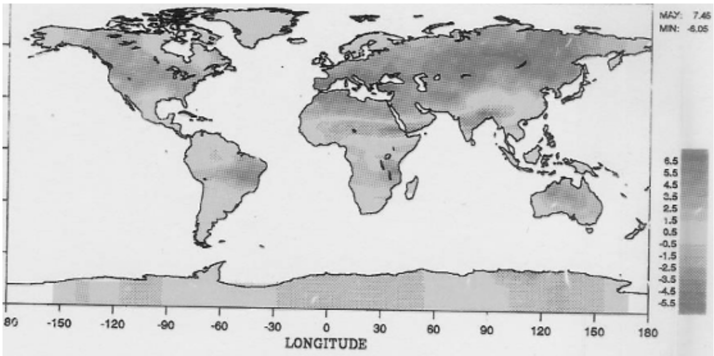


Figure 1.35. *Surface summer temperatures between 9000 BP and now (01.06–30.08). Temperature differences on the ground during June, July and August in Celsius (Source: Berger and Loutre (1991))*

In Figure 1.35, we note that the past climate was warmer during the summer (cooler places are represented in blue.). We can observe a big monsoon all over central Africa/India/Bangladesh; this was a consequence of the solar input being different. A change of precipitation in summer with a strong monsoon over central Africa and India/Bangladesh was observed 9000 BP, and it lasted until 6000 BP. It is important to understand that some changes in the past were due to solar effects; they played a role at scales of thousands of years for which they have been acting very effectively. However, this long scale of time is not comparable to the scale of time of human life, and therefore, this is not something we can expect to drive the system in the next decades.

1.4. A global evaluation of climate stability

Let us come back to equation [1.8]:

$$C_t \frac{dT}{dt} = R_S (1 - \alpha) - R_t(T) \quad [1.8]$$

with α being the albedo, T being the local surface temperature, C_t being the local heat capacity, and R_t being the terrestrial radiation to space.

This equation has been the starting point for our discussion about past climates. We will now consider the effects of solar inputs (direct effects, and effects that are a bit less direct with a demonstrated link between the solar input and the response of the climate). This simple equation contains a lot of complex information and is still not completely solved.

1.4.1. *Let us consider the first term of equation [1.8]*

Let us consider the first term of equation [1.8]. When considering those cycles, some phenomena cannot be explained by the solar input. Let us now work very briefly with a few equations that cannot be completely solved but are nonetheless used to show a more complex behavior than a simple dependence on solar input, with implications for the future climate. In equation [1.8], if the albedo α varies in a simple way, there are three equilibrium states shown in Figure 1.36:

– one is unstable;

– two are stable.

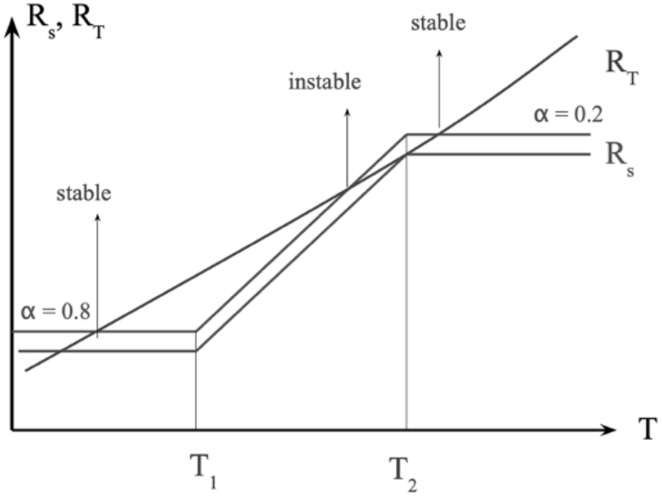


Figure 1.36. *A simplified representation of R_S (1-α) and R_T as a function of temperature*

If we note M the mass of ice, we can write another equation similar to equation [1.8], and the balance in a simplified expression would be:

$$C_t \frac{dM}{dt} = \text{Precipitation} - \text{Melting} \qquad [1.11]$$

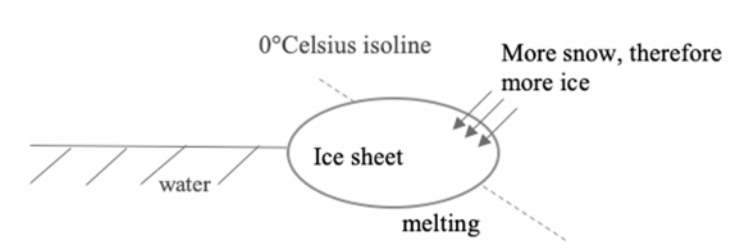


Figure 1.37. *Scheme with the water, an ice sheet and the 0°C isoline for the Arctic*

