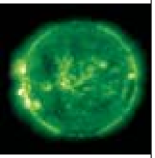


The influence the Sun exerts on the climate of the Earth-like planets is due equally to the evolution of the star itself, to the planets' positions relative to it, and to the makeup of their atmospheres. On Earth, human activity is added to geological factors, causing an accelerated influence on climate.

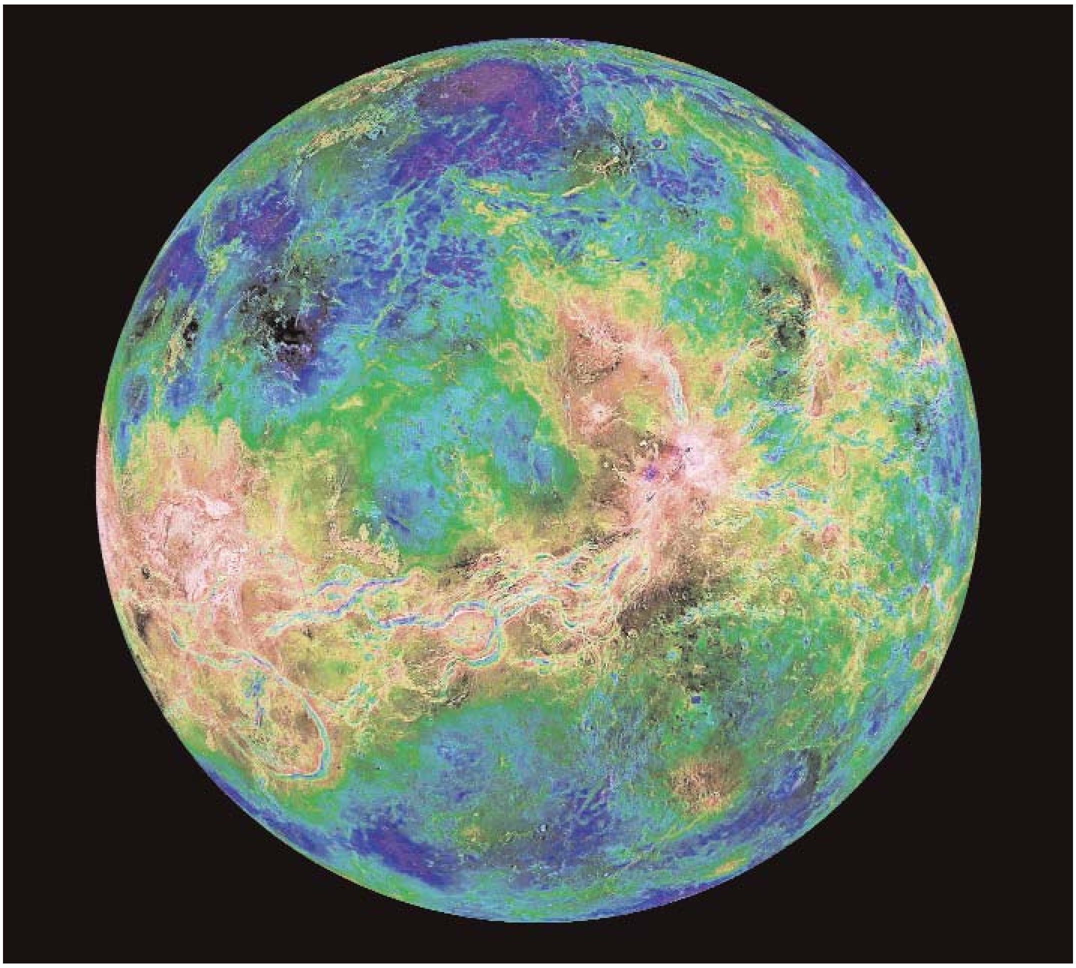
When **the Sun** meets **the Earth**

Seen from space, the Earth does earn its appellation as the "blue planet."

NASA

A blue and distinctive Earth

The ground temperature of Earth-like planets with little or no atmosphere is essentially determined by their position relative to the Sun. Mercury, for instance, the planet closest to the Sun, with the Sun's rays beating down on its surface, registers day temperatures of 430 °C, whereas night temperatures drop down to – 100 °C. Nor is there any way of countering strong seasonal contrasts: no ocean to mitigate such variations is to be found on its cragged surface! What of our two close neighbors, Mars and Venus? Mars, the further out of the two, probably benefited from balmier times than the present, when it only has a very tenuous carbon-dioxide atmosphere left, and temperatures vary from + 20 °C by day to – 140 °C by night. It climate has probably been much altered. First, because the tilt of Mars's axis of rotation may vary, more so than the Earth's, for which the Moon acts to restrict drastically angular displacement. And also because, as on Earth, the presence of **greenhouse-effect gases** (GEGs), and most emphatically of **carbon dioxide**, up to $2 \cdot 10^5$ pascals (2 bars) in its early, youthful state, would have allowed the planet to experience a milder climate. The case of Venus is different: its very dense, GEG-rich atmosphere turned it into an inferno, with ground temperatures of 470 °C! In between these two planets, the Earth, where ground temperatures allow the presence of water in all three phases, has oceans, at times ice caps, and, well represented in its atmosphere, water



NASA/JPL

Image of Venus (in false colors) obtained from radar data from the Magellan probe.

