The environmental challenges of the 21st century

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2022 Edition

This course was written by **Ivar Ekeland** and **Aicha BenDhia**, with the collaboration of **Jacques Treiner** for chapter 7 and **Margot Malpote** for the illustrations. It was supported by **2050** and the **Madeleine Foundation**.

Forewords

Marie Ekeland

It was the end of the 90s. It was time for the digital revolution and I was moving to New York, full of curiosity, energy and enthusiasm, to participate in the advent of this new era. With my keyboard in my backpack, I was coding, developing the algorithms and interfaces that would replace raised hands and shouted orders on Wall Street or Paris stock exchanges.

Then came the 2000s. Startups were moving to Paris despite the bubble. So did the venture capital industry, that I was discovering and that I haven't left since then. And to help steer it in the best direction, I was trying to understand, beyond technology, the nature, the stakes, the consequences, the opportunities and the risks of this 'digital revolution'. How it was transforming our lifestyles, our social organizations and our economic equilibrium.

The 2010s rolled around with the advent of social networks, bitcoin, artificial intelligence, virtual reality. I understood that rather than passively participating in the digital revolution, we could and had to choose what we wanted it to contribute to. Because digital technology can make the best, as well as the worst, and because finance acts as an amplifier, they both offer tremendous power to act and shape tomorrow. So, what kind of "tomorrow" do we want?

We are in 2021. A new Covid year, a new masked year. I believe it is time for a fertile mutation. A cycle of transformations is starting again and I can feel the same curiosity, energy and enthusiasm as 25 years ago. The eras are echoing each other. Once again, young people, researchers and entrepreneurs are at the forefront. Once again, this transformation impacts all sectors, all continents, everyone. Once again, the speed at which we have to adapt takes us by surprise and shakes existing organizations; organizations that were still adapting to the previous revolution.

I choose to take the cycle back to the beginning: understanding what's going on. The fertile mutation is based on adapting to the environmental upheavals we are experiencing: global warming and loss of biodiversity. The purpose of this book is to understand them with thoroughness and depth, in all their dimensions, in order to create valuable knowledge that will allow us to act effectively. This knowledge is transdisciplinary, and it is meant to be completed with contributions by others, deepened, confronted with practice and applied to all sectors and jobs.

To share this intelligence, avoid worst-case scenarios and aim for the best, we created 2050. From agri-food to insurance services, we deploy an investment strategy that aims to regenerate the fertility of our economies. We finance ecosystems of companies that align their economic interests with those of society and the planet. These companies are nurtured by strategic shared resources that enable them to gain power and resilience. This book is the first of these strategic commons. The authors, Ivar Ekeland and Aicha Ben Dhia, put it under a free license so that anyone can access this knowledge, augment it, and pass it on to others. This is not commonplace in the academic world and I want to thank them for this.

This book is also a fruitful inter-generational collaboration, a source of hope and openness, and a family transmission. My father was the first to raise my awareness about global warming, biodiversity loss and their consequences, after his stay in Vancouver in the 2000s. His scientific collaborations had made him feel the reality of the progressive extinction of fishes in the oceans due to overfishing. The same goes for the disappearance of trees in the forests of British Columbia, as they get attacked year after year by a parasitic beetle that no longer dies in winter. He had also studied the consequences of these phenomena on the local economy and the Canadian society, their role and their inertia.

I am so pleased that he has done this tremendous transdisciplinary work of exploration, understanding and synthesis of state-of-the-art science, and that Aicha worked with him in making this knowledge accessible and lively. And I am delighted that we can now share it with you.

2050 starts today. I hope you'll join the adventure!

Ivar Ekeland

Should we be afraid of global warming? Of the loss of biodiversity? Of soils' chemical pollution? And of all of the 21st century's threats, which we somehow feel are linked and all the more frightening as we know little about them? In the face of uncertainty, ignorance creates fear, and fear paralyses. I will use a maritime metaphor. When you leave by car, you can plan your trip to the last detail: on the first night I will sleep there, on the third day I will have lunch here, and I will arrive at my destination at such day and such time.

But when you go on a cruise, it's another matter: the route depends on the weather, as well as on the sea, and you can't predict them long in advance. Whatever precautions you take, you may encounter bad weather, even very bad weather, and it can fall on you very quickly. Then it is better to be prepared, to see the squall coming, to change the boat's course if needed and to know how to maneuver with the blade.

What is a danger for one is an opportunity for the other. Yes, you have to be afraid of the sea if you know nothing about it. But if you have learned, you don't have to be afraid anymore, you just have to know that it has its laws, and that you have to respect them. Global warming is the same. So many things can happen between now and 2100, and we don't know where it will lead us. But it has its laws, and it is better to know them if we want to be able to face the crossing.

There are physical laws, like the greenhouse effect. There are historical laws, like the rebound effect, also called the Jevons effect. There are biological laws, like the great natural cycles. I believe we must understand them all if we want to act efficiently. The goal of this course is therefore to give you the minimal background to understand global warming and biodiversity loss. It is condensed and selective on purpose: we did not go into the greatest depth possible (for those who wish to do so, there is a lot of information online), we rather tried to show the deep unity of the phenomenon. To implement a carbon tax, for example, we need to understand both how CO_2 emissions contribute to the greenhouse effect, which is a matter of physics, and why such a tax will be rejected if it is not perceived as fair, which raises questions of ethics and law.

Oh, one last thing: you are free to leave on a cruise or not, you can even choose your departure date. For global warming, we have no choice: we are in the same boat, and the boat has left already. It has even left very quickly: the concentration of CO_2 in the atmosphere has risen from 313 ppm in 1958 to 419 ppm today, in September 2021.

Aicha Ben Dhia

Do you know the fable of the elephant? In a room, there is a large elephant (yes, it's a big room). Ten brave explorers are brought in and blindfolded. They have never heard of an elephant before. They grope their way to the animal and start touching it. When they leave the room, they need to answer: What is an elephant? What does it look like?