Let us consider the Arctic, for instance. We can represent it in the scheme on Figure 1.37, showing the water, the ice sheet and the 0°C isoline. Some snow and therefore more ice is added, and some of the ice is melting. There is a balance between addition of ice and melting, which is also dependent on how much the ice sheet may sink into the ground. In fact, one third of the ice at isostatic equilibrium is getting down under the current layer of the water. We also know that the weight of the ice sheet – because it is a viscous elastic body – is linked with its mass. Therefore, we can write a new equation taking that into consideration. A non-obvious phenomenon is that precipitation tends to increase with temperature, because the evaporation of the ocean increases with temperature, and the melting is also increasing with temperatures, but at a different pace. Therefore, we anticipate that when we write those more complete equations, we may have some kind of internal cycle of the climate system.

For example, if we consider the albedo parameter α, reflecting more or less M (the mass of snow/ice), we have two effects:

– If α increases, so the temperature decreases (albedo effect).

– T increases, inducing more precipitations, and therefore α decreases.

This represents what we call a nonlinear system with two opposite feedbacks, characterized mathematically by the fact it may oscillate freely. Therefore, we have the possibility to have, with the glaciers, simple oscillations of the climate system that can be demonstrated with simple equations.

This is a phenomenon that we think is happening, and there was a demonstration of that in a case which is a bit different, done with the direct role of the Sun: climate records do not only reflect the Milankovitch forcing, as illustrated by Figure 1.36. This requires some careful diagnosis.

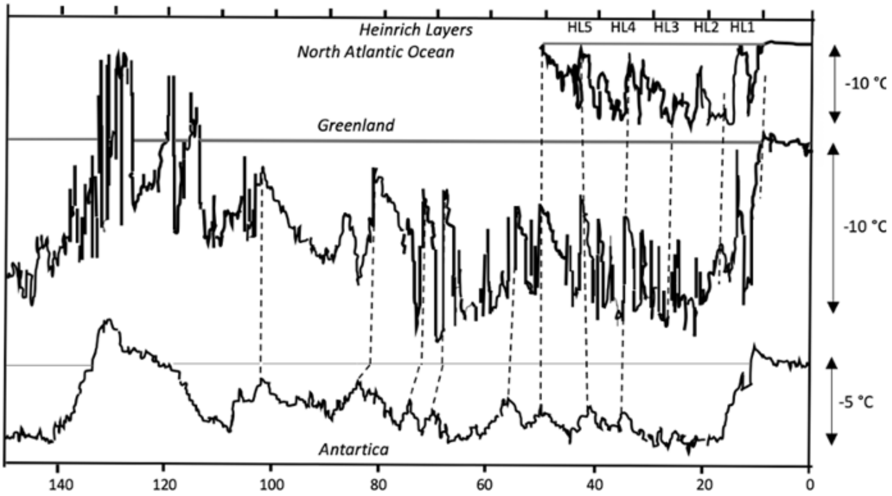


Figure 1.38. *Scheme of reconstructed climate records showing rapid changes in North Atlantic and in Greenland (ground temperatures) (Source: adaptation from Jouzel et al. (1994))*

Figure 1.38, adapted from Jouzel et al. (1994), is based on a work which radically changed the views on past climates. Reconstructed climate records showing rapid changes in North Atlantic and in Greenland are represented: the corresponding events indicated by thin dashed vertical lines are damped in the Antarctic records. Temperature (at ground) changes are estimated from the isotopic content of ice (Greenland and Antarctica) and from faunal counts (North Atlantic). “HL1” to “HL15” refer to different “Heinrich” layers. The time goes from left to right, and we see the last interglacial events: 120,000 thousand years ago, the present Holocene (warm episode).

We can also distinguish fluctuations with an indisputably astronomical origin. As for the quick deglaciations, we note that they are difficult to be linked as solar input. There are also very rapid fluctuations which are quite different and also difficult to explain directly by solar radiation. The measurements were made over

Greenland, the local temperature deduced from isotopes. In Figure 1.38, we can see a warm period, followed by a period which is cooler, various stages, and then it becomes warm again. This is a behavior similar to what we observe in the south with a larger range. This larger range is also a well-known phenomenon: the Northern Hemisphere is reacting to changes more quickly than the Southern Hemisphere. In this figure, we can also observe a large number of small events: at first sight, people thought that it was a wrong measurement. However, there were actually two kinds of measurements from an American group and a European one, working at some distance, and they got exactly the same results.