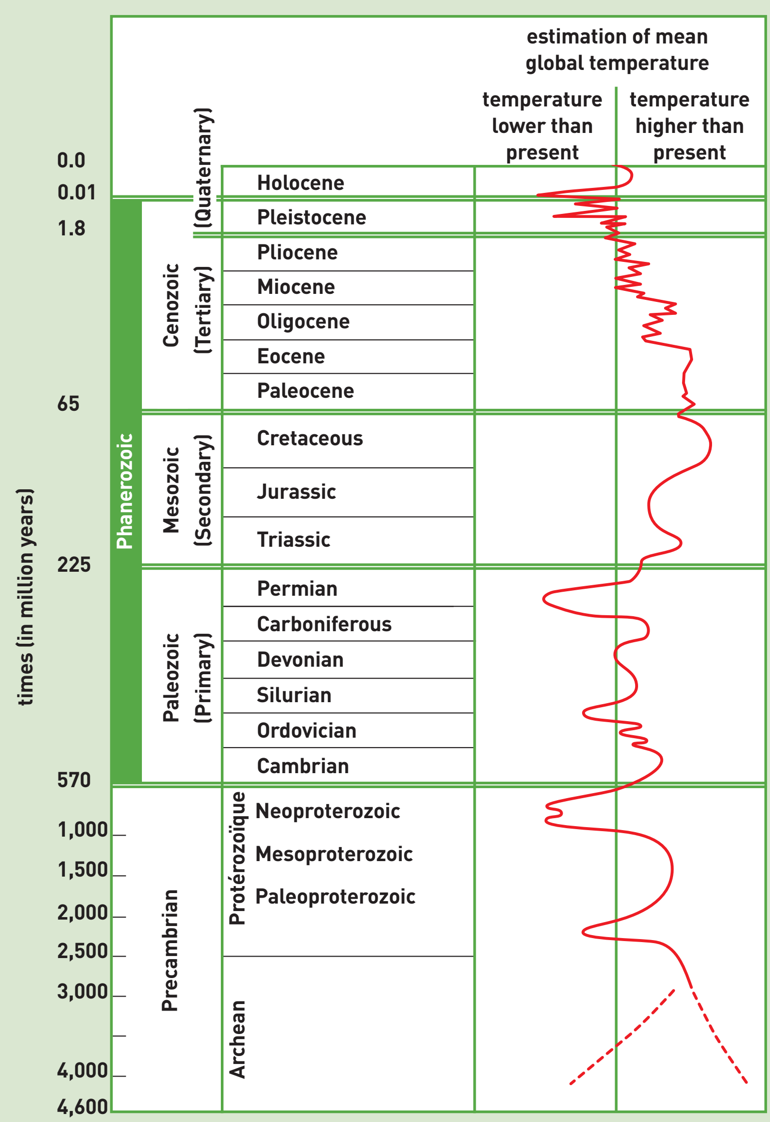
vapor, the main greenhouse-effect gas. Only the Earth, barring any new information to the contrary, is host to life. Is this due to its privileged position relative to the Sun, being closer to it than cold Mars is, and further out than oven-hot Venus?

A history more fraught with turmoil than had been thought...

In fact, the climatic history of all these planets is greatly bound up with the evolution of the Sun itself. Nor has the Sun always glared as brightly as it does nowadays. In its infancy, it was "dimmer" by some 20%. 800 million years ago, for example, solar radiation was weaker, by an amount of the order of 6%, than the "nominal" level it has slowly reached. Such faintness, in the star round which they gravitate, should have proved fatal to the young planets, Earth, Mars and Venus, inexorably resulting in temperatures below zero. In fact, no such thing occurred: outgassing from the mantle of water vapor, carbon dioxide, **methane** and other such GEGs allowed these planets to experience, in their youth, much milder climes. Subsequently, their climates diverged. Mars and Venus underwent the transformations we have seen, no doubt after less extreme climatic periods. As for the Earth, did it only experience, under that selfsame Sun, variations between hot climates, such as those of the Cretaceous, when the dinosaurs flourished, and major glacial ages such as those in the Quaternary, that the Neanderthals lived through in Europe (see Figure 1)?

NASA/JPL/Brown University

Simulation of Mars, as the planet may have appeared at the height of a relatively recent ice age (courtesy of Nature Publishing Group: *Nature*, Vol. 426, No. 6968).



(Source: *Climat d'hier à demain*, S. Joussaume, 1999)

Figure 1.
Evolution of temperatures on Earth through the geological eras.