"It's vertical, solid, cylindrical and it doesn't move," the first explorer goes, mimicking hands. A second replies: "Quite the contrary! It's curved, smooth and cold." The third one gets angry: "Neither smooth, nor cold, it's full of hair and it flies in the wind!" Perhaps the fourth leaves the room slamming the door because no one even thought to listen carefully to the noises the elephant was making.

What is global warming? What does it sound like? A melting glacier, an offshore wind turbine or young activists protesting instead of going to school? The book you are holding in your hands would like to be the eleventh character of the fable: not an expert in anything but someone who listens to everything in order to build a coherent picture. We believe everyone should be able to understand these issues, whether a scientist or not, an economist or not, rather than being subjected to a distressing and disorganized flow of information. And more than anything, we believe that understanding is already acting.

This course is structured in several volumes. This first volume lays out the foundations and explains the natural mechanisms that regulate Earth's climate. We will see that the climate has always changed, at a geological pace of hundreds of thousands of years. We will learn that living beings are not passive and isolated but interconnected actors of this climate story. For two hundred years, this regime has been disrupted and we will discuss the possible future trajectories. How did societies seize the power of fossil energies, transforming their relationship to the world, and their economic and social organizations?

We wrote this course for the launch of a mandatory course on the ecological challenges for all first-year students at the University Paris-Dauphine University. A first in higher education — and not only in France! This rightfully acknowledges that all our professional — and personal — lives will now play out in the midst of the ecological whirlwinds that this book recounts. All undergraduate students, whether they are studying marketing, finance or social entrepreneurship, should understand what these whirlwinds are made of.

Rather than a terrifying tsunami, I hope that reading this book you will end up seeing these whirlwinds somehow like the great wave painted by Hokusai: huge and impressive, but fascinating and interesting. Perhaps this can help us achieve this very subtle balance between contemplative humility and joyful audacity. I believe we need to surf on this wave!

This course is a common good.

Declaration of interests: Ivar Ekeland is self-employed and receives no other remuneration than his retirement pension. Aicha Ben Dhia is employed by the company 2050.do, whose mission is to finance and create common resources available to all to craft a fertile future.

Acknowledgements

We thank the University of Paris-Dauphine for creating a mandatory course on global warming and biodiversity for all students, regardless of their discipline. This course was launched in September 2020, for all first-year students. It is based partly on the lessons available here, written by us, and partly on lessons written by Dominique Méda, Valérie Guillard and Stéphanie Monjon. During the 2019-2020 academic year, this project was piloted by a working group chaired by Eric Agrikoliansky, and the LSO department, directed by Renaud Dorandeu, created an optional course for second-year students. This allowed us to test this course on a small group of motivated students.

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This is only the second edition of this course, and we are eager to make it better! If you spot any typos, errors or omissions, or if you have any suggestions for improvements or additions, please write to us at coursclimat@2050.do.

1

Climate has always changed, but never as fast as today

Introduction

“There are two major discoveries of physical science. The first is that the Earth is round, the second is that it revolves around the Sun. Since ancient times, we have known that the Earth is round, but we had to wait until the 16th century to know that it revolves around the Sun. Once these two facts were understood, we were able to infer many more things about our planet.

We have been able, for example, to explain the alternation of the seasons, from hot summers to cold winters, by the inclination of the axis of rotation of the Earth with respect to its plane of rotation. This inclination means that we don't receive the Sun's rays from the same angle depending on which side of the orbit we are on. We will return to this later in the course...

However, we can also explain many other things, such as wind patterns, essential for sailing, for forecasting the day's weather and for understanding ... the climate variations that await us!

Because indeed, our climate is changing. If we go way back in the history of the Earth, we know that it has changed enormously. Just to give you an idea, 120,000 years ago, New York was under sea ice! Similarly, it is certain that climate will also be changing in the distant future. This change is linked to changes in the Earth's orbit.

Then, you may ask: why worry if the climate is changing right now?

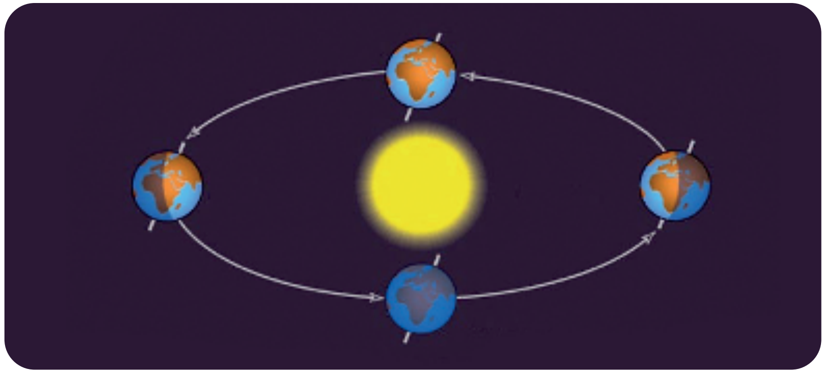
The problem is that it’s changing very quickly. Much too quickly in fact. Until now, change has been gradual, as it followed the very slow changes in Earth's orbit. These changes can take tens of thousands of years. This gave life time to adapt. However, the change that we can observe today is concentrated over just a few decades, and the consequences are very different. It's a bit like driving a car at 100 km/h and having to stop: are you going to have the same experience if you are given 1000 meters to stop, or 1 metre? In the first case it's braking, in the second, it's crashing.”

1 Earth’s movements around the sun and the cycle of seasons

1.1. The two rotations of the Earth

Earth is animated by two main movements. On the one hand, it revolves around the Sun. Its trajectory is flat (unlike a moth turning around a light bulb, constantly rising and falling, but rather like an ice skater, who remains on the same horizontal plane). In the 16th century, Kepler (1571-1630) discovered that this trajectory is not exactly a circle but an ellipse, which means that there's a point which is closest, and a point which is furthest from the Sun. Earth takes a year to complete the ellipse. On the other hand, Earth spins too. The axis of this rotation passes through the poles. The time it takes to complete a full rotation is the day. Each of these movements is simple.

When we consider their combination, things start to get more complex.

