ABC of Climate Science

4

By changing the atmosphere composition, fossil fuel emissions couple humanity energy use to the climate. This chapter will focus on climate science, uncovering the link between climate and anthropogenic greenhouse gases emissions.

Let us start answering an extremely frequently asked question: What is the difference between "climate" and "weather"? How can we forecast climate change 20 years ahead, when it is difficult to forecast the weather 20 days from now? Another question may answer this one: if you live in the Northern Hemisphere, like me, how can you be sure August will be hotter than January? I reside in Southern Spain, where summers are extremely hot. Absolutely no one would bet August might be cooler than January. How can we be so sure? Simply because Spain receives more sunlight in summer than in winter. If more energy enters, temperature has to rise. Likewise, storms are not exceptional in summer. You can thus claim without risk that August will be hotter than January, *and* that there will be a few storms. But it would be extremely hazardous to pinpoint the stormy days.

Climate is easily predicted, weather is not. Climate has to do with what happens *on average*. Weather has to do with what happens *really*. As the climate scientist Mike Hulme simply puts, "climate is what you expect, weather is what you get" [1, p. 9]. For any given place at any given time of the year, average temperature, precipitation, humidity, etc., are known and predictable. But it is impossible to know with certainty whether it will rain or not in Paris, France, one month from now. Such is the difference between climate and weather.

Since this chapter is all about elucidating the link between human emissions and climate change, we shall start taking notice of the change. Even before we understand what is going on, it is useful to notice that "something" is happening. Sea level is rising, global mean temperature is increasing, glaciers are receding. This is all happening right now. The question is not "is there such thing as a climate change?" but rather "what are the causes of the climate change?"

Answering this question requires the ABC of Climate Science. And the "A" of the ABC is the concept of energy balance, namely that all the energy the Earth receives from the Sun eventually goes back to space. Much of the climate science lies there, between how much energy enters, how it enters, and how it leaves. Once this point

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will be understood, we will see what numerical models, who successfully reproduce past climate evolution, have to tell about the future.

4.1 Something's Happening

A number of measurements performed over the past decades are unambiguous indicators that climate is changing.[1] Though not the best indicator (see below), let us start with global mean temperature. It is rising. What exactly is "global mean temperature"? Before going on vacation, it is easy to check the mean temperature for any given month at any given place. Taking the mean value of all the average temperatures around the globe for a given month, gives the mean *global* temperature for that month. From this *monthly* global temperature, you can derive an *annual* global temperature, simply averaging from January to December. The mean global temperature is therefore an average in space, around the globe, and in time, in general over a month or a year.

For brevity, let us denote our mean global temperature by the symbol T_g. A few general principles regarding mean values may be worth reminding. Suppose observations show T_g is decreasing over two decades. You will deduce the Earth is cooling, in the same way you would deduce summers in Paris, France, are getting cooler if you find out the mean June through August temperature in Paris has been going down over the last years. Note that you would deduce cooling even if some years were hotter than the previous one. You would focus on the *trend*. It is like the evolution of a share in the stock market. Claiming Apple Computer has been on the rise in September does not mean its share went up every single day. It means the overall September trend was rising.

Also, a decreasing T_g does not imply temperature must decrease at every single location on Earth. Consider a classroom with 20 children. The teacher gives a test each month, and after a few of them observes that the mean grade is rising. Does it mean every single kid got better grades, test after test? Not at all. You can perfectly have a rising average grade *and* a few kids receding. The year 2010, for example, got the highest T_g since 1880 (see Fig. 4.1). Yet, 2010 was hotter than the 1971–2000 average in Canada, but *cooler* than the same average in Scandinavia.[2]

To summarize, T_g is an average in time and space. The important is the trend over a few years, not the evolution from one year to the next. As an average in space, every locations do not need to mimic the evolution of T_g. Some of them can even go against. This is simply mathematical.

[1] As early as 1859, John Tyndall found out carbon dioxide greenhouse properties. Mike Hulme's book *Why We Disagree About Climate Change* [1] contains a great exposition of the discovery of climate change.

[2] See www.noaa.gov.

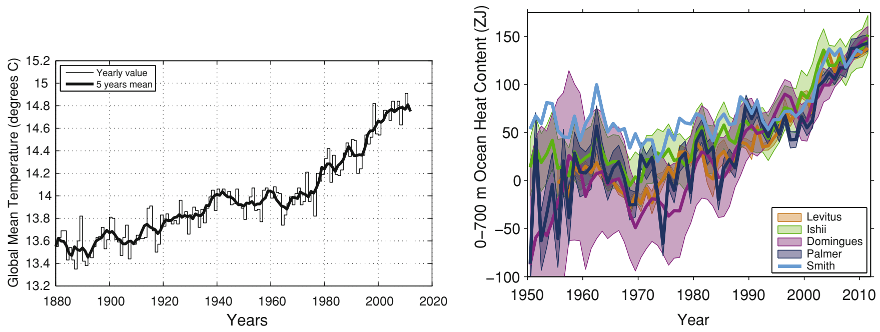

Fig. 4.1 *Left* Global mean temperature in °C since 1880. *Source* Hansen, J.E., R. Ruedy, M. Sato, and K. Lo, NASA Goddard Institute for Space Studies. Data available at http://cdiac.ornl.gov/. *Right* Oceans heat content between 0 and 700 m from various studies, in ZJ (1 ZJ $= 10^{21}$ J). *Source* Climate change 2013: the physical science basis. Working group i contribution to the fifth assessment report of the intergovernmental panel on climate change, Fig. 3.2a p. 262. Cambridge University Press [2]

Turn now to Fig. 4.1-left that pictures the evolution of T_g from 1880. The overall trend is obviously to the rise as more than one degree has been gained between 1880 and 2012. The yearly value fluctuates significantly, and even the 5-year mean does not increase steadily. The warming is thus appreciable over, say, 10-year-long periods of time.[3]

The atmosphere is warming, so do the oceans. It is quite logical as both are in close contact. Figure 4.1-right shows the upper (0–700 m) oceans heat content evolution from various studies. Here also, the trend is unequivocal.

As a consequence of the observed warming, land and sea ice extensions are shrinking. In the Northern Hemisphere, the portion of the Arctic Ocean covered by ice is receding while Greenland ice sheet is losing mass. In the South, the amount of ice accumulated over Antarctic is equally decreasing. Everywhere on the continents, glaciers are also losing mass. Figure 4.2 evidences these trends. As a consequence of the ice loss, sea level has been raising for the last decades.