This observation is now demonstrated to be true, and subsequently, people found out that when looking at the sediments in the North Atlantic Ocean, variations at the same time scale are also found. Those very short events are still however being disputed. There are a large number of oscillators: this one is a global one, but local ones also exist with the Northern Atlantic and Greenland glaciers, which can oscillate.

Those results from Jouzel et al. (1994) show that there are one or several nonlinear free oscillations. Those oscillations generally take the size of a limit cycle with a specific range/amplitude already given by the shape of the equations. It is not similar to a pendula, when put aside; it is revolving with an amplitude that may change depending on how much impulse is given: linear oscillations have a fixed amplitude and may (or may not) have enough energy to oscillate.

Solar input serves as a clock which gives a timing of events within the system. This is fairly consistent with a lot of observed phenomena. These oscillations are simple to translate into equations (note that there are actually many other possibilities to write equations, leading to free oscillations in the system). When we talk about tipping points, the fact that the system may have properties we have yet to master is a phenomenon present in all minds.

Global models generally have no complete ice physics included in them. They involve local ice physics, but they are not able to include motions of the ice at the time scales we consider here because the physics of sea and continental ice are very complex to be described. However, intermediate models with simplified dynamics of the atmosphere, simplified dynamics of the ocean and the ice shelves exist, as well as conceptual models. The integration of ice physics in global models has started with some examples of the inclusion of feedbacks with glaciers. The slow evolution of the glaciers is one of the many reasons which may explain internal oscillations of the climate system.

1.4.2. *Let us consider the second term of equation [1.8]*

Let us now consider the second term of equation [1.8], which anticipates Chapter 2 on radiative processes.

We will describe this as an introduction which will be developed, and we will spend more time on this in Chapter 2.

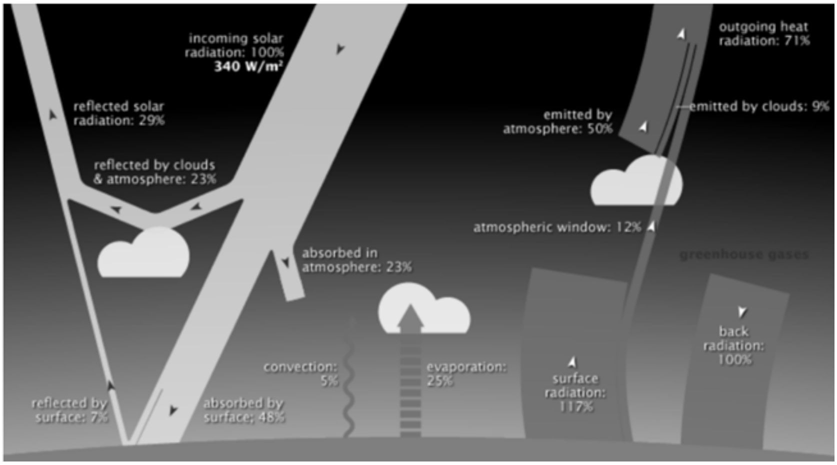
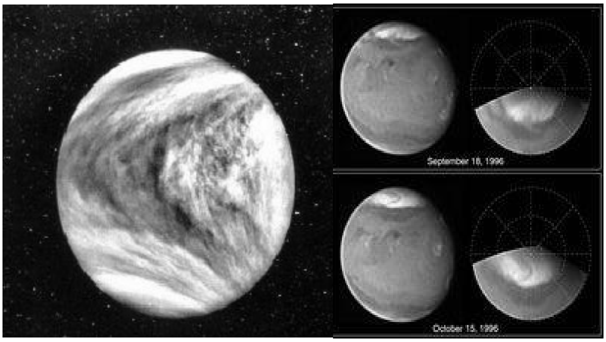


Figure 1.39. *Earth Global Radiation Budget. NASA illustration by Simmon, adapted from Trenberth et al. 2009, using CERES flux estimates provided by Norman Loeb*

Figure 1.39 shows the solar energy entering the climate system, the energy leaving it through diffusion, and what the surface emits in terms of radiation. Only a little part of this terrestrial longwave radiation goes directly to space, it being absorbed and reemitted, partly downward, partly upward. The difference between what is emitted and what actually goes to space is really what we call the greenhouse effect. It means that the surface has to really make a strong effort to be much warmer to send energy to space.