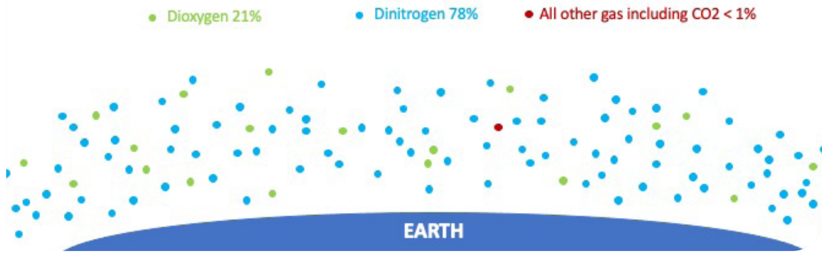


Variation of Earth's exposure to the Sun due to the inclination of its axis of rotation.

Why do we have seasons? Because the axis of rotation of the Earth is not vertical. It always keeps the same direction in space, and this direction is at an angle of about 23° to the vertical. In fact, for half of the year, one of the hemispheres will be tilted towards the Sun, whereas for the other half the other will be. When one of the hemispheres is oriented towards the Sun, it will be the warm period in that hemisphere. The seasons represent the most familiar example of the dependence of climate on astronomical movements.

1.2. The Atmosphere

To complete this section, we need to introduce a final key factor in order to understand climate: **the atmosphere**. The atmosphere is a gas blanket surrounding the Earth, made up of 78% dinitrogen molecules, 21% dioxygen, 0.93% argon, and less than 0.05% other gases, such as carbon dioxide (the famous CO_2). Many planets in the solar system have atmospheres. However, their compositions are very different compared to Earth. For example, the atmosphere of Mars contains mostly carbon dioxide molecules and almost no oxygen at all. That of Venus is mostly made of carbon dioxide. On both planets, it would be impossible for Earth animals to breathe.



Summary

Atmosphere, the Earth's revolving around the Sun, and Earth's tilted rotation on itself: these are the astronomical factors which determine Earth's climate.

2 The mixing of the atmosphere by the winds

If you ask what the weather will be in Paris tomorrow, what exactly do you want to know? The ground temperature of course. It's the first element of weather. What is the second? Wind. What is wind? Nothing more than the molecules in suspension we were talking about (dinitrogen, dioxygen...) which move together through the atmosphere. However, does this really depend on astronomical movements?

The answer is yes. If we were to climb onto a satellite and observe the large movements of air on a planetary scale for a year, we would see that there is great regularity and that these movements can be explained by the Earth's astronomical movements.

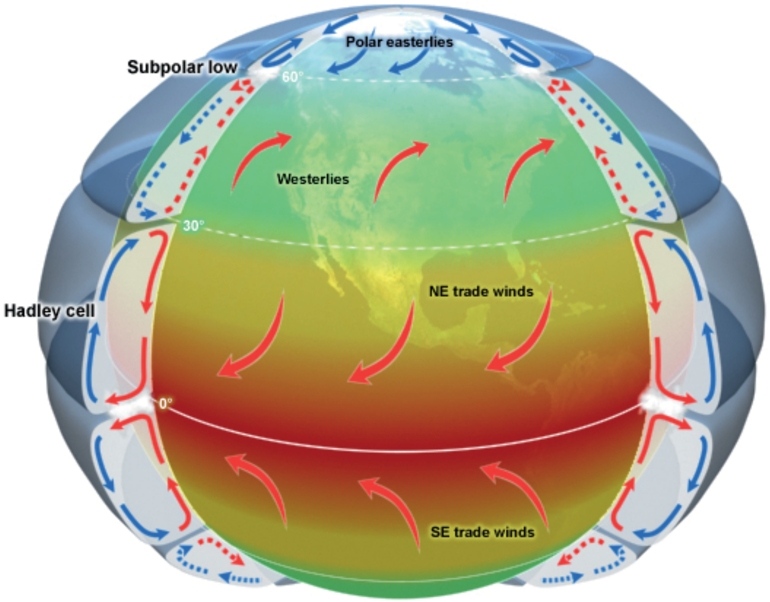
By the way, you too, certainly, know some regular and predictable air movements. In a sauna, for example, does hot air rise or fall? It rises! And what happens when you boil liquid water in a pan? The molecules break off from each other and liquid water turns into gas water, also called water vapour. In what direction do these water molecules in gaseous form go? Upward! Because as a gas, what is hot rises and what is cold falls.

Here's a final example to illustrate the impact of Earth's rotation on the direction of winds. Imagine you are holding your boiling pan at the edge of a carousel that is spinning very fast. Think about the water vapour that's released: will it end up scalding your eyes or on the face of the person next to you? Because of the spinning carousel, it will land on the person behind you on the carousel.

These mechanical rules also apply on a planetary scale (hot air currents rise, they are deflected toward the West because Earth turns like a carousel, from West to East, etc.). This explains why the winds blow regularly from one point of the globe to another. The figure below provides a schematic representation of wind patterns on Earth, with hot streams in red and cold streams in blue. Here, it's not a question of knowing each of the movements, but to understand that these air movements are as predictable and regular as hot air rising in a sauna.

Let's stop for a moment to observe a second fundamental point. This figure shows that Earth's atmosphere is constantly agitated. This means that if we send a persistent molecule to be suspended in the atmosphere, it will remain in suspension, but it will not remain in place. It will be moved from one point of the globe to another, according to the winds.

Thus, if a factory emits CO_2, the gas emitted will not stagnate above it. If this were the case, the emitter would suffer the impact itself, and would no doubt very quickly take the necessary steps to remedy it. But because the gas is dispersed, it can neglect this and let it spread over the planet. When not regulated locally, pollution then becomes a global problem.



Circulation of winds in the atmosphere.

Source: The COMET Program

Summary

- Earth winds are governed by the astronomical movements of the planet. They follow predictable and regular movements.
- The atmosphere is constantly stirred: any molecule which stays in suspension travels from one point of the globe to another.