Regarding this last effect, two points are to be made. First, only melting land-ice contributes to the rising. It is easy to check that an ice cube melting in a glass of water does *not* raise the level, simply because once it is melted, the cube occupies exactly the volume of ice below water at the beginning. Therefore, only glaciers, Greenland, and Antarctic melting, contribute to sea-level rise. Arctic sea ice does not have anything to do with it. Second, sea level rise originates only in part from the melting. The other part comes from water dilatation due to the warming evidenced on Fig. 4.1-right [2, p. 1151]. Though less famous, probably because most of us do not sense it directly, oceanic warming accounts for 90 % of the global heat increase [2, pp. 8, 265]. No wonder James Lovelock wrote [5, p. 42],

[3] The reasons why T_g fluctuates around its trend are discussed in Sect. 2.7 of Ref. [2].

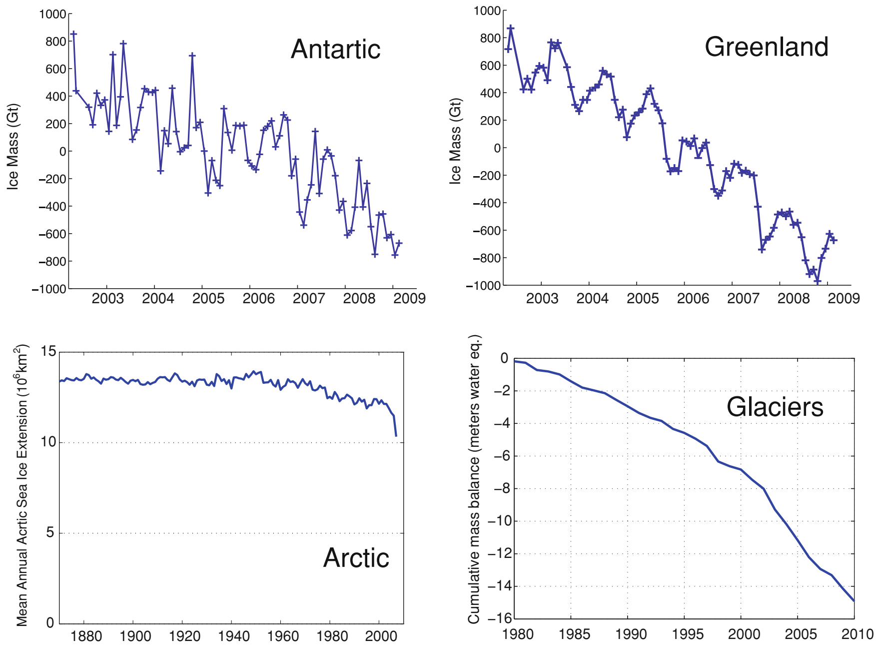

Fig. 4.2 Ice loss in Antarctic [3], Greenland [3], Arctic and world glaciers. *Sources Arctic* [4]. World glaciers: world glacier monitoring service, www.wgms.ch/

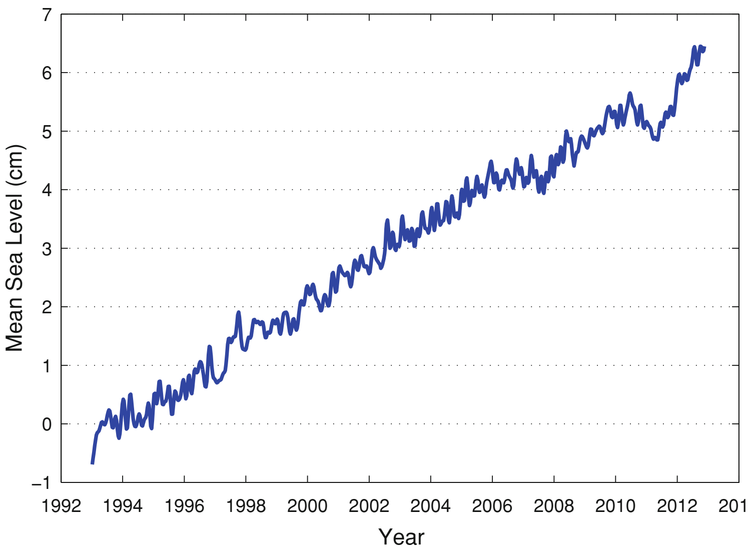

Fig. 4.3 Satellite measurements of the mean sea-level rise since 1993. The observed trend is 3.16 mm/year. *Source* CLS/Cnes/Legos, www.aviso.oceanobs.com/msl

> Sea-level rise is the best available measure of the heat absorbed by the Earth because it comes from only two main causes. The melting of the glaciers on land and the expansion of the ocean as it warms—in other words, sea level is a thermometer that indicates the true global warming.

Figure 4.3 displays some satellite measurements of the mean sea-level rise since 1993. The year 1993 is taken as the reference. An overall rising trend corresponding to 3.16 mm/year is observed. Something, definitely, is happening. The cryosphere, a word that now designates the portion of our world where water is solid, is melting. Global temperature and sea level are rising. Let us now try to understand what is happening, starting with the crucial concept of energy balance and the corresponding equation.

4.2 Energy Balance

A surface oriented toward the Sun on the Earth orbit receives from the Sun about $C_S = 1{,}370$ W/m^2 (see calculation in Sect. 6.2). The Earth radius R_e being 6,400 km, it intercepts the total solar power,

$$P_S = \pi R_e^2 C_S = 1.76 \times 10^{17} \text{ W}. \tag{4.1}$$

In just one second, the Earth receives 1.76×10^{17} Joules. And it has been like this for some 4.5 billion years. How is it that the Earth is not burning? How is it that the Earth has not been vaporized yet? We find here an instance where the law of energy conservation (see Sect. 2.3) becomes tangible and yet, enigmatic. It is obvious that energy arrives every second from the Sun. If energy conservation is true, where does it go?

Like cars entering a parking (where do they go after?), the problem has only two possible solutions. Either Sun's energy gets stored somehow on Earth, or it eventually comes back to space. Let us start examining the first option.

The problem under scrutiny is therefore: to which extent could the Earth store the energy it receives from the Sun? Regardless of the timescales and mechanisms involved, it could be stored under the form of chemical energy in plants and trees, or fossil fuels. Another possible reservoir could be the heat of the oceans. We will now perform a series of order of magnitude calculations to quantify, even loosely, the capacity of these reservoirs.