Figure 1.40 shows two sister planets: Mars and Venus. We may wonder whether the future of the Earth is more likely to be like cold, like Mars or extremely hot, like Venus. Venus is hot not only because it is close to the Sun, nor Mars cold only because it is far from the Sun; there are other explanations detailed in Table 1.2.



a) b)

Figure 1.40. *a) Venus. b) Mars. Source: nasa.com*

We would like to provide some indications about how we can look at the Earth when we try to compare it with neighboring planets.

Let us describe it line by line:

	Venus	**Earth**	**Mars**
Distance from the Sun (in Astronomical Unit (AU))	**0.72**	**1**	**1.52**
Solar Flux (in W.m^{-2})	**2,643**	**1,370**	**593**
Albedo	**0.8**	**0.3**	**0.22**
Temperature without greenhouse effect (K)	**220**	**255**	**212**
Real temperature (K)	730	288	218
Greenhouse effect (K)	**510**	**33**	**5**

Table 1.2. *A comparison between three sister planets. For a color version of this table, see www.iste.co.uk/letreut/energetics.zip*

The distance between the Sun and the Earth defines a reference unit that we call one astronomical unit (AU). Table 1.2 shows that Venus (0.72 AU) is closer to the Sun than the Earth (1 AU) and that Mars is further away than the Earth (1.52 AU).

Table 1.2 also delivers the corresponding solar fluxes, and the albedo that may vary a lot with the state of the planet.

This occurs in a way that is different from the Earth for those two planets:

– Venus is very warm but has a very strong albedo (0.8) because the gases over Venus are reflecting a lot. Venus has a very deep atmosphere, with very toxic gases, and large temperatures compared to Mars and the Earth.

– The present albedo of the Earth (0.3) is smaller than that of Venus (0.8).

– Mars has changed a lot in the past; now, it is a planet with a few ice caps, which are made of CO_2. Its albedo is not very strong (0.22) because of its lack of water and because of its very thin atmosphere.

Table 1.2 also presents those three planets' temperatures without the greenhouse effect. It is interesting to note that if we just take the albedo effect and the solar input, then those three planets are mostly equivalent, with temperature differences only between 8 to 33 K.

The greenhouse effect comes from the fact that the atmosphere absorbs part of the energy emitted by the ground. This part of energy emitted by the ground may largely vary from one of the three planets considered here to another, and the energy that has to be emitted to balance out the incoming solar radiation and the albedo effect may completely change. Therefore, when we consider the respective greenhouse effects of Venus, the Earth and Mars, there are consequently huge temperature differences between those three planets.

For the case of Venus, there is a very strong greenhouse effect, leading to high temperatures (hundreds of degrees). For the Earth, we will discuss it in the course of this book. For Mars, there is a small greenhouse effect and its temperatures remain rather cool (unlike what it may have been in the past).

The figures included in Table 1.2 raise the following question: why are those three planets so different?

First, the differences come from the fact that the greenhouse effect plays a big role, and an important derivative question is: can the greenhouse effect drastically change the Earth's temperatures in the future?

When coming back to equation [1.8] and given the fact that the terrestrial radiation depends on T, we note it R_t (T). The first greenhouse gas is actually water vapor.

Therefore, we can infer that a potential feedback would reasonably be due to some kind of change due to water vapor.

The link between water vapor and temperature can be made as follows: what determines the amount of water vapor in the atmosphere is precipitation, which happens when the condensation level is reached, a level directly dependant on temperature.

The dependence of the water vapor on temperature is represented in Figure 1.41, also known as the Clausius–Clapeyron graph.

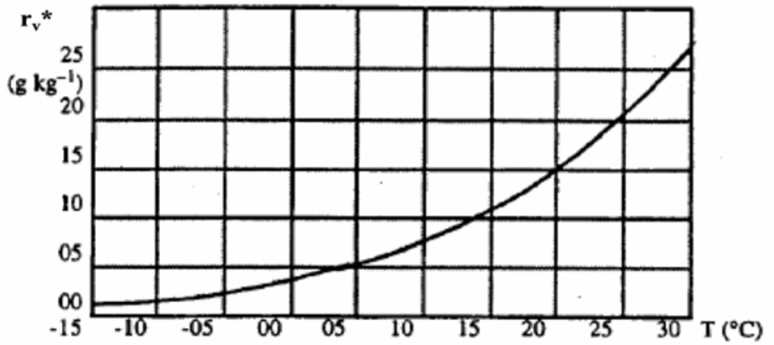


Figure 1.41. *Clausius–Clapeyron ratio of water vapor in the atmosphere at saturation. The saturation level for water vapor increases very quickly with temperature*

r_v* is the ratio of water vapor in the atmosphere at saturation. Each point of the curve refers to the value of this ratio for a given temperature where the condensation point occurs. It is expressed in grams of water vapor per kilogram of air.