The belief, nowadays, is that indeed it did not. Not only did the climate of our planet vary, going through very long warm periods such as the Archean, Carboniferous, or Cretaceous with no ice caps present, and a few, infrequent colder intervals (amounting to less than 10% of the Earth's climate history), when such ice caps were in existence, such as the Permian–Carboniferous boundary, the Ordovician and the Quaternary in which we are living. But the Earth has doubtless also been widely, or even completely, frozen over – twice at least during the Neoproterozoic, 800 million years ago.

The white Earth, a disaster scenario?

The early climate models developed in the 1960s, in particular by Russian climatologist M. I. Budyko, were based on the utilization by the Earth system of incoming solar energy, and its conversion into **infrared radiation**, taking on board the properties of the surfaces involved, and the dynamic and thermal characteristics of the atmosphere. There were derived from this, from the end of the 1960s, one-, two- or three-dimensional models, the so-called energy-balance models. On the basis of findings from such models, Budyko showed that, had the Earth completely frozen over, then it would remain so yet! Indeed, our planet's reflective power (its albedo), nowadays, stands at 0.3, which means, broadly, that only 70% of the energy from the Sun is available to be used as fuel for the ocean and atmosphere, so that they may redistribute and take out the energy they receive; 30% of solar radiation is reflected away, and does not enter the system. The albedo of a "white", completely frozen Earth (with continents covered in ice and oceans under a thick ice sheet) would have at least twice that value (0.6), meaning that only 40% of solar energy would be usable. To raise the Earth from such deep slumber, considerable energy would be required, calling in effect for a Sun 1.25 times more powerful than it is presently, which is absurd: hence, the Earth could never have undergone complete glaciation – QED. This paradigm stood for thirty years, only coming radically under question in recent years.

La Villette

The Earth experienced its last glaciation about 20,000 years ago (at right).
Did it completely freeze over 750 million years ago?

Carbon dioxide, a major component

Indeed, a major component was missing, in Budyko's brilliant argument: carbon dioxide. For ours is a living planet, geologically speaking, contrary to what pertains for the Moon, or Mars, where all volcanic activity has ended. Should a global glaciation occur on Earth, this will have repercussions for the carbon cycle, on a geological scale. The first being that, if land-based and undersea volcanic emissions continue, carbon dioxide will be stored in the atmosphere, since there is no "well" left for it to be sunk in. And were glaciation to extend over a long period (a few million years), concentration of the gas will reach phenomenal values, and its greenhouse-effect properties will bring about a thaw. Not only did carbon dioxide, particularly by way of its atmospheric content, have the ability to compensate for the young Sun's faintness: it also has a capacity to regulate the Earth's climate.

On a geological scale, it is not the only factor to wield such privileged power. Plate tectonics, which, for billions of years, has ceaselessly been altering the face of our planet, also determines its climates. We shall see that these two "regulators" of solar activity are also closely bound up together.

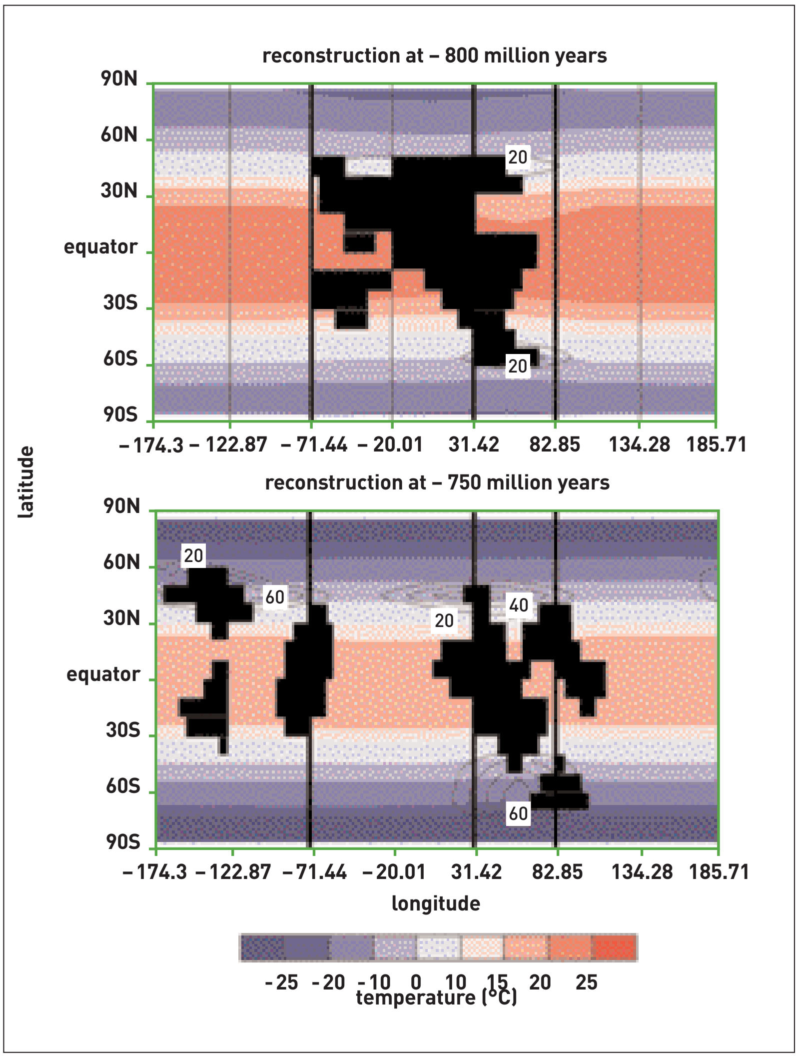
Even though the first four billion years of our planet's climate history are not so well known as the last 600 million years (the Phanerozoic) – these in turn being far less well known than the last two million years (the Quaternary) – one observation is striking. In a context where the young Sun was less powerful, the Earth experienced, over these four billion years, climates that were warm, with infrequent glaciations: a first cold episode at 2.4 billion years, and a second one between 800 and 600 million years. Now, these glaciations are not, on a first analysis, linked to variations in solar energy, but to changes in the composition of the Earth's atmosphere. Research workers thus believe that emergence of life in bacterial form caused a rise in the oxygen content of the Earth's atmosphere, and the oxidation of methane, a powerful greenhouse-effect gas. The atmosphere, thus becoming depleted in highly efficient GEGs, would have allowed ground temperatures to fall, resulting in a massive glaciation, the so-called "Huronian" glaciation, of which many geological traces are to be found. The second glacial episode occurred much later, at a time when the Earth's atmosphere was far more similar to what it is now.