4.2.1 Capacity of Forests as a Reservoir

One meter square of Earth receives[4] on average $P_S/4\pi R_e^2 = C_S/4 = 342$ W. Considering photosynthesis can exploit at best 5 % of it ([6], [7, p. 140]), a growing forest can absorb 17 W/m^2. Assuming it reaches maturity after 100 years,[5] it will

[4] We forget here about the "albedo." See Sect. 4.3.

[5] Regarding these 100 years, see the calculation performed in Sect. 5.5.

eventually contain at most

$$17 \times 100 \times 365 \times 24 \times 3600 = 53 \;\; \text{GJ/m}^2. \tag{4.2}$$

Let us now assume (certainly exaggerating) that 50 % of dry land is made of forest. Since dry land is 30 % of the Earth surface, forests amount to some 77×10^6 km^2. Multiplying this surface by the energy density previously derived, we come to the conclusion that the amount of energy stored in vegetation is about,

$$E_V = 53 \text{ GJ/m}^2 \times 77 \times 10^6 \text{ km}^2 = 4.16 \times 10^{24} \text{ J}. \tag{4.3}$$

It is now worth comparing this number to the total power received from the Sun derived in Eq. (4.1). Dividing the former by the later, one finds the Sun irradiance "fills" the vegetation reservoir in just 273 days! Because we are talking billion years, this reservoir is obviously inadequate. Let us now turn to the energy oil can store.

4.2.2 Capacity of Oil as a Reservoir

This calculation can obviously be made for gas, or coal, as the result will prove this kind of reservoir equally inefficient. The conclusion is here even more straightforward. According to the most optimistic estimates of the oil industry, the total amount of conventional oil ever present in the ground was about 3×10^{12} barrels, of which some 1×10^{12} have already been extracted.[6] With a 160-liters barrel, and considering a density of $\sim$1 g/cm^3, this amounts to 4.8×10^{14} kg of oil. Since the combustion of 1 kg of oil releases some 42 MJ, the overall reservoir contains,

$$E_O = 2.16 \times 10^{22} \text{ J} \;=\; 34 \text{ hours of Sun}. \tag{4.4}$$

Here again, we find the reservoir far too small to play a role in containing the Sun energy received by the planet during the last billion years. The number itself shows that adding unconventional oil, coal or gas to the calculation will not solve the problem.

4.2.3 Capacity of the Oceans as a Reservoir

Let us now check how much energy could be stored in the oceans. The volume of water they contain is about 1.3×10^9 km^3. Considering a heat capacity of 4.2 kJ/kg/K, we find the energy absorbed by the oceans when gaining 1 K,

$$E_W = 5.43 \times 10^{24} \text{ J} \;=\; 356 \text{ days of Sun}. \tag{4.5}$$

This third reservoir is equally found wanting. Even if an increase of 1 K can capture almost one year of Sun energy, the process cannot proceed for more than 100 years.

[6] See Chap. 3. The $3 \times 10^{12} = 3{,}000$ Gbarrels are a little more optimistic than the 2,500 we found.

4.2.4 Conclusion: The Energy Balance

These three Fermi-like calculations make it clear that the power from the Sun cannot be stored on Earth on a billion year timescale. Indeed, we just checked that given its consequences, the imbalance time in 4.5 billion years must be smaller than ~ 1 year, which amounts for some 10^{-10} of the total. Returning to the image of a parking facility, we find some 10^{10} cars (the energy) entered, while there is room for just one car. The only solution is that the number of cars leaving the parking in (almost) any amount of time, is (almost) exactly the number of cars entering it.

At this stage, the conclusion is inescapable: If there are no long term storage solutions, the energy coming in *must* eventually come out. Now, there are three ways of transporting energy: You can put it inside some container, and take the container away. This is convection. You can also heat one side of an object and have heat propagate. This is conduction. Finally, you can have light carry away the energy for you. This is radiation. Because Earth is surrounded by virtually nothing, you cannot get rid of the energy through convection nor conduction. The only way out is *radiation*. Assuming an average temperature T_e, the Stefan-Boltzmann law tells the radiated power per meter square is σT_e^4, where $\sigma = 5.67 \times 10^{-8}$ W/m^2/K^4 is the Stefan-Boltzmann constant.[7] Equating this quantity with the amount of power received, we find,

$$C_S/4 = \sigma T_e^4. \tag{4.6}$$

Though the evaluation of the reservoirs capacity is highly approximate, the orders of magnitude involved are so disparate that there is no way to escape the need for an energy balance. Accounting for unconventional oil reserves such as “tar sands”, or for a higher photosynthesis yield, cannot yield some reservoir large enough to retain a significant portion of the energy poured by the Sun over billions of years.

4.3 Elements of Climate Modeling

4.3.1 Elementary Model

Equation (4.6) is the starting point of climate modeling. It relates the temperature to the amount of energy received from the Sun. Now, T_e has to be an average temperature, as every place on Earth does not receive the same amount of sunlight. If our planet were a single point, T_e would be the temperature of this point. Let us start examining this “zero dimension model,” as Kendal McGuffie and Ann Henderson-Sellers name it in *A Climate Modeling Primer* [8].

Our Eq. (4.6) needs some tuning in order to account for two kinds of processes. First, part of the incoming energy never really enters. Sunlight enters the atmosphere as visible light. It gets absorbed by the Earth, which in turn emits radiation in the

[7] In terms of fundamental physical constants, $\sigma = \pi^2 k_B^4 / 60\hbar^3 c^2$ where k_B is the Boltzmann constant, $\hbar$ the Planck constant h divided by 2π, and c the speed of light.

infrared range, which is *not* visible. How is it then that astronauts could take pictures of the Earth from the Moon? Because part of the Sun visible radiation bounces back to space as soon as it hits the Earth. The bounced back percentage is called the "albedo" and is conventionally labeled by the Greek letter α. Therefore, the power that really comes in and has to be re-emitted is not $C_S/4$, but $(1-\alpha)C_S/4$. With $\alpha = 30\ \%$ (see Table 4.1), the average power received is not 342 but 240 W/m^2.