We observe a very strong increase with temperature. We have negative temperatures on the far left, and we get to positive temperatures near the equator. If we place our attention on those cool temperatures, we note that r_v* is bordering 1 g.kg^{-1} at −10°C, while, for instance, at 25°C, we have: r_v* = 20 g.kg^{-1}.

This means that at a temperature of 25°C, the amount of water in the atmosphere is 20 times larger than at a temperature of −10°C. Therefore, with 35°C degrees of difference, there is a factor 20 more or less in the amount of water vapor that can stay in the atmosphere, which actually represents a very large change.

In fact, it is even more than a factor 20 because the temperatures can get very easily up to −40°C in the higher atmosphere and in tropical areas; temperatures can be occasionally higher than 35°C degrees. Therefore, there is a huge spread of water vapor content between low and high temperature values.

We now want to find a criterion for stability, and for that, we will consider a simplified version of the climate system with an ascending motion near the equator – unlike what was discussed for the albedo, what may modify the climate in terms of the greenhouse effect is occurring more strongly near the equator.

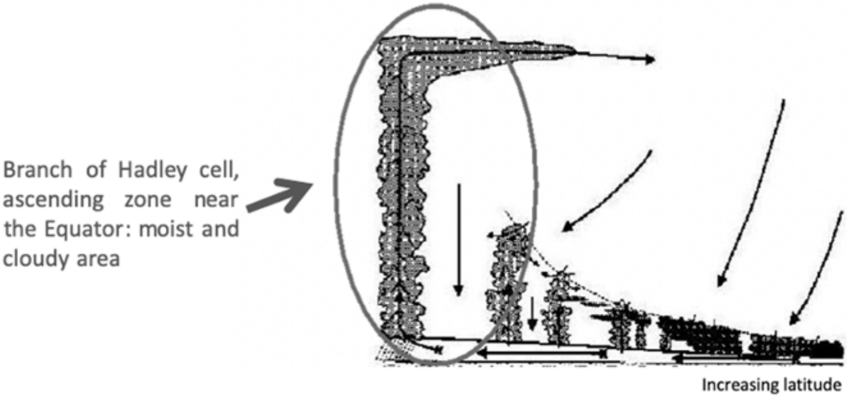


Figure 1.42. *A simplified scheme of the intertropical climate*

In Figure 1.42, an ascending region near the equator is highlighted in red, then the air is being brought to high latitudes, and afterward, it gets down. In the gray area on the left, a branch of Hadley cell is represented, and in the descending part of the Hadley cell, there can be low clouds or deserts, depending on if there is an ocean at this place.

It is possible to write a simple equation to describe this phenomenon.

1) Let us first write a simple representation of the emissions for the case of a blackbody radiation: $\boldsymbol{\sigma} \mathbf{T}^4$.

2) However, the Earth is not an actual blackbody and the terrestrial emission is less than the one that a blackbody would be, as the greenhouse effect brings back radiation to the ground: we can note this greenhouse effect $G(T)$.

3) Therefore, we can write the two components of the terrestrial emissions as the sum of the blackbody radiation minus the greenhouse effect:

$$R_t(T) = \boldsymbol{\sigma} \mathbf{T}^4 \times (1 - G(T)) \qquad [1.12]$$

4) Of course, the greenhouse effect G(T) increases with temperature, which is a source of main potential destabilization of the system.

Let us now just consider stability–instability criteria for such a system. In the case of an equilibrium, we can consider that for a fixed point that does not change, the temperature T_{eq} can be written as:

$$\mathrm{T} = \mathrm{T}_{\mathrm{eq}} + T \qquad [1.13]$$

We can write:

$$\frac{\mathrm{dT}}{\mathrm{dt}} = \mathrm{f}\,(\mathrm{T}) \qquad [1.14]$$

Therefore, the equation becomes:

$$\frac{\mathrm{dT}}{\mathrm{dt}} = \mathrm{f}\,(\mathrm{T}_{\mathrm{eq}} + T) \qquad [1.15]$$

Also, we may develop it when we take a first development as:

$$\frac{\mathrm{dT}}{\mathrm{dt}} = \mathrm{f}\,(\mathrm{T}_{\mathrm{eq}} + T) = \mathrm{f}\,(\mathrm{T}_{\mathrm{eq}}) + \frac{\mathrm{df}}{\mathrm{dt}} T \ldots \qquad [1.16]$$

with $\mathrm{f}\,(\mathrm{T}_{\mathrm{eq}}) = 0$ because it is equilibrium; therefore, we can write:

$$\frac{\mathrm{dT}}{\mathrm{dt}} = \frac{\mathrm{df}}{\mathrm{dt}} \mathrm{T} \qquad [1.17]$$