One hypothesis, however, does account for this glaciation, which took place in a specific geological context. Indeed, this was the time when a supercontinent, Rodinia, which had formed at 1.1 billion years, began to break up into smaller fragments, between 800 and 750 million years, mainly in tropical regions (see Figure 2). This major event, on a geological scale, for the Earth's climate also had a major impact on atmospheric CO_2 content. All these small continents underwent rock erosion and soil alteration, thus trapping huge quantities of CO_2, which were transported to the ocean depths. This brought about a fall in the atmosphere's CO_2 content – which may be evaluated, by way of a climate–carbon model, at some 1,000 ppm – and thus a considerable decrease in atmospheric greenhouse effect, which would account for the traces of glaciation. There remains to understand why this could have been global.

From the Precambrian glaciations to the Phanerozoic glaciations

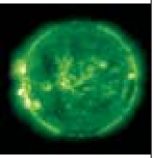
A first paradox, regarding the Precambrian glaciations, whether Huronian or Phanerozoic, becomes apparent: from paleomagnetism, it can be ascertained that these occurred at low latitudes, whereas all glaciations, for the past 530 million years, have always taken place at high latitudes, this being fully consistent with solar energy distribution as a function of latitude (see Figure 3). However, other paradoxes yet, concerning the Phanerozoic glaciations, have kept geologists puzzled, for the past thirty years.

First such paradox, the reappearance of the so-called banded iron formations (BIFs), which had vanished at 2.4 billion years, after atmospheric and oceanic oxygen levels allowed iron oxidation, interfering with its solubility. Why should there have been, around 800 million years, a return to an anoxic (oxygen-poor) ocean? A second puzzle lies in the observation of varia-



(Source: Yannick Donnadieu, PhD thesis.)

Figure 2.
Simulations of climate on Earth before and after fragmenting of the Rodinia supercontinent, at 800 and 750 million years respectively. Initial findings show that the models reach equilibrium for carbon dioxide contents (pCO_2) of 1,800 ppm and 500 ppm respectively, i.e. with mean global temperature falling over the same time from 10.2 °C to 2 °C. Prior to fragmentation, a tropical position of the continents does not appear to provide a condition sufficient for formation of an ice cap, even though the climate is relatively cold. After the breakup of Rodinia, the configuration (smaller, more dispersed continents) appears to be highly favorable to development of a major glaciation. (Note: these simulations do not factor in volcanic processes which, through the more rapid alteration of basalts, will bring about global glaciation.)



tions in carbon-13 content, this being the stable heavy **isotope** of carbon. Finally, as a last, spectacular characteristic of these glaciations, are the indications of glaciation: the tillites (a type of glacial moraine deposit), overlain by a thick layer of carbonates, as can be found nowadays in warm seas throughout the world. Harvard Professor Paul Hoffman was the first to provide, with the "snowball Earth" theory, in 1994, a conceptual framework that could account for all of these paradoxes. Indeed, a global glaciation made it possible to understand both the return of "BIFs" in an ocean covered by a thick ice sheet and poorly oxygenated, and variations in carbon 13, linked to a complete standstill of the carbon cycle. Carbon dioxide released by volcanoes would have been stored in the atmosphere, until, as a result of a "mega-greenhouse effect," global thaw occurred and the Earth became warmer, this causing, through very rapid erosion due to very strong precipitations, burying of carbonates yielding the "cap carbonates" that overlay the glacial sediments.