Second, the planet may have an atmosphere (it does not have to be the Earth) that could be opaque to some radiations. We all know how x-rays may see through our body, while visible light cannot. This is why we cannot see behind someone while x-ray radiography allows to monitor broken bones. The thing is, some materials are transparent to some wavelengths, and opaque to others. The radiation a planet emits to outer space consists in various wavelengths. And depending on its composition, an atmosphere can be opaque to some wavelength, and transparent to others. In the absence of atmosphere, the amount of energy carried away by all the emitted wavelengths is σT_e^4. But if the atmosphere blocks some of them, the amount of energy eventually escaping is lower and can be written $\varepsilon\sigma T_e^4$, where ε is smaller than unity. This phenomenon ends up increasing the temperature, because if the number of wavelengths energy can "ride" is reduced, temperature must rise for the authorized wavelengths to carry out the same amount of energy. This mechanism is exactly the one operating in greenhouses, where incoming radiation is trapped inside a glass-like room. This is why it is called the "greenhouse effect". The new energy balance equation then reads,

$$(1-\alpha)C_S/4 = \varepsilon\sigma T_e^4, \tag{4.7}$$

which gives directly the temperature

$$T_e = \left(\frac{(1-\alpha)C_S}{4\varepsilon\sigma}\right)^{1/4}. \tag{4.8}$$

The value of C_S will be calculated later in this book, when talking about solar power in Sect. 6.2. Borrowing its expression from Eq. (6.7), we find a very simple expression for the average temperature of a planet orbiting at distance D from the Sun,

$$T_e = T_S\left(\frac{1-\alpha}{\varepsilon}\right)^{1/4}\sqrt{\frac{R_S}{2D}}, \tag{4.9}$$

where T_S is the Sun surface temperature, and R_S its radius.

While an increasing albedo α cools the planet (it receives less), the greenhouse parameter ε warms it all the more that it is small. Figure 4.4 may help illustrate this point. Our planet needs to balance the incoming power adjusting its $\varepsilon\sigma T^4$ emission. For lower values of ε, the $\varepsilon\sigma T^4$ curve gets lowered as well. But because the incoming power has not changed, it takes a higher temperature to give it back to space. Note that every single Watt received is eventually sent back. It just takes a higher temperature to do it.

The mechanism through which temperature automatically adjusts to its equilibrium value is quite simple. Suppose temperature is too low. Then, we see on Fig. 4.4 that the amount of energy out is lower than what comes in. There is a net energy gain,

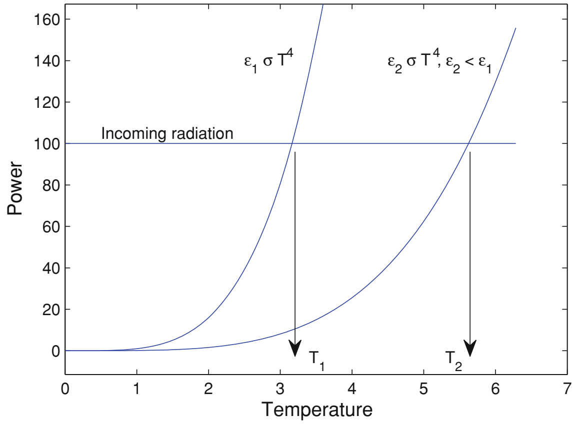

Fig. 4.4 The temperature balancing the incoming and outcoming power increases when the greenhouse coefficient decreases. Units are arbitrary

Table 4.1 Parameters entering Eq. (4.9) for the planets of the solar system

Planets	D (10^6 km)	Albedo	T measured	T from Eq. (4.9)
Mercury	58	0.068	440	436
Venus	108	0.9	737	183
Earth	150	0.3	288	253
Mars	228	0.25	208	208
Jupiter	779	0.34	163	109
Saturn	1,434	0.34	133	80
Uranus	2,873	0.3	78	58
Neptune	4,495	0.209	73	48
Pluto	5,870	0.5	48	37

Temperatures, all in degrees Kelvin, have been computed setting $\varepsilon = 1$ in Eq. (4.9). *Source* NASA Planetary Fact Sheet, http://nssdc.gsfc.nasa.gov/planetary/factsheet/

and temperature rises. Suppose now temperature is too high. The same figure shows energy out now surpasses the incoming one. We now have a net energy loss, and temperature falls. Like a marble in a bowl comes back to the bottom, temperature spontaneously comes back to its equilibrium value.

Since there is more than one planet in the solar system, why do not we test our formula on some of them? Table 4.1 gathers the parameters involved in Eq. (4.9) for the planets of the solar system, with the theoretical temperatures given by this same equation when neglecting greenhouse effect (i.e., setting $\varepsilon = 1$ in the equation). In order to visualize the agreement between the measured temperatures and the computed ones, Fig. 4.5 plots both quantities for each planet in terms of the planets' distance to the Sun. Several comments are appropriate.

- First, our little toy model is not that wrong. Even forgetting about greenhouse effect, we get the correct orders of magnitude and capture the trend $T \propto D^{-1/2}$.

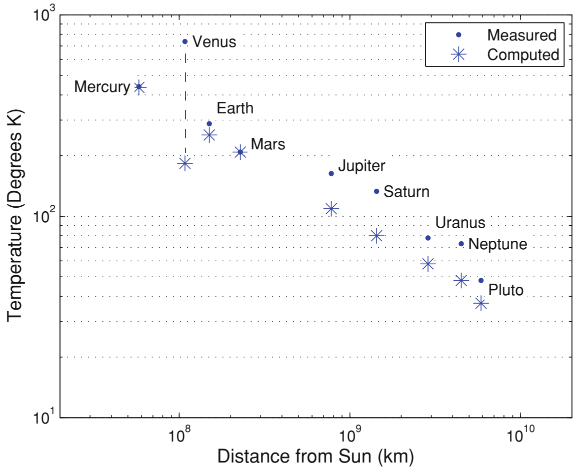

Fig. 4.5 Plot of the measured and computed temperatures listed in Table 4.1. The dashed line linking the Venus data is just an eye guide

- Second, the measured temperatures are always *higher* than the computed ones. This is because setting $\varepsilon = 1$ implies we systematically miss the greenhouse warming factor (see Fig. 4.4).
- Third, for the planets with almost no atmosphere, namely Mercury, Mars and Pluto, the agreement is very good. Note that the logarithmic scale amplifies the discrepancy for Pluto, while the error is only 22 %. For the others, the greenhouse effect operates through their atmosphere and warms them. Yes, such effect is not specific to Earth and operates throughout the Solar System.
- Fourth, Venus data are striking. Here, the actual temperature is four times the greenhouse-less one. Venus is 737 K hot (464 °C) and would be only 183 K (−90 °C) without greenhouse effect.[8] What happens there? It turns out that CO_2 amounts for 96.5 % of Venus' atmosphere [9]. And CO_2 is a notorious greenhouse gas.