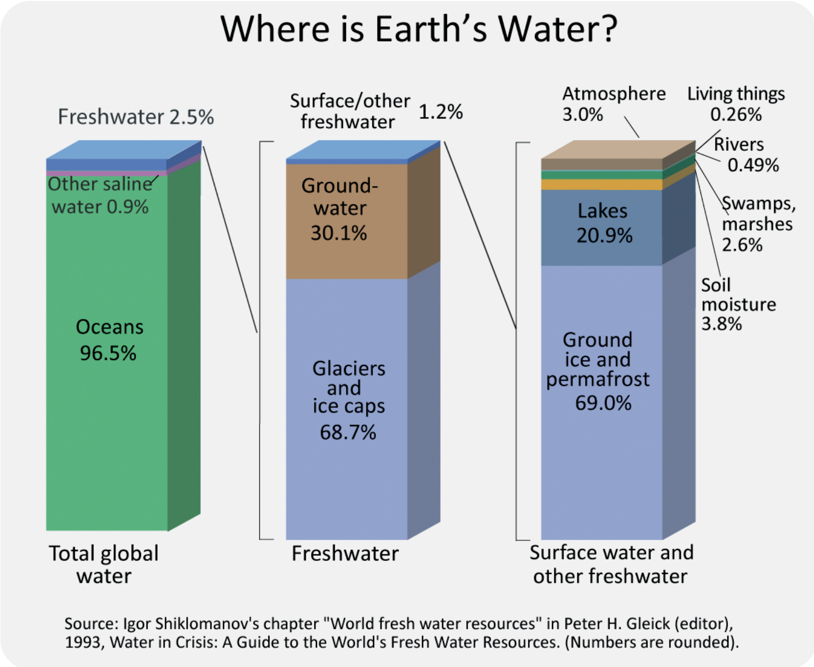
3 Water

Ground temperature, wind force and direction. What is missing from this weather forecast if one wants to know if it's better to organise a picnic or go to the movies? Water, of course!

Water, in other words: clouds, rain, snow, hail, ice. Earth is the only planet in the solar system where the temperatures are mild enough for water to be found in its three forms: solid, liquid and gas. The vast majority of water on Earth is found in its liquid form, in the oceans (97%), in rivers, in vegetation and in the soil. Moreover, it's also found in its solid form, in the ice caps (2%), mainly as sea ice.

There is less than 0.001% in gaseous form: it's water vapour in the atmosphere.

This is a tiny proportion of water on Earth, but nevertheless, it plays a fundamental role, as we will see later. For now, let's just observe how it's extremely visible, in the form of clouds or precipitation, and that humidity is, together with temperature and wind, the third essential figure in meteorology.



Interpretation: 96,5% of water molecules on Earth are to be found in liquid form in the oceans. Freshwater only represents 2.5%, of which 68% are stored in glaciers and ice caps. There is only a tiny fraction of water (2,5% x 1,2% x 3%) that is in gaseous form in the atmosphere.

Source: Igor Shiklomanov in "Water in Crisis: A Guide to the World's Fresh Water Resources.", Peter H. Gleick

4 The climate

Temperature, humidity, and wind at a given point at a given time: these are the three components of weather.

These components vary from moment to moment and from place to place. However, if you record these variations over several days, and do the same for several months, you will see that they follow periodic cycles. Most of these cycles have become very familiar to us (we all know that in the Northern hemisphere it's almost always hotter in July than in March, and in March compared to December; or even that it rains more in November than in June).

This is why we can extrapolate averages over several years and talk about the "climate" of a given location, without specifying a particular year. These averages are generally calculated over thirty years, and depend on the location.

These averages of temperatures, wind and precipitation constitute the "climate".

Summary

- A very small proportion of water on earth is in gaseous form, suspended in the atmosphere (cloud, humidity, fog), but locally, it plays an important role on the climate.
- The climate at any point is the average data of temperature, wind and humidity at that point. Averages are generally calculated over thirty years of observations.

5 Climate change over the course of Earth's history

5.1. The climate is changing. How do we know?

Based on logic, if astronomical factors, such as the Earth's orbit or the tilt of the axis, change, the climate must change, as well.

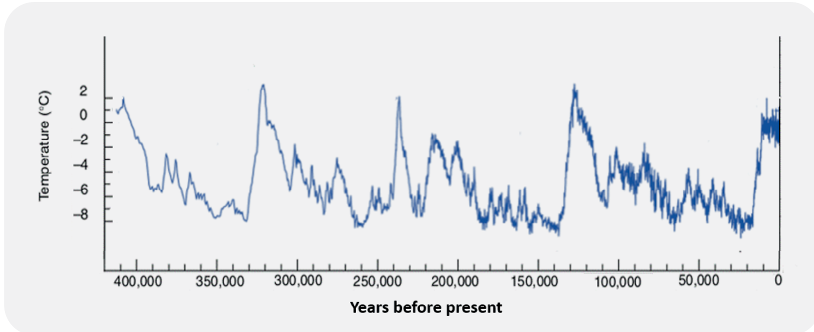
At present, Earth's orbit is almost circular: if it becomes more flat, with solstices moving closer to the Sun, then winters will be farther away from it, and, as a result, we will have hotter summers and colder winters. Likewise, if the axis deviates further from the vertical, summer days will be longer and winter days shorter.

In fact, all these factors do change, following regular cycles: of the magnitude of 400,000 years for the orbit, 40,000 for the tilt, and 26,000 for the solstices. And the climate, as a result, changes too. But how do we know? How do we go back in time and reconstruct past climates?

Climate change has left traces in fossils, such as pollen. However, the great breakthrough is due to polar drilling. The basic idea is that the composition of snow and ice depends on the temperature and solar radiation when it is formed. Moreover, air bubbles are trapped inside, from which the composition of the atmosphere at that time can be extrapolated. Therefore, we have some sort of 'archives' that allow us to compare the temperature and carbon dioxide (CO_2) and methane (CH_4) content. The first cores collected in the Arctic, allowed us to go back 80,000 years, while the cores collected in Antarctica allow us to go back ten times further!

5.2. Relationship between temperature and greenhouse gas

This curve below, taken from the article shows the history of temperatures in the ice under the Russian basis Vostok in the Antarctic. It gives the temperature deviations with respect to a reference temperature of -55°C. Observe that temperatures vary between -64°C and -53°C. But the most striking thing you will notice is the regularity of these variations, with a spike approximately every 100,000 years.