To determine the stability or instability condition of a system, the following considerations can be done:

$$\frac{\mathrm{dT}}{\mathrm{dt}} = \mathrm{f}\,(\mathrm{T}) \frac{\mathrm{dT}}{\mathrm{dt}} = \mathrm{f}\,(\mathrm{T}_{\mathrm{eq}} + T) = \mathrm{f}\,(\mathrm{T}_{\mathrm{eq}}) + \frac{\mathrm{df}}{\mathrm{dt}} T \ldots$$

with $\mathrm{f}\,(\mathrm{T}_{\mathrm{eq}}) = 0$

$$\mathrm{T} = \mathrm{T}_{\mathrm{eq}} + T$$

with T_{eq} referring to a fixed point.

Box 1.1. *Stability condition of the climate system*

A little increase in temperature would mean that if the term:

$$\frac{\mathrm{df}}{\mathrm{dt}} < 0 \qquad [1.18]$$

then it will bring the system back to equilibrium.

Therefore, to know whether the system is stable or instable, we should look at the sign of $\frac{df}{dt}$.

1.4.3. *A global estimate of climate stability considering another source of complexity: the greenhouse effect*

If we rewrite the energy budget equation, we have:

$$C_t \frac{dT}{dt} = R_S\,(1 - \alpha\,(T)) - \sigma\, T^4\,(1 - G(T)) \qquad [1.19]$$

G(T) is a “greenhouse index”. We then obtain, as a stability condition:

$$-R_S \frac{d\alpha}{dT} + \sigma T^4 \frac{dG}{dT} - 4\sigma T^3 (1 - G(T)) < 0 \qquad [1.20]$$

After derivation of the equation, the stability of the equilibrium according to the criterion of equation [1.18] would therefore be:

$$-\left(-\frac{DG}{DT}\right) \sigma T^4 - \; 4\sigma T^3 (1 - G(T)) < 0 \qquad [1.21]$$

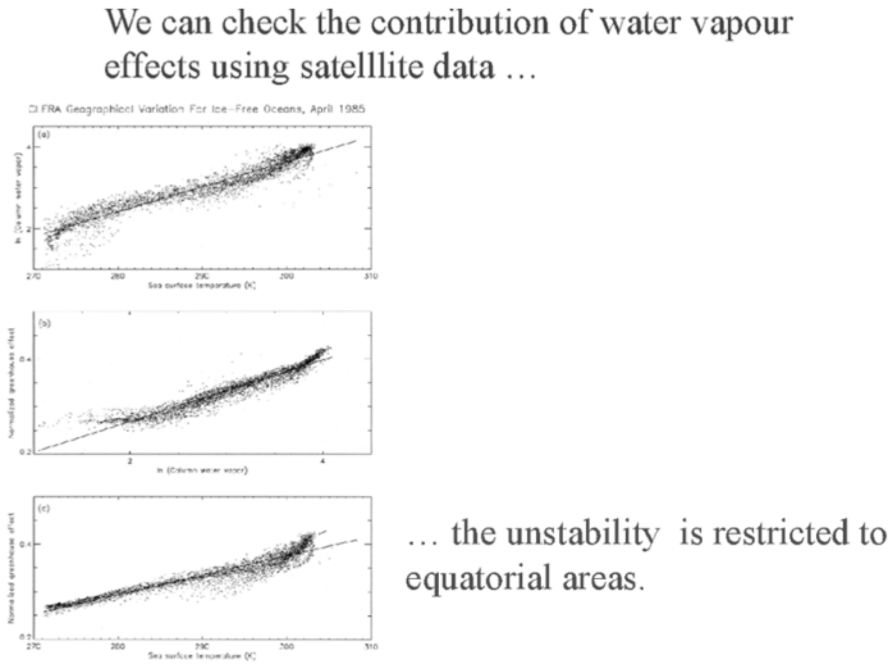
From equation [1.21], we found that the criterion of stability that we need to have is:

$$\frac{dG}{dT} < \frac{4}{T}\,(1 - G(T)) \qquad [1.22]$$

NOTE.– Difficulties to get temperatures from satellite data come from the fact that for oceans, surfaces are mostly black bodies: they emit depending on their temperatures, but in cloudy areas, measurements must be done in between the cloud in clear-sky holes.