Without greenhouse effect, Eq. (4.9) gives a mean temperature equal to 253 K, −20 °C, for the Earth. Quite cold indeed. The reason why we experience a mild average temperature of about 15 °C is the greenhouse contribution. Setting $\varepsilon = 0.6$ in Eq. (4.9) readily gives $T_e = 288$ K, or 15 °C. Without greenhouse effect, it would be far too cold down here.

4.3.2 Beyond the Elementary Model

Our basic climate model is therefore able to provide the average temperature on any planet, once its albedo and greenhouse parameters are known. How can we go further that this? We would like now to describe a real planet Earth, and have something to say about the average temperature in Africa or Asia for example. A complete

[8] Such a low temperature without greenhouse effect is due to Venus' extremely high albedo $\alpha = 0.9$.

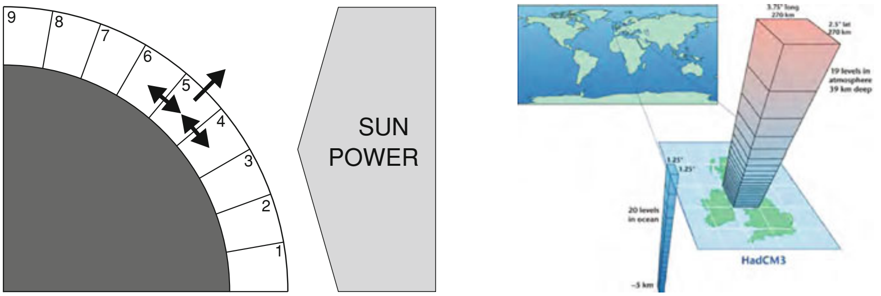

Fig. 4.6 *Left* Basic principles for a more elaborated climate model. Each cell receives Sun power, radiates to space and exchange energy with its neighbors. Not to scale. *Right* Cell structure of the "HadCM3" global climate model. *Source* [12, p. 30]

exposition of contemporary climate modeling clearly goes beyond the scope of this book, and we refer the reader to excellent treaties on this topic [8,10,11]. Yet, it is useful to give a flavor of how a more complete model can be constructed from the physical basis we just exposed. We thus now describe how to elaborate a still simple 1D climate model. It is not a full fledged 3D model yet, but it can help figuring out how to get there.

Consider a 2D disk-like planet with a 1D atmosphere. It means we do not care so far about climate differences with altitude (state of the art models do). Figure 4.6-left represents a quarter of the disk. The planet surface is here divided into 9 cells, but a computer treatment of the problem would let you chose much more. The basic idea is to write an energy balance equation for each cell. Consider cell number 5 for example. The Sun power entering it will read $(1-\alpha_5)C_{S5}$. Note that both the albedo and the incoming Sun power appear with the subscript "5" because these quantities are now cell-dependent. Land, sea, or ice do not have the same albedo, and incoming Sun power varies with latitude. Cell 5 also radiates energy out, as $\varepsilon_5\sigma T_5^4$. Here again, greenhouse parameter and temperature are cell-dependent, hence the subscript "5". Finally, cell 5 exchanges energy with cells 4 and 6. The energy exchange can be modeled in terms of the temperature difference between adjacent cells, like $\delta_{5,4}(T_5-T_4)+\delta_{5,6}(T_5-T_6)$ where the δ's are coefficients that may vary from cell to cell. The energy balance equation for cell 5 eventually looks like,

$$(1-\alpha_5)C_{S5} = \varepsilon_5\sigma T_5^4 + \delta_{5,4}(T_5-T_4) + \delta_{5,6}(T_5-T_6). \tag{4.10}$$

If $T_5 > T_4$, cell 5 gives energy to cell 4 so that $\delta_{5,4}(T_5-T_4) > 0$ appears on the "loss" side. What has been done for cell 5 can obviously be done for every cell. The result is a system of 9 equations with 9 T_i's unknown. It can be solved provided the physical parameters $(\alpha_i, C_{Si}, \varepsilon_i \ldots)$ are known for each cell i. Because these parameters usually depends on temperature (for instance, sea becomes ice for $T < 0\,°\mathrm{C}$, which changes the albedo), numerical calculation is required.

Such division of the outer disk of a 2D planet can be performed on the surface of a real, 3D planet. Modern "Global Climate Models" divide the Earth surface into N cells, N being as large as your computer power allows. On the top of each cell, more cells sample the atmosphere. And on the bottom of each ocean cell, even more cells dive into the sea to render its evolution. The "Hadley Centre Coupled Model 3" (HadCM3), developed at the Hadley Centre in the United Kingdom, implements the kind of grid displayed on Fig. 4.6-right, allowing it to model the coupled evolution of the atmosphere and the ocean.[9]

4.3.3 Testing the Models

Before we ask them about the twenty-first century, what do models have to tell about the twentieth? This is obviously the first question to ask. Do they reproduce correctly what already happened? Yes. Global climate models successfully reproduce *past* Earth climate, which allows to trust them for the future.

For example, they correctly render the mean global temperature over the twentieth century, including the drops due to major volcanic eruptions [13, p. 600]. Beyond global data, *local* climate variations already observed are equally depicted faithfully [2, pp. 18, 930]. Indeed, "Evaluation of Climate Models" is the title of the ninth chapter of the IPCC report *Climate Change 2013, The Physical Science Basis* [2].

Interestingly climate models have been found efficient at modeling Mars [14] or Venus [15] climates as well. Such is one of the many benefits of Solar System exploration. There is only one Earth, and only one Earth history. The number of benchmarks Earth climate models can pass is thus limited. By gathering in situ data from Mars and Venus, the physics and the modeling can be thoroughly tested, resulting in increasingly trustworthy forecasting tools.

4.4 So, What's Happening?

These elements of climate modeling show that global mean temperature results from a balance between the incoming solar power and the outcoming radiation. Therefore, if the Earth is warming, as it has been observed in Sect. 4.1, it can be only for two reasons. Either there is more energy coming in, or radiation coming out does it differently.

4.4.1 It Is Not the Sun

Sun activity is obviously the first suspect in this matter. It has been known for long that cyclical variations in the Earth' orbit and inclination, the "Milankovitch cycles",

[9] The French "Institut Pierre Simon Laplace" has posted on YouTube a great video on climate simulations at www.youtube.com/watch?v=ADf8-rmEtNg.