The Earth's climate history, in the hundreds of millions of years that followed, at a time when the Sun had reached a luminosity close to what we find nowadays, saw its pace essentially driven by plate tectonics. As early as the beginning of the twentieth century, as Alfred Wegener put forward his theory of continental drift, his father-in-law, Wladimir Koppen, drew up the first climate maps associated to such drift in latitude. Thus, 300 million years ago, very heavy glaciation occurred in the southern hemisphere, when the south of the Gondwana supercontinent was occupying a polar position. Traces of this glaciation are found in Africa, India, Australia and in the Antarctic (see Figure 3). As a matter of fact, glaciation periods entailing that a continent was in a polar position are rather infrequent, and it is the warm periods, showing no trace of glaciation, that predominate over the last 530 million years. The scene changed with the gradual icing over of Antarctica, at the end of the Tertiary, and of Greenland, more recently, 3 million years ago.

Variations in orbital parameters

The Sun has thus stopped being, from Cambrian times, the prime mover of climate change, on a geological scale. In the Quaternary, in which we live, the variation in the orbital parameters of the Earth has been the clock pacing, on a secular scale, the climate of our planet. Paradoxically, this period has been governed by the rhythm of variations in these parameters, determining as they do the amount of insolation from the Sun reaching the top of our atmosphere, with far-reaching repercussions. On scales of tens of thousand years, celestial mechanics computations show that eccentricity of the Earth's orbit varies in the range 0–0.6, with periods of 100,000 and 400,000 years, that obliquity of the ecliptic varies by ± 1° around 23.5°, with a period of 41,000 years, and finally that precession of the equinoxes also varies, with periods of 19,000 and 23,000 years (1) (see Figure 4). These computations, covering several million years, were carried out by Jacques Laskar, of the Celestial Mechanics and Ephemerides Calculation Institute (Institut de mécanique céleste et de calcul des éphémérides) of the French Bureau des Longitudes, and Professor André Berger, of Louvain-la-Neuve University (Belgium). Such computations had been initiated as early as 1940 by a Serbian scientist. Milutin Milankovitch had the stroke of genius, of comparing the decrease in summertime insolation at high latitudes in the northern hemisphere, due to secular variations in orbital parameters, occurring every 100,000 years or so, with the occurrence of very extensive glacial periods, covering with vast ice caps the northern parts of Europe and North America. This theory was not really taken seriously until the first cores from the ocean floor provided evidence of climate variations arising with precisely the same frequency as the variations in orbital parameters. Subsequently, highly sophisticated models showed that fairly small variations in the insolation reaching the top

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(1) The latter two effects result in differences in insolation of 15 W/m2 and 65 W/m^2 respectively.

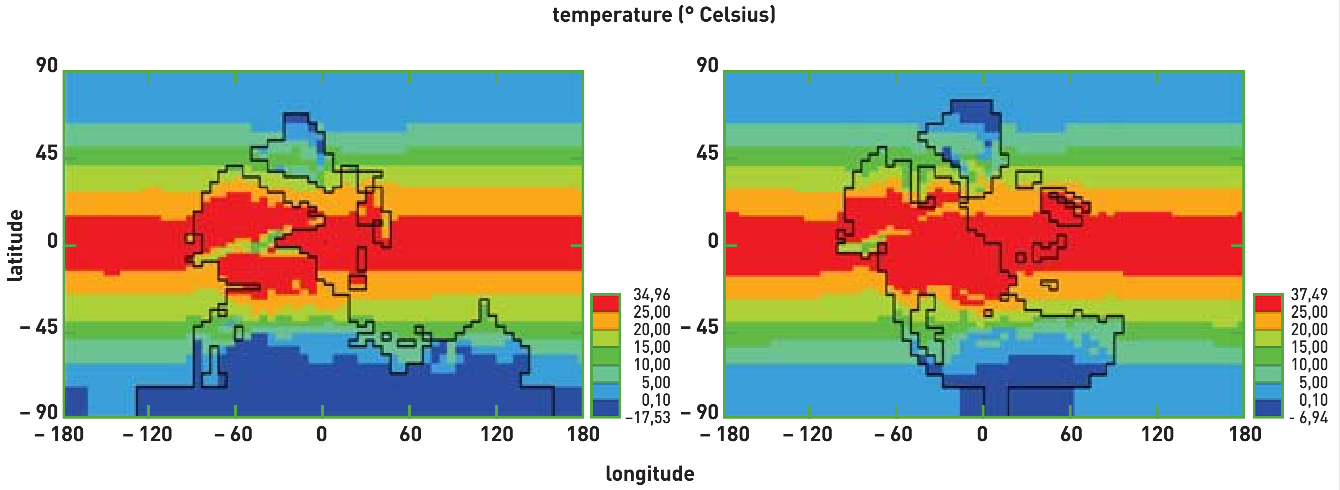

Figure 3.
Evolution of mean atmospheric temperatures over Pangaea between the Permian–Carboniferous (295 million years ago, at left) and the Permian–Triassic (250 million years ago, right). During the Carboniferous, temperatures were strongly negative in the south of Gondwana (high latitudes of the southern hemisphere), this being consonant with existence of a large ice cap.