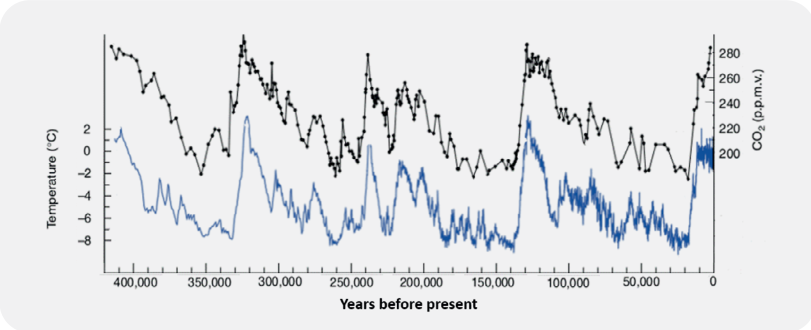


Evolution of the temperature above station Vostok.

Source: www.climatedata.info

The pace is consistent with variations of astronomical parameters, like distance to the Sun. The almost vertical drop that we observe around every hundred thousand years (and which corresponds to temperature drops of around 10°C) still takes place over 10,000 years!

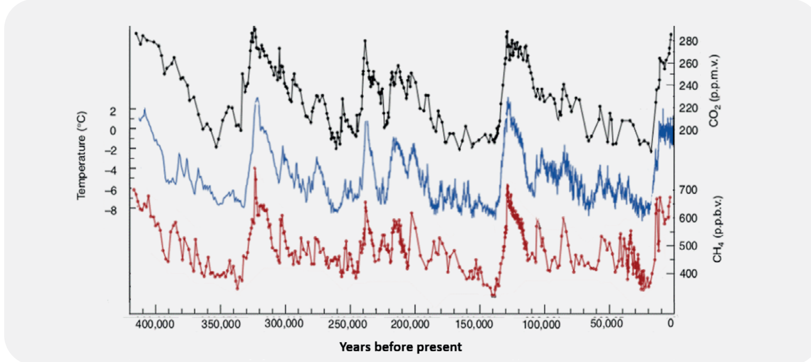
Let's overlay the CO_2 concentration curve in black. The variations are remarkably similar. As we have seen in the previous section, the air in the atmosphere contains very few molecules of CO_2, around 0.05%. In order to express the CO_2 content of air, we don't use percentages but "per-millions", that is, we indicate the number of CO_2 molecules per million air molecules. This is called "part-per-million" and is denoted by "ppm".



Joint evolution of temperature and CO_2 concentration above station Vostok.

Source: www.climatedata.info

Finally, let's overlay the methane CH_4 curve in red: it follows the same pattern as the two first variables. There are even fewer particles of CH_4 than CO_2 in the atmosphere. Therefore, the content of air in CH_4 is expressed in "parts-per-billion". This is denoted by "ppb".



Joint evolution of temperature, CO_2 and CH_4 concentrations above station Vostok.

Source: www.climatedata.info

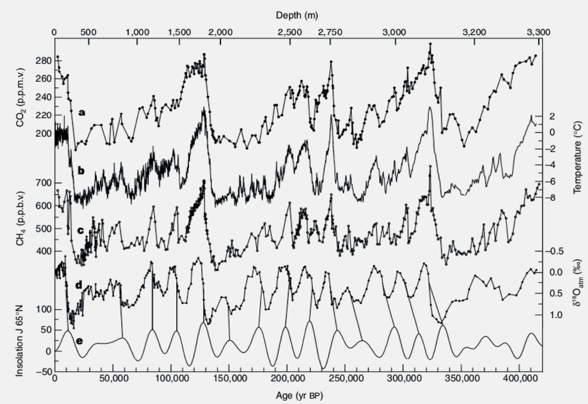
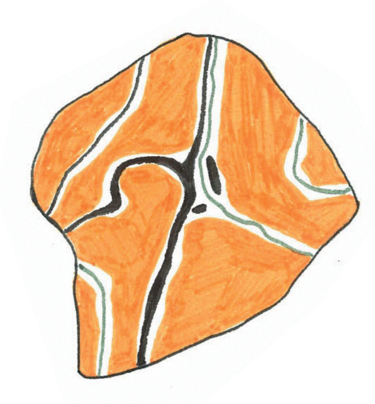


Figure 3 Vostok time series and insolation. Series with respect to time (GT4 timescale for ice on the lower axis, with indication of corresponding depths on the top axis) of: **a**, CO_2; **b**, isotopic temperature of the atmosphere (see text); **c**, CH_4; **d**, $\delta^{18}O_{atm}$; and **e**, mid-June insolation at 65°N (in $W m^{-2}$) (ref. 3). CO_2 and CH_4 measurements have been performed using the methods and analytical procedures previously described[5,9]. However, the CO_2 measuring system has been slightly modified in order to increase the sensitivity of the CO_2 detection. The thermal conductivity chromatographic detector has been replaced by a flame ionization detector which measures CO_2 after its transformation into CH_4. The mean resolution of the CO_2 (CH_4) profile is about 1,500 (950) years. It goes up to about 6,000 years for CO_2 in the fractured zones and in the bottom part of the record, whereas the CH_4 time resolution ranges between a few tens of years to 4,500 years. The overall accuracy for CH_4 and CO_2 measurements are ±20 p.p.b.v. and 2–3 p.p.m.v., respectively. No gravitational correction has been applied.

Evolution over time of climatic parameters above station Vostok.