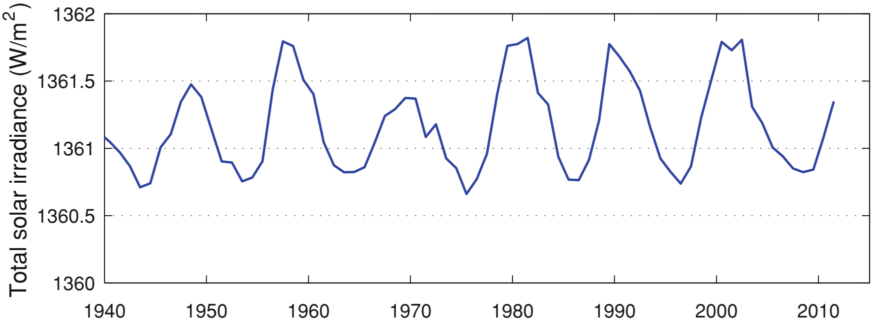

Fig. 4.7 Total solar irradiance since 1940. This is the C_S of Eqs. (4.1, 4.7). *Source* Solar radiation and climate experiment

result in climatic cycles which aftermaths have been detected[10] in ice cores records [8, 17]. The problem is that the shortest is about 19,000 years long, so that they cannot be held accountable for the recent 100 years or so warming trend.

Are there shorter cycles more appropriate to the present problem? Yes. Our Sun presents an 11-year activity cycle worth noticing (similar cycles have been detected for other stars [18]). Figure 4.7 displays the evolution of the total solar irradiance measurements since 1940. This is the C_S of Eqs. (4.1, 4.7). Though frequently called the "solar constant", we can check it is only nearly constant as it fluctuates by 0.1 %. Displaying on the vertical scale numbers from 0 to 1,362 W/m^2 would give an uninteresting flat line. Equation 4.8 shows, after a little math,[11] that a 0.1 % change in C_S should produce a $\frac{1}{4}0.1$ % change of the mean temperature. Putting the numbers gives a temperature shift of only 0.1 K. We miss a factor 10. Variations of the solar constant are indeed so faint that their influence on the climate is difficult to quantify [19]. In addition, there is hardly any correlation between the evolution of C_S observed here, and the trends displayed on Figs. 4.1, 4.2 and 4.3.

Moreover, the 11-year cycle is linked to the internal Sun dynamic [20]. As such, it has been there for a very long time. How could such an 11-year cycle suddenly drive the CO_2 concentration beyond 400 ppm,[12] when it has remained[13] below 300 ppm at least for the last 800,000 years [21]?

10 The French glaciologist Claude Lorius tells how he got the idea in 1965 that ancient air bubble could be trapped in ice cores: "It was when I saw these bubbles bursting when an ice cube melted in a glass of whiskey that I had the feeling they could be reliable and unique indicators of the composition of air, something we subsequently proved was correct". In vino veritas… [16].

11 Just compute dT_e/dC_S.

12 See definition in Appendix A.

13 By the way, this very objection holds against the Milankovitch cycles as well. Besides their improper timescale, how would they suddenly produce something they never did during the last million years?

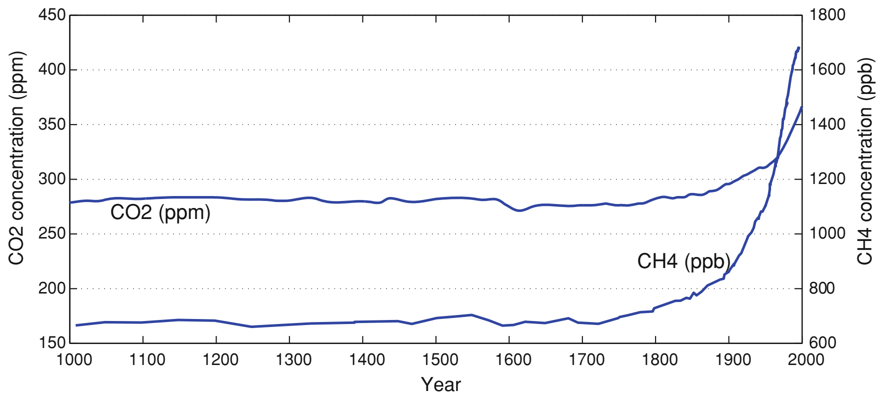

Fig. 4.8 Evolution of the CO_2 (*left scale*, “ppm” = part per million) and CH_4 (*right scale*, “ppb” = part per billion) average annual concentrations during the last 1,000 years. 2012 values are about 390 ppm and 1,800 ppb for CO_2 and CH_4 respectively. *Sources* For CO_2, www.ncdc.noaa.gov/paleo/icecore/antarctica/law/lawdata.html—For CH_4, http://cdiac.ornl.gov/trends/atm_meth/lawdome_meth-data.html

4.4.2 It Is the Atmosphere

If recent warming cannot be attributed to the amount of energy coming in, then the problem must be in the way it comes out. The time has come for greenhouse gases to enter the scene. Sun’ radiation makes its way to the ground because the atmosphere is roughly transparent to the wavelengths involved (visible). This energy heats the Earth which in turn re-emits it. But the re-emitted light, or radiation, is in the infrared range.

Now, greenhouse gases interact strongly with infrared light, not with the visible. As already mentioned, temperature has to rise if the same amount of energy is to be expelled to fulfill the energy balance. The most efficient greenhouse gas in the atmosphere is water vapor. Anthropogenic emissions in this respect are so far negligible, and the increase of water vapor detected in the atmosphere simply stems from the fact that warmer air can hold more vapor [2, p. 666]. The second most efficient greenhouse gas in CO_2. Remember Sect. 3.3, where it was established that as of 2009, 355 gigatons of carbon had been added to the atmosphere since the beginning of the industrial era, while 720 gigatons represents the total amount in the atmosphere today. Here, human emissions are not negligible at all.

During the last 800 thousand years and until 1800, CO_2 concentration has been oscillating between 200 and 280 ppm [2, p. 400]. Then, suddenly, concentration rises like pictured on Fig. 4.8. And methane, CH_4, the third most efficient greenhouse gases, follows exactly the same trend.

The expected drop in the outgoing infrared emissions is more than a conjecture. Satellite measurements of the radiation the Earth emits to space have definitely confirmed a decreased of infrared emissions. And the depleted wavelengths do correspond to the ones absorbed by CO_2 and CH_4 [22,23].