of the atmosphere could be amplified by the Earth system (atmosphere–ocean–**biosphere**–cryosphere), in such a fashion as to flip climate from that of an interglacial phase, such as ours, to a glacial climate, corresponding to a fall in sea levels by 120 meters.

Man, a factor of deep imbalance, takes over

About 200 years ago, the industrial revolution began in Europe, and went on to spread to the rest of the world, causing an unprecedented growth in the energy requirements of the population of Earth denizens, these being multiplied overall by a factor of 2.3 between 1900 and 2000. The major part of this demand was met by the burning of fossil carbon. Indeed, the Earth's crust holds vast reserves of coal, liquid **hydrocarbons** and natural gas, which have formed over the entire evolution of the Earth, and exhibit substantial inertia relative to the changes affecting their superficial containing layers. Currently, global energy demand stands at 400 EJ (exajoules = 10^{18} joules). Coal was dominant up to

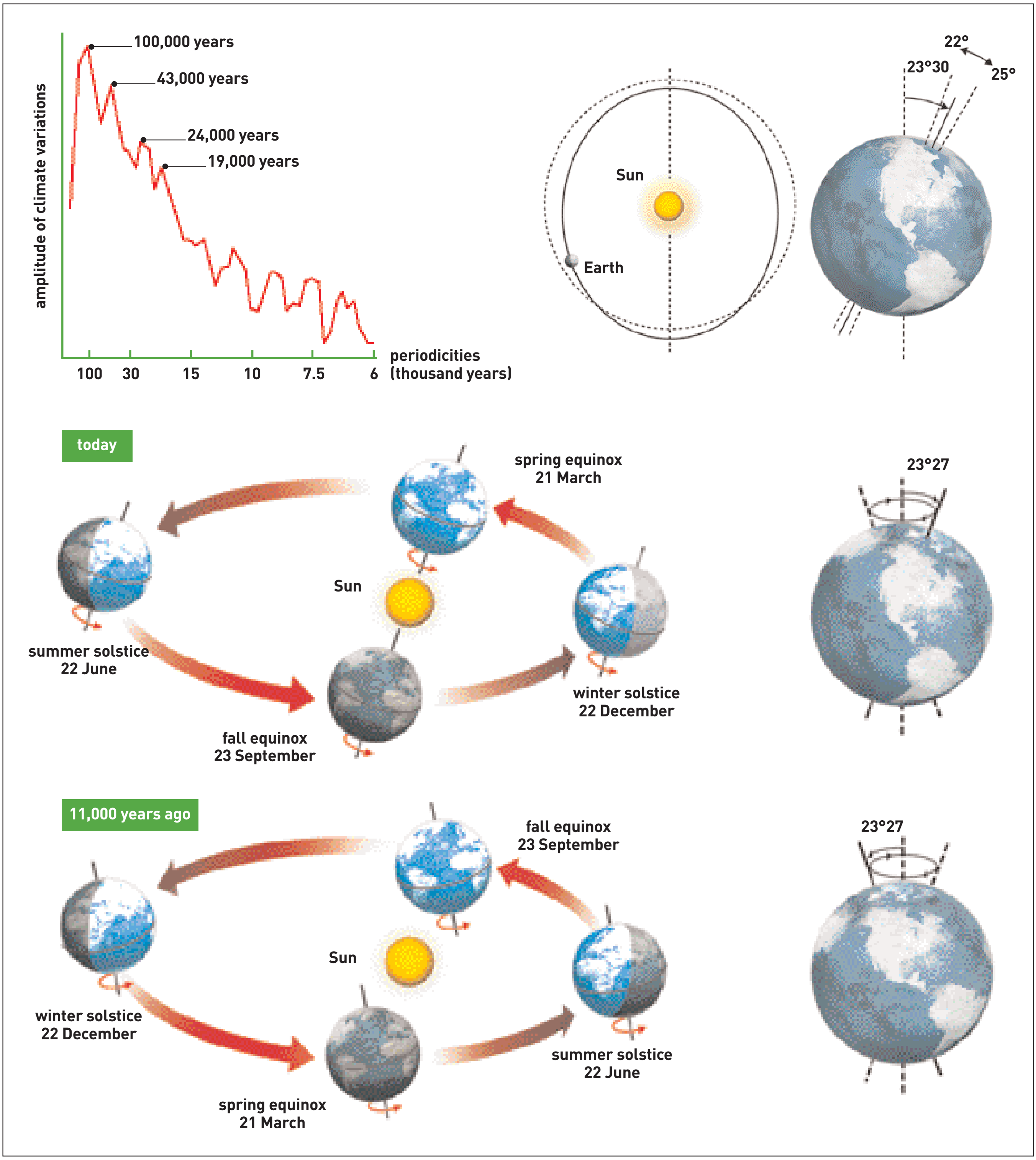

Figure 4.
The Earth's orbital parameters vary, whether it be the eccentricity of its orbit, the obliquity of its rotation axis, or the precession of equinoxes.