Petit, J., Jouzel, J., Raynaud, D. & al., Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399, 429–436 (1999). https://doi.org/10.1038/20859



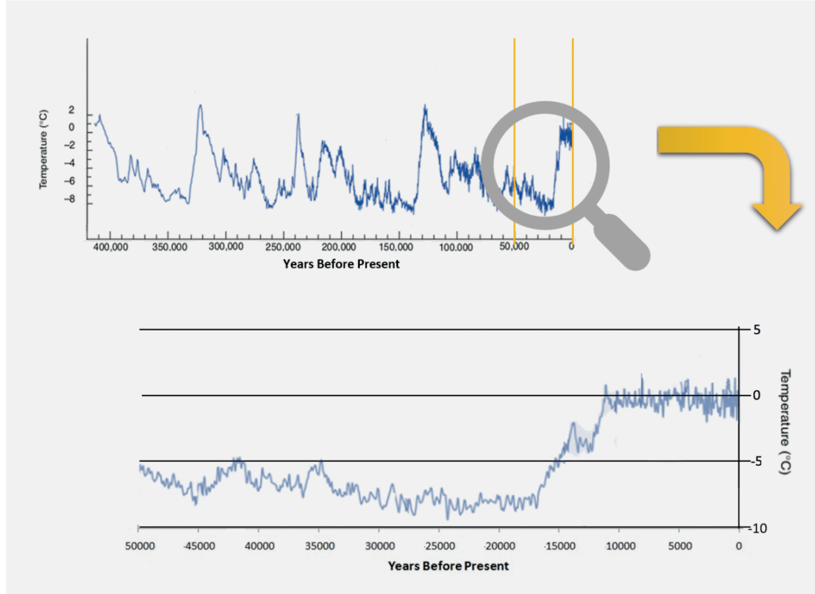
There is an obvious correlation between the content of the atmosphere in CO_2 and in CH_4 (methane) and temperature. Does this imply that the CO_2 and CH_4 content is the cause of temperature variations? In this case, it is the opposite: the astronomical changes in the orbit of the Earth cause an increase in temperature which induce an increase in CO_2 and CH_4. We will see the causality is reversed in the current episode of global warming.

5.3. Recent climate change

To end this chapter, let's get back to the metaphor of the car and the crash. When we see these variations, we could say to ourselves that the Earth has experienced other warming periods! Perhaps, after all, there is no reason to be worried if we are to go, once again, through an era of climate turbulence.

As for the Earth, yes, but how about for humans? Over this long period of time, which is still not much compared to the scale of the age of planet Earth, we can say, approximately, that human species appeared 10,000 years ago. What do you observe during this period?

If we zoom in on the last 50,000 years, we observe an unusual stability with relatively high temperatures, between -56°C and -54°C. This stability helped humans and their ecosystems to adapt, maintain and develop themselves.



Focus on the last 50,000 years.

Source: www.climatedata.info

Summary

- We know the past temperatures and composition of the atmosphere thanks to the ice cores from the sea ice and frozen lakes of Siberia.
- Temperature on Earth has varied cyclically, depending on the variations of astronomical factors, over time scales in the order of tens of thousands of years.
- Changes in temperature and in the atmospheric content in CO_2 are very strongly correlated, which suggests that there is a link.
- The climatic changes observed during the last two centuries are of the same order of magnitude as the past terrestrial changes, but on a time scale which is 100 times faster.

Conclusion

We now have introduced the main characters of our play: the Earth and its atmosphere, winds and suspended molecules (dinitrogen, dioxygen, and in tiny proportion: water vapour, carbon dioxide, methane...). Then the scenario: cyclical and joint variations of the central characters (temperature, CO_2, methane) due to astronomical factors. This scenario is at least 500,000 years old and is encrypted in ice cores from the sea ice and frozen lakes of Siberia. Pretty fascinating, isn't it?

But since 1800 there are some unexpected developments in the play: the climatic changes observed during the last two centuries are of the same order of magnitude as the past terrestrial changes, but on a time scale which is 1,000 times faster.

And to put certain numbers of this chapter in perspective, it is also interesting to remember that the difference in temperature between an ice age and an inter-ice age is roughly 5°C. During the last ice age, Northern Europe was covered by a 3km thick ice cap and the sea level was 120 meters lower than today.

2

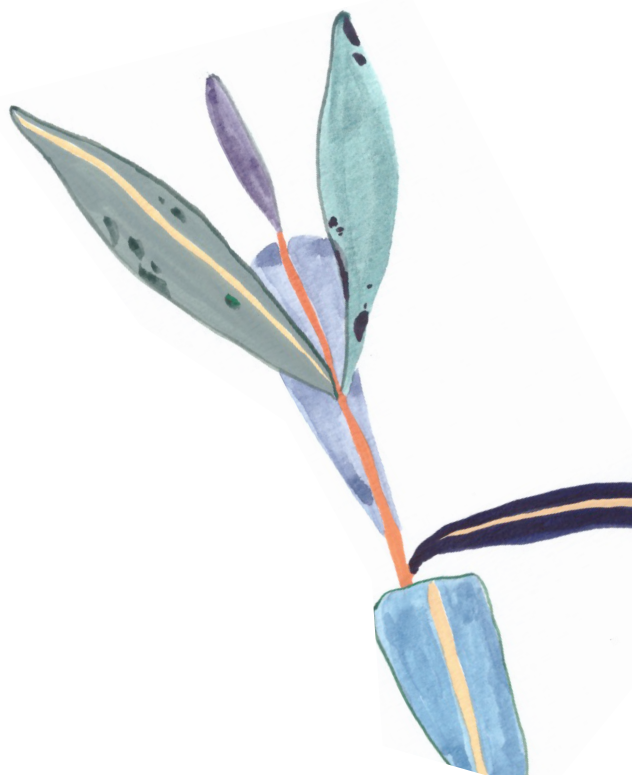
The atmosphere: greenhouse or sleeping bag?

Introduction

When you go camping, don't forget your sleeping bag. If you don't have one, you will be too cold to be able to sleep: your body will radiate around you, and at most, it will warm the tent, if you have one, but for you it will be lost. If you have a sleeping bag, it will reflect back towards you a big part of the heat that you produce, and that's how you'll get warm. Well, our planet also has a sleeping bag: it's its atmosphere. It prevents the heat emitted by the Earth from radiating into space.

The atmosphere is usually compared to a greenhouse, but the comparison with a sleeping bag is instructive as well. As you know, sleeping bags are more or less warm depending on their thickness and the quality of their filling: the warmest and most expensive sleeping bags are filled with duck feathers. Well, what takes the place of duck feathers, in the case of the atmosphere, are certain molecules which are able to retain heat very well. These are the gases that we call greenhouse gases: those you know (carbon dioxide, methane, etc.) and another one that you may not think of: water vapour.