But how can we be sure we are responsible for the increase in CO_2 and CH_4 up there? After all, they could originate from somewhere else. Three facts leave almost no doubt:

- First, if carbon emissions come from combustion reactions, then the amount of oxygen in the atmosphere should drop because each time you generate a CO_2 molecule through such reaction, you pair up a carbon atom with an O_2 molecule. Is it observed? Definitely. Atmospheric oxygen concentration is decreasing by the expected amount [2, p. 51].
- Second, carbon on Earth can be found under 3 forms. The "usual" carbon-12, with 6 protons and neutrons in its nucleus, amounts for 99 % of the carbon population. Then, the nuclear isotopes carbon-13 and carbon-14, still with 6 protons, but 7 and 8 neutrons respectively. Carbons 12 and 13 are stable. Carbon-14 is not. It is continuously produced in the upper atmosphere by cosmic rays collisions, and decays to nitrogen with a half-life of 5,730 years.[14] Now, because carnivores eat herbivores and herbivores eat plants, organic matter has the carbon composition of plants. It turns out that photosynthesis, which absorbs atmospheric carbon for the plants, is less efficient with C-13 [24]. If organic matter is poor in C-13, fossil fuels as well because they are made of organic matter. As a result, burning fossil fuels results in massive emission of carbon with less C-13 than normal. Like pouring alcohol free beer in normal beer results in a mixture with less alcohol, the atmosphere C-13 concentration should therefore decrease. Is that observed? Yes, and in the expected proportion [2, p. 51].
  Moreover, fossil fuels are deprived of C-14 since they have been buried for millions of years.[15] Anthropogenic emissions are therefore expected to lower the atmospheric C-14 concentration for the same reason. This was foreseen in 1955 [25] and is definitely observed, again in the expected proportions [26].
- Third, Fig. 4.9 has interesting lessons to teach. The left panel represents the evolution of the CO_2 concentration measured at Hawaii, averaged over a month and a year. A one year long cycle is clearly superimposed over a growing trend. This yearly cycle pertains to the vegetation cycle: because most of it is in the Northern Hemisphere, it "dies" *together* from fall, to get back to life from spring. As trees lose their leaves before growing them again, they release CO_2 through the decomposing leaves, before they absorb it to generate new leaves. Looking at the amplitude of the oscillation, you could deduce the amount of CO_2 emitted and absorbed and check it fits very well the total amount of leaves. What we see here is nothing but the respiration of the Earth biosphere.

[14] Suppose you have 1,000 carbon-14 atoms before you. Wait 5,730 years, half of them, will have turned to nitrogen. Wait another 5,730 years, and half of the remaining carbon-14 decay. Every 5,730 years, half of the carbon-14 decay. Until there is no more left.

[15] The number of C-14 atoms is divided by 2 every 5,730 years. So in 1 million years, it is divided (1 000,000/5,730) times by 2, which means divided by $2^{174} = 2.4 \times 10^{52}$. So even if you started with 10^{50} of them, the number of atoms on Earth according to *Wolfram Alpha*, there is not any single one left after 1 million years (the number 10^{50} can be easily checked, order of magnitude wise, knowing the Earth' mass and assuming it is made up of iron).

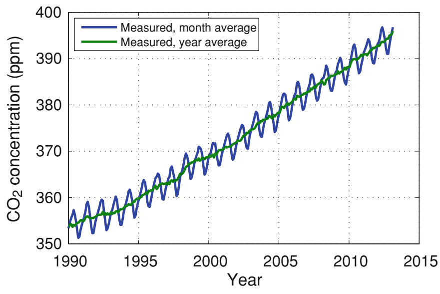

Fig. 4.9 *Left* Monthly and annual mean carbon dioxide measured at Mauna Loa Observatory, Hawaii. *Source* http://noaa.gov. *Right* Measured and (loosely) computed CO_2 concentrations. *Source* Same as Fig. 4.8

Now, what about the upward trend? Its steady pace does not fit punctual natural events like volcanic eruptions for example. But it does fit very well steady human emissions. We can even check the numbers: We know from Fig. 3.4 the amount of carbon emitted since 1750. About 55 % of it stays in the atmosphere, and the rest goes into the oceans ([2, p. 467]). Also, there were about 600 Gt of carbon in the atmosphere before the industrial era [2, p. 471]. Knowing what was before, and what has been added, we can loosely compute the amount of carbon up there from 1,750, hence CO_2 concentration,[16] accounting *only* for human emissions. Why don't we compare now our calculation to the *measured* CO_2 concentration? This is done on the right panel of Fig. 4.9. We cannot expect perfect a fit as our calculation is quite rough and deforestation not accounted for, but the agreement is noteworthy.

Let us summarize what we have so far: We have an observed warming, starting circa 1,800. From the physical basis of climate science, we know such warming must come either from an increased solar flux, or a change in the way the Earth radiates its energy. Looking at the Sun' behavior, we can discard the first hypothesis. Turning now to the second hypothesis, the best candidates to alter energy radiation to space are greenhouse gases. The most efficient, water vapor, has not moved much in the last 200 years. But the second and third of these gases, carbon dioxide and methane, have seen their atmospheric concentration rising tremendously during the last 200 years, in response to fossil fuels burning. Both the expected effect and time window perfectly fit observations. Anthropogenic emissions of these gases are definitely the ideal suspects. Finally, Global Climate Models based on basic physical principles, are very efficient at reproducing what is already known on Earth, Mars and Venus climates.

[16] One ton of carbon gives 3.67 t of CO_2 by virtue of the atomic weights of carbon and oxygen. For the calculation, we also need the volume of the atmosphere, 4×10^9 km^3, and the CO_2 density, 1.96 kg/m^3.

4.5 Men and Greenhouse

4.5.1 Climate Models and Recent Years

Based on the suspicions we now have, we can ask climate models to quantify the consequences of human emissions. Granted, they fit the expected time window and they go into the right, warming, direction. But this is not enough. Suppose calculations tell human emissions could have produced +0.1 degrees since 1880. Then, we would have to find another culprit because the observed value on Fig. 4.1 is rather 10 times higher. We wrote previously climate models correctly render the mean global temperature over the twentieth century. Let us give some more details about how they do so.