1950, however its contribution has fallen back to 27%, with a concomitant growth in that of petroleum (40%), and more recently of natural gas (2.3%). Energy generation from nuclear power stations accounts for about 7% of the total, i.e. 30 EJ.

Now, extracting fossil carbon and burning it to draw energy from it causes release of CO_2 into the atmosphere. CO_2 is a greenhouse-effect gas, which intercepts thermal infrared radiation emitted by the Earth, reemitting it in all directions, this warming the atmosphere, and the surfaces of oceans and continents. CO_2 is found in the form of traces in the atmosphere (0.03%), however it is absorbent in a broad range of the **infrared spectrum**, between 2 µm and 20 µm. Content in this gas has risen from 280 ppm (parts per million) 200 years ago to 360 ppm currently, i.e. a jump of 30%, reaching the highest levels recorded over the past 25 million years.⁽²⁾ The *amplitude* in the rise in CO_2 registered since 1800 is comparable to that observed during the last post-glaciation thaw, when climate warmed by 4 °C. On the other hand, the *rate* of CO_2 rise is much greater, and is undoubtedly unparalleled in all of Quaternary history.

To understand such a rise, one must add to the release of fossil CO_2 the contributions from deforestation and changes in land utilization, and factor in the reabsorption of part of the excess CO_2 by oceans and vegetation. Over the past 40 years or so, it has been found that only about half of manmade releases accumulates in the atmosphere, thus generating an incremental greenhouse effect. Dissolving into the ocean, through the sheer effect of solubility and the mixing of water masses, and carbon sequestration by terrestrial ecosystems – which is more fraught with mystery, since all of the processes involved in this are not as yet known – are valuable allies in restricting the greenhouse effect and climate change. Without these two carbon wells, CO_2 would be rising twice as fast.

The grain of sand in the climate machine

If, as is likely, CO_2 were to double in the near future, every region of our planet's surface would receive, on average, an extra 4W/m², an amount that would be modest, all considered, compared to the 242 W/m² or so received from the Sun. (3) That small energy surplus, however, plays the role of the grain of sand that throws the climate machinery out of gear. Just as, as we saw, a small initial perturbation, of orbital origin, in the energy received from the Sun could, through interplay of feedback and amplification effects in the climate system, bring about the onset or disappearance of vast ice caps, it may be anticipated that the small perturbation induced by CO2 from manmade emissions will have major repercussions on climate. Doubling of CO_2, or even a rise, for an equivalent radiative effect, in other greenhouse-effect gases with even more "warming power," such as methane (CH_4: 20 times the effect of CO_2 over a period of 100 years) or nitrous oxide (N_2O: 200 times the effect of CO_2) would bring about a rise in temperatures of 1.5–6 °C. Such warming is computed by means of complex numerical models, putting into equations a large number of the amplification mechanisms at work for CO_2 perturbation, by way of nonlinear changes in oceanic and atmospheric circulation, continental surface albedo, water vapor, cloud cover, and the extent of sea ice. Numerical climate models are designed to compute, on regional scales, not only mean temperature, but also variability of this quantity as of other climate variables, particularly precipitation. However, to gain an idea of the robustness of equilibrium warming, relative to a doubling of CO_2, it will be sufficient to use the formula: $d(\sigma T^4)/\sigma T^4 = 4\ \text{W/m}^2 / 242\ \text{W/m}^2$, this yielding an "order of magnitude" of + 1.2 °C, a value not taking into account amplifications due to the climate system. It is not so much the mean value of the warming associated to a rise in CO_2 that is disturbing – after all, the Earth has experienced other such upheavals through its turbulent history – as its rate, compared to the adaptive capacities of ecosystems and human societies. One of the most important impacts of warming concerns regional alterations in precipitation regimes, and their repercussions on

(2) A content of 1 ppm corresponds to one CO_2 molecule for one million molecules of air.

(3) Globally, the solar flux (I = 1,365 W/m²) intercepted by the Earth (radius R), having albedo α, is equal to $\pi R^2 I (1-\alpha)$, i.e., per unit surface: T = 242 W/m².

Icebergs in Antarctica. Evolution of the ice shelf is one of the major issues facing climatologists, as a result of planetary warming.