$R_t(T)$ is the radiation that gets out to space, this is the most obvious satellite data: the satellite collects all of the radiation in the infrared that gets out and $R_t(T)$ is known. This type of work is largely done by teams of Laboratory of Meteorological Dynamics (LMD) of the Institute Pierre Simon Laplace (IPSL) who have been designing such instruments.

Also, as we have the value of σT^4, $R_t(T)$, and we know how to derive G(T), we therefore can solve the equation.



We can check the contribution of water vapour effects using satelllite data …

… the unstability is restricted to equatorial areas.

Figure 1.43. *Satellite data can be used to check the contribution of water vapor, with instability restricted to equatorial areas. CLERA project (Source: British Meteorological Office)*

Figure 1.43 shows the results from the project CLERA run by the British Meteorological Office. It shows regressions. On the top diagram, for example, a column of water vapor as a function of sea surface temperature is represented: the water vapor is increasing with sea surface temperature, with a trend comforting our previous computational results.

The middle graph of Figure 1.43 shows the greenhouse index G represented as a function of a column of water vapor. This index increases with water vapor: the greenhouse effect is largely dependent on water vapor. Mostly, this work has been done in locations allowing measurements on clear-sky conditions to get rid of clouds, observing the holes of clear-sky between clouds if necessary.

The bottom graph of Figure 1.43 emphasizes the main result by displaying the normalized greenhouse effect as a function of sea surface temperature. This is the element that has to follow some criterion for the respect of a stability condition of the equilibrium.

This criterion is quite easy to define as based on two parameters that are already known thanks to the diagram:

– the slope with a value of $\frac{4}{T}$ which depends on the temperature T;

– multiplied by (1 – G (T), and we can measure G (T) at any point on the graph.

Therefore, we have the value of $\frac{4}{T}$ (1 – G(T)), and we are able to compare this result with the value $\frac{dG}{dT}$.

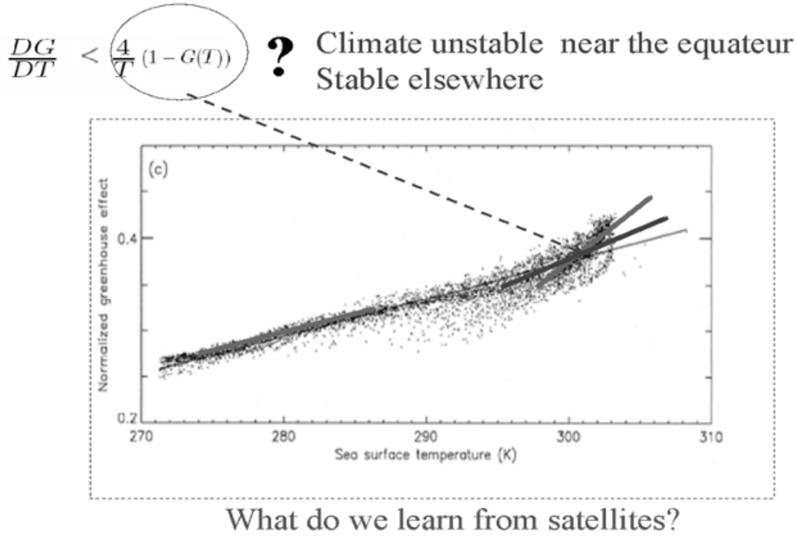


Figure 1.44. *Zoom on the regression of the normalized greenhouse effect as a function of sea surface temperature (in K) (Source: CLERA project, British Meteorological Office)*

Regarding the graph of Figure 1.44, we see temperatures going from 270 K to 310 K; the regression line in black shows a good correspondence between the normalized greenhouse gas effect and sea surface temperature.

If we imagine a zoom around 270 K of the graph in Figure 1.44 representing the normalized greenhouse gas effect as a function of sea surface temperature, we can draw the scheme of Figure 1.42 of greenhouse effect as a function of temperature G (T).