From the physical point of view, neither comparison is fully satisfactory. However, one thing is for sure: adding greenhouse gases to the air warms the Earth. And you can easily remove feathers from a sleeping bag, but you can't easily remove carbon dioxide from the atmosphere.



1 The greenhouse effect

1.1 The radiation from hot bodies

The surface of the Sun has a temperature of around 5,700 degrees Celsius. This is a massive temperature level! Do you think that this temperature has something to do with the light that the Sun sends to us? Well, yes! Actually, it's because it's hot that the Sun sends us light rays. Even more surprising: this principle is true for any object. Any object (your watch, your toe, a blade of grass) radiates and this radiation depends directly on its temperature.

Of course, you'll answer that when your kettle heats up, it does not start to light up the kitchen. On the other hand, you must have heard of infrared glasses. These secret agent goggles allow you to detect human bodies in the dark because they are warmer than the rest of the objects in the room. Well, if you put on your infrared goggles while making yourself some tea, you will be able to see your kettle also in the dark! Why? It would be complicated to go into the details of this great law of modern physics and we will settle for a pictorial and simplified representation.

1. Heating up any object of matter (a piece of wood, your hand, water vapour) creates **agitation among the atoms and molecules inside**. This should remind you of the previous chapter: as we have seen, if you heat liquid water, water molecules begin to agitate in the pan and end up scattered throughout the kitchen, which is what we call water vapour. Even before reaching 100 degrees Celsius, heating liquid water creates agitation inside the pan. This is also why you need to put hot water to brew your tea: tea: the water molecules quickly carry the aroma of the leaves around the whole volume.

2. More mysterious: when an atom (or a molecule) is agitated, it can discharge its energy by sending **light waves**. The surface of the Sun is at a very high temperature. Therefore, it is made up of very agitated atoms, and these atoms are just waiting to discharge part of their energy by sending light back all over the solar system. This is one of the great laws of physics, which was discovered in the twentieth century.

3. Let's get back to the kettle: why, in this case, does it not illuminate your kitchen? This is due to both the **shape of the waves** it sends and the **sensitivity of our eyes**. In fact, a light wave, as a water wave, can take several forms: some are spread out (the peaks of each wave are very spaced), others are compact. We say that a wave can have a long wavelength (widely spaced peaks) or a short wavelength (very close peaks). With light waves, there is no relation between the speed of the wave and its **wavelength** (by the way, this is also true for acoustic waves and that's why all the notes of a chord reach your ear at the same time).[1]

The highest the temperature of an object is, the more it radiates compact light waves, that is, having short wavelength, and the more **numerous** these waves will be. As the Sun temperature is very hot, it mainly emits light waves at very short wavelengths, and a lot of them. Those that our eyes have become accustomed to detecting are of a wavelength between 0.4 and 0.7 micrometres (a micrometre is 100,000 times smaller than a meter). This is what we usually refer to as visible light. The kettle is much cooler than the Sun: therefore, it emits light rays at longer wavelengths, that our human eye is not able to "see", and it emits much less of those.

1 — As a consequence, waves with long wavelengths have low frequency.

4. A hot object loses part of its energy by emitting light waves. Waves are therefore charged with energy, and when coming into contact with a new atom, on Earth for example, they can transfer this energy to it, for example by heating it. This is why we say that the Sun "heats" the Earth, which, in other words, means that it transfers energy to it by sending light waves.

Summary

- An object is at a higher temperature than another if its atoms and molecules are more agitated. Agitated molecules can discharge part of their energy by emitting light waves.
- All light waves have the same speed, but can have longer or shorter wavelengths. The human eye perceives light waves only at certain wavelengths, between 0.4 and 0.7 micrometres.
- The higher the temperature of an object is, the more waves it emits and the shorter such waves are.
- Light waves carry energy which they can transfer to objects they reach and which, as a result, get heated.

1.2 Earth radiation and equilibrium conditions

Therefore, the energy transported by solar radiation ends up heating the celestial objects it encounters, in particular the Earth. When this is being heated, it will, in turn, re-emit radiation, like all hot bodies. Therefore, the Earth receives energy (solar radiation), as well as emitting it (its own radiation). However, in what quantities? Which of these two radiations has the most energy?

Let's argue. As we saw in the previous chapter, over the past 10,000 years, the temperature on Earth has been very stable. If the radiation received by Earth over the course of a year were to be more than it returns, what would happen? Earth would then have a "surplus" of energy, therefore a surplus of heat! The Earth would therefore start to heat up, a little more each year, which is not what we observe over the 10,000 years of the Holocene.

Summary

- To remain in thermal equilibrium, the Earth can only emit exactly the same amount of energy that it receives.

1.3 The role played by the atmosphere and the greenhouse effect

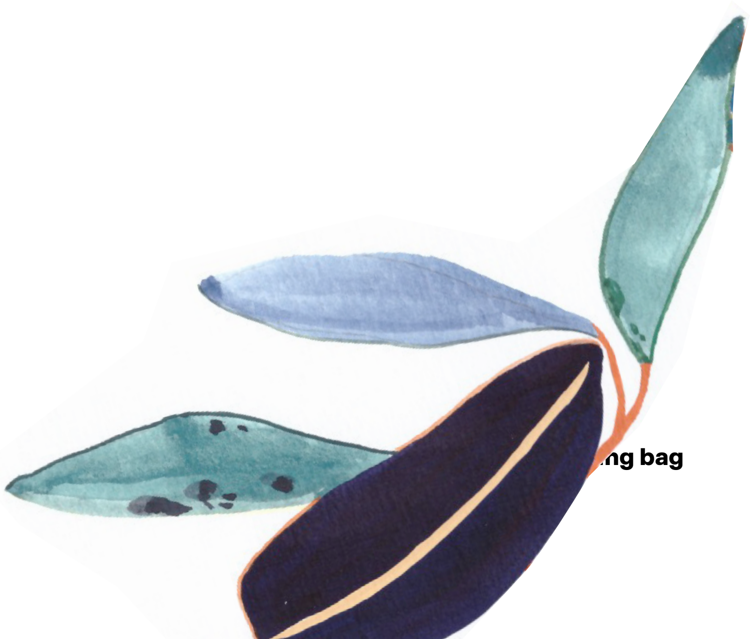
Physicists have studied extensively the radiation emitted by a hot body and found an equation which allows us to perfectly predict the shape of light waves emitted by a hot body as a function of its temperature. We saw that in the case of the Sun, at 5,700°C, most of the light waves emitted possess a wavelength between 0.4 and 0.7 micrometres (this is visible light, between red and purple). Since the Earth's soil temperature is much lower than that of the solar surface, the radiation emitted by Earth's soil is shifted towards long wavelengths. It ranges within what is called **the infrared**, with wavelengths of around 10 micrometres, well away from the light visible to the human eye.