PhotoLink


EyeWire

Extraction and burning of fossil carbon to draw energy result in emission of CO_2 into the atmosphere, half of which accumulates in the atmosphere, generating an incremental greenhouse effect.

agriculture and water resources as a whole. One should also factor in extreme events (heat waves, torrential rains, storms…), and a destabilization of bioclimatic living conditions for ecosystems, which could have major consequences, for instance as regards dissemination of diseases propagated by carrier organisms, or a rise in fire levels.

Is the carbon dioxide age unavoidable?

If one computes that there are, remaining in the Earth's crust, some 10,000 petagrams of fossil carbon (1 Pg = 10^{15} g), complete burning of this in the atmosphere would cause a rise in concentrations by 5,000 ppm! In actual fact, the ocean will absorb a large part of the CO_2 released. At equilibrium, it can even be computed that 85% of any perturbation in atmospheric CO_2 content will end up, ultimately (after a few centuries), in the ocean, inducing an asymptotic atmospheric content of 0.15 × 5,000 = 750 ppm. However, over the coming decades, during which transition period we shall go on using fossil carbon to generate energy, the oceanic carbon reservoir will not instantly reach equilibrium with the atmosphere, and there is thus a danger that we may experience, during the 21st century, a CO_2 "peak" much higher than 750 ppm, with consequently much warmer climates than the present one. It will also be realized that 15% of the perturbation in atmospheric CO_2 due to fossil energy use is more or less irreversible, and will take us, in a few centuries, to a durably warmer climate. It may be, moreover, that during the transition period, when CO_2 concentrations will go through a peak, climate will pass a "stability threshold," and truly go into a different state, featuring for instance a different oceanic circulation mode. The climate of the coming millennia will thus be at stake in the 21st century, and will depend on our ability to restrict, or even lower, atmospheric CO_2 contents. Future scenarios for fossil carbon emissions range from 20 PgC in 2100, for the most "polluting" case, to 3 PgC for the most "environmentally-friendly" scenario. If CO_2 is to be stabilized, by 2050, at a level close to doubling, it will be necessary to go for the low trajectory, at 3 PgC per year. This shows, in a way, that humankind is faced with two futures: one will see CO_2 rising, and climate will change, making our planet less habitable; the other will witness a stabilization in CO_2, or even a reduction, with a lowering of the greenhouse effect, as an echo to the saying of Saint-Exupéry: "We do not inherit the Earth from our ancestors, we hold it on loan from our children."

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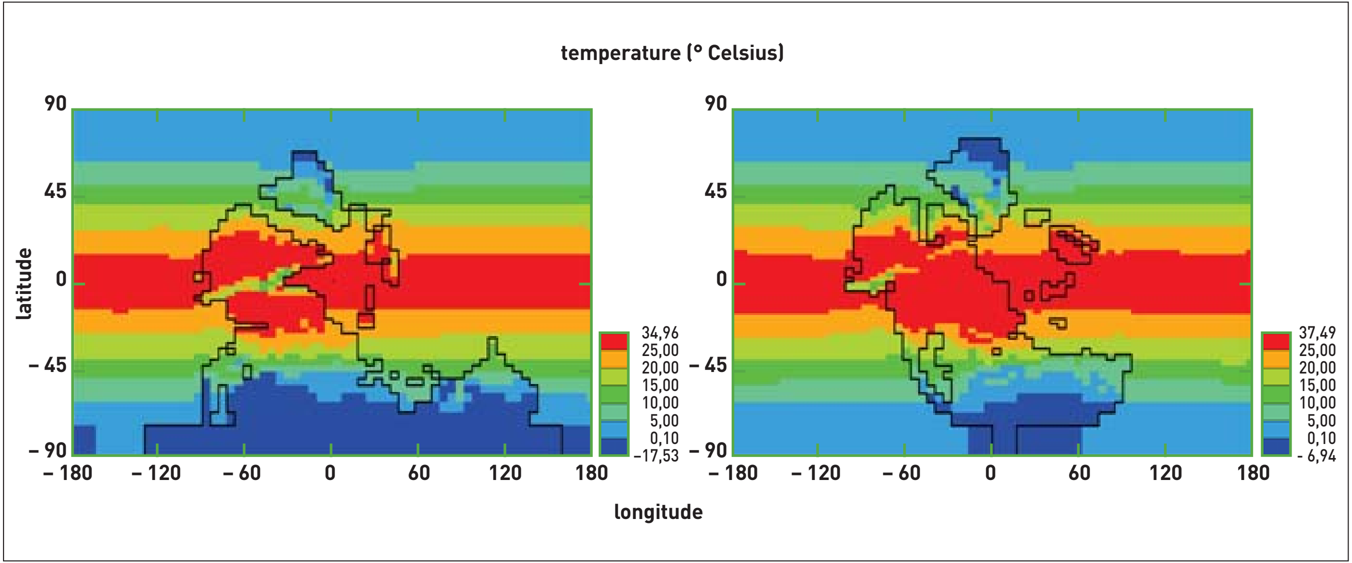

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