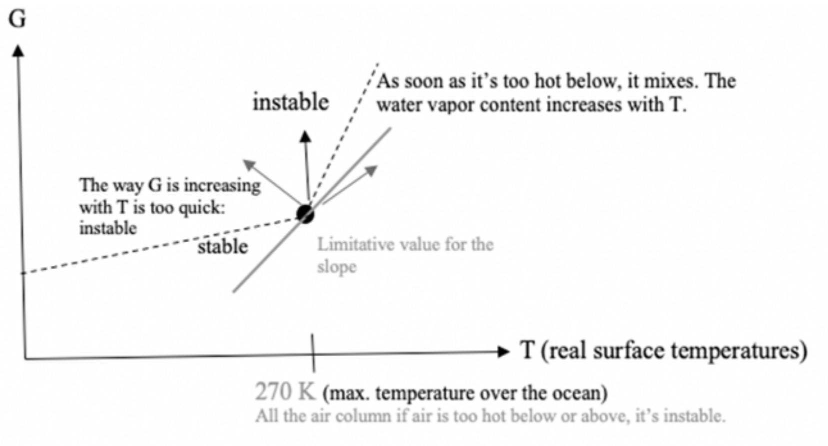


Figure 1.45. *Scheme of the regression of the normalized greenhouse effect as a function of sea surface temperature (in K) (Source: Hervé Le Treut)*

At around 270 K, the point of the curve takes on a curvy shape. When analyzing the dotes of G(T) in more detail, there is actually a limit value for the slope represented in red in Figure 1.45, meaning that where the slope is smaller than this limit value, there is a stable condition.

This shows that a simple equation can give much information, because this in fact means that 270 K represents more or less the maximum temperature over the ocean on average: between 30 N and 30 S, the surface temperature of the ocean is almost always 270 K, meaning that the way G increases with temperature at this point is too quick, and the equation is unstable. Whereas, before this point, the way G increases with temperature is smaller, so the condition is stable.

If we go back to Figure 1.42, we note that the atmosphere is ascending near the equator and descending north of the equator, with a similar situation in the other hemisphere. Where the atmosphere is descending, there is a stable climate, while where it is ascending near the equator, the climate is unstable: it means that, in fact, the climate near the equator is very warm, and when the amount of water vapor is large, the associated water vapor feedback is proportionally growing; therefore, the enlarged amount of water vapor at the equator can bring about a phenomenon named the "runaway greenhouse effect" in those regions, as it may escape out of control.

Another important feature is that near the equator, on the descending areas of the Hadley cells, on the contrary, there is a stabilizing effect: indeed, very dry air is descending in those locations, with little water vapor capacity to send back infrared radiation to space through the atmosphere because of the very little amount of greenhouse gases there. Additionally, there is a phenomenon of albedo reemitting much solar energy because of the deserts in parts of those territories.

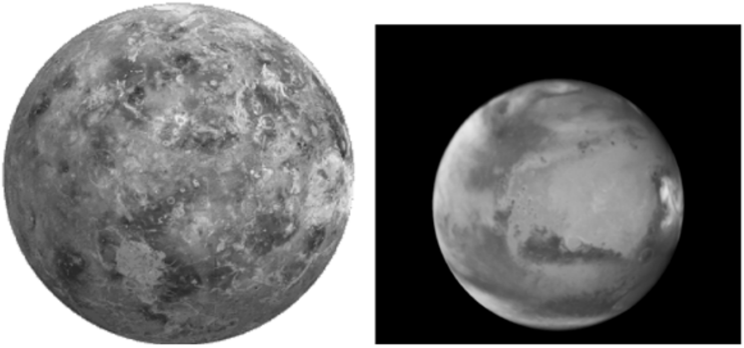


Figure 1.46. *Are we on Mars or on Venus? Source: nasa.gov*

To the question, “are we closer to Mars or Venus’ situation?”, a very simple answer can be found through basic physics: we are closer to Venus near the equator, but contrary to Venus, the Earth system is not really in a situation of water vapor runaway effect because there is a stabilizing effect on each side of the equator that manages to keep the system stable.

When considering the possible versions of the Earth relative to the features of Mars and Venus, this stabilizing effect on the Earth is fundamental and has played a role for thousands of years, despite the change in the shape of the continents, as this phenomenon does not really depend on the position of the continents, but instead on the gradient of temperature between the equator and the poles – and the dynamics establishing this gradient is mostly driven by the Earth’s rotation speed. Therefore, it is a rather permanent feature of the Earth system.

1.5. Conclusion

In the first part of this introductory chapter, we have seen that life is a first possible reason for a rather stable climate over years.

Another reason explaining the Earth's climate is due to the Earth's rotation upon itself and the fact that this rotation is quick enough to bring deserts very close to the equator, over an area named the desert belt. For example, over Mars, the Hadley cells go to the Poles and the situation is very different in terms of stabilizing effect.

Other factors favoring the stability of the Earth climate have been discussed among the scientific community, which we did not discuss in this chapter: one of these is the moon influence, which has kept the variations of the Earth orbit within a solar range and that may also have played a role in the climate of Earth system stability.

In Chapter 2, we will discuss radiation processes in detail.