Therefore, this terrestrial radiation escapes our vision... but not the atmosphere! Or rather: not all the molecules in the atmosphere. Some large molecules in the air (CO_2, H_2O, etc.) are particularly sensitive to the long-wavelength waves emitted by the Earth. Instead of letting them pass (like a buoy in the sea lets the waves pass or a window lets the sunlight pass), they manage to absorb the energy carried by terrestrial light waves, heat up and get agitated, then end up discharging themselves by sending back light waves in all directions (this is again the black-body radiation principle in action).

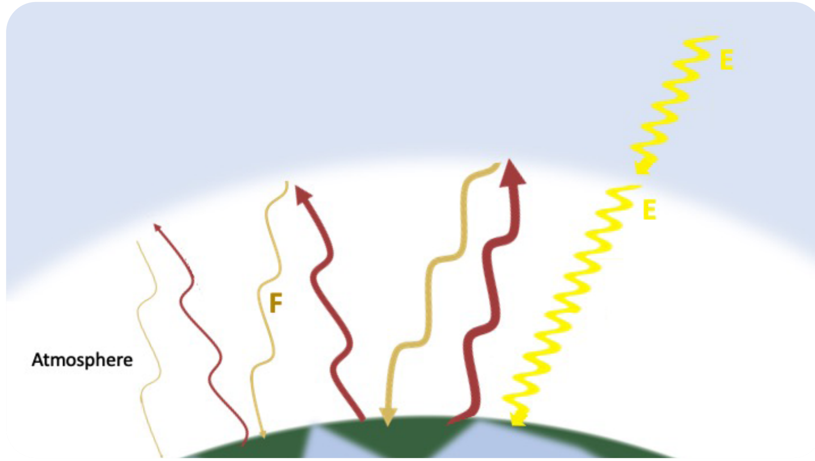
All things considered, this means that the Earth receives not only direct radiation from the Sun, but also that which is partially absorbed and then reflected toward it by its atmosphere. Like a sleeping bag retains your body heat when you sleep or a greenhouse traps warm air near the ground to grow tomatoes, the atmosphere retains some of the Earth's heat.

We can decompose these flows of energy in a state of climatic equilibrium. Radiation from the Sun (E) reaches the system Earth + Atmosphere. These waves with short wavelengths mostly pass through the Atmosphere and when they get to the ground, some are directly reflected like with a mirror. By what? Mostly by sea ice, but also by glaciers and by any other surface that reverberates light. The rest gets absorbed by the Earth: by your skin that gets red under the Sun, by plants that use this energy to grow, by oceans that get hotter.

Conversely, the Earth gets warm and emits light waves, but with a shorter wavelength than the Sun, mostly in the infrared. Molecules like H_2O or CO_2 absorb about 40% of these waves and re-emit waves towards the Earth. What is not absorbed goes through the atmosphere and is released back in the Solar system. A new “emission-absorption-reemission” loop is initiated as illustrated below by the beige arrows that point towards the Earth.



ng bag



In the end, the Earth gets heated up in two ways: from direct solar waves, and by the sum of all re-emitted waves from the atmospheric blanket. Let’s call this sum F. If Earth's climate is stable, then the Earth should receive no more energy than what it emits. In other words, the Earth needs to be at a temperature such that it emits exactly E+F. With no atmosphere, F would be 0 and in equilibrium, the Earth would stay at a temperature such that it emits E. Physicists have precisely calculated that this temperature would be -19°C (on average). Instead, the average temperature on Earth is 15°C, which is 34°C hotter. Quite a significant difference!

What happens if the concentration of CO_2 suddenly increases in the atmosphere? You can easily guess that the Earth will get hotter, as F will increase. There is more: such a change is a structural change. It usually takes some time for the Earth temperature to adjust and reach a new equilibrium. In other words, a one-off yet structural change can have lasting effects and the consequences cannot be immediately observed.

Summary

- The atmosphere is responsible for the "greenhouse effect", which warms the Earth up.
- This is due to a few specific molecules which act as partial mirrors, absorbing and re-emitting long wavelength waves back to Earth.

2 Greenhouse gases (GHG)

The air, in other words, the atmosphere, is a mixture of different molecules: it mainly contains dinitrogen N_2 (78%) and dioxygen O_2 (21%). Both are made of two atoms and are insensitive to long wavelength waves. Therefore, they don't play a role in the greenhouse effect.

It all happens within the remaining 1%. The greenhouse effect is due exclusively to other gases, whose molecules at least include three atoms and which are present in tiny quantities (a few tenths of a percent for water vapour, less than 0.1% for the others). Thus, they have a weak concentration in the air, but this does not prevent them from being extremely effective in terms of greenhouse effect.

The main molecule responsible for the greenhouse effect is water vapour, H_2O. Its concentration in the atmosphere can vary a lot: it is measured by relative humidity, which ranges from 0 to 100%. When 100% humidity is reached, water vapour condenses into droplets, and we get the clouds, which eventually fall back as rain, snow or even hail.

Let's consider the other greenhouse gases (GHGs), that is, dry air. The remaining GHGs are, in order of importance[2]:

- carbon dioxide, CO_2, current concentration 420ppm, but constantly increasing, responsible for 65% of the remaining greenhouse effect (that is, excluding water vapour)