To simulate past climate, models need some inputs like the amount of solar irradiation, the timing of volcanic eruptions which send ashes into the atmosphere, and human emissions evolution. In short, inputs consist in a mix of natural factors (Sun, volcanoes…) and human ones. Now, models successfully reproduce past climate evolution all the way to 2011 only when accounting for natural *and* human factors. When switching-off the latter in the calculation, simulations and observations clearly *diverge* during the second half of the last century [2, pp. 18, 930]. The *quantitative* test is therefore successful. At this junction, let us simply quote a paragraph from the 2013 IPCC report,

> Human influence has been detected in the major assessed components of the climate system. Taken together, the combined evidence increases the level of confidence in the attribution of observed climate change, and reduces the uncertainties associated with assessment based on a single climate variable. From this combined evidence it is *virtually certain* that human influence has warmed the global climate system. Anthropogenic influence has been identified in changes in temperature near the surface of the Earth, in the atmosphere and in the oceans, as well as changes in the cryosphere, the water cycle and some extremes. There is strong evidence that excludes solar forcing, volcanoes and internal variability as the strongest drivers of warming since 1950. (emphasis mine).
> *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, p. 871. Cambridge University Press* [2].

Within this IPCC reports terminology, "virtually certain" means more than 99 % confidence [2, p. 36]. Already in the 2007 report, and confidence has grown since then, one could read "it is *extremely unlikely* [<5 %] that the global pattern of warming during the past half century can be explained without external forcing, and *very unlikely* [<10 %] that it is due to known natural external causes alone" ([13, p. 86] emphasis mine). Granted, the confidence level is not 100 % straight, and will never be. But elements are definitively in place to pay attention to models predictions.

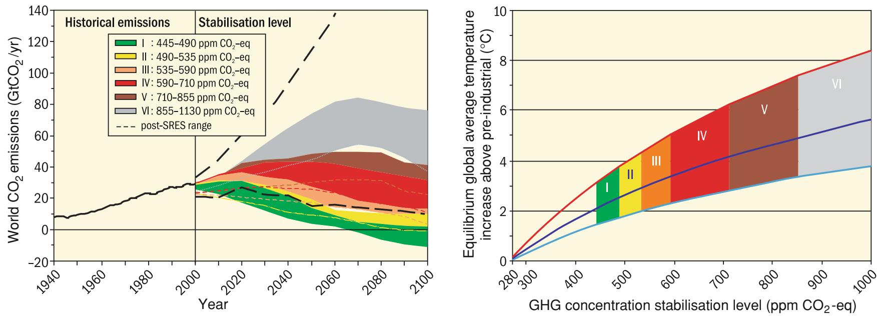

Fig. 4.10 *Left* CO_2 emissions scenarios, from global successful thrive to cut emissions (I), to business-as-usual (VI). *Right* Corresponding long term atmospheric level of greenhouse gases and global average temperature increase above pre-industrial. *Source* Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Fig. 5.1, p. 262. IPCC, Geneva, Switzerland [27]

4.5.2 Climate Models and the Future

When it comes to forecasting climate evolution for the twenty first century, natural *and* human factors again need to enter the equation. On the natural side, future volcanic activity is an unknown quantity which can be modeled assuming an activity similar, on average, to the twentieth century. Other modalities are possible and explored, and we refer the reader to Refs. [2, 13] in this matter. Still, "the eruptions that produce climatologically significant forcing represent just the extremes of global volcanic activity" [13, p. 797]. On the human factors side, the IPCC considers various emission scenarios briefly explained below.

Figure 4.10 can be considered as the climax of this first part, as it gathers all the issues and the questions raised so far. The left part displays various emissions scenarios, from number I where efficient emissions cut policies are globally implemented, to number VI where every single gram of fossil fuels is burnt. Note the peak of emissions in scenario VI around 2060, corresponding to the overall peak of fossil fuels.[17] For each scenario, the right panel shows the equilibrium global average temperature increase above pre-industrial, versus the greenhouse gases (GHG) concentration stabilization level in ppm CO_2 equivalent.[18]

Simply put, scenario VI yields a most probable temperature increase of +5 °C. Not a big deal, one could think. But do not forget we are talking global mean temperature. In this respect, it is sobering to know that some 20,000 years ago, during

[17] See a full description of the scenarios in [13] p. 18. Figure 4.10 comes from the 2007 IPCC report. Similar information can be derived from figures SPM.7 & TS.19 of the 2013 document [2], pp. 21 & 94.

[18] CO_2 is not the only greenhouse gas. Methane (CH_4), for example, is another one. All GHG emissions are therefore converted to "CO_2 equivalent" according to rules we will not detail here (see [2, p. 710]). This allows to represent the full amount of GHG emissions with a single number.

the last Glacial Maximum, global mean temperature was only 3 to 8° cooler than now [2, p. 405], with a northern polar ice sheet covering Northern Europe down to Moscow, Berlin and the North of France, and coming as low as New York in North America. So +5°C are definitely a very big deal [28].

Is it about "saving the planet"? Not necessarily. Near-tropical forests could grow in Antarctica some 50 million years ago (early Eocene), at a time where average temperature in winter down there would surpass 10 °C [29]. CO_2 concentration was probably beyond 4,000 ppm [30], and obviously, no ice was to be found on Earth. So high temperature, lots of CO_2 and no ice are not a problem for the Earth. It already happened, and it is still there. But a sea-level rise of 10 m would definitely be a problem for a world where more than 60 % live within 150 km of the coast [31].[19]

Suppose we want to limit warming to 2 to 3° maximum. According to the right panel of Fig. 4.10, we need to stick to scenarios I or II. No more. Turning now to the left panel, we see both scenarios peak around 2020. In other words, fossil fuels renouncement would have to start *tomorrow*. With coal resources that could peak as late as 2050 (see Sect. 3.2), the message is clear: even if there is plenty left, we cannot afford the comfort of fossil fuels anymore. We need to turn away from them even before they are over. The price to pay to postpone 40 years the search for alternative could simply be too high. Let us now review the possible alternatives.

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[19] The complete melting of Greenland and Antarctica ice sheets would result is a sea-level rise of $7 + 58 = 65$ m [2, p. 321]. Just take their volume, divide by the surface of the oceans, and you find the good order of magnitude. A +5 °C temperature rise could submerge the home of 600 million people, together with 150 of the 981 UNESCO world heritage sites [32]. For more on the impact of climate change, see the 2014 report of the IPCC Work Group II, *Climate Change 2014: Impacts, Adaptation and Vulnerability* (www.ipcc.ch).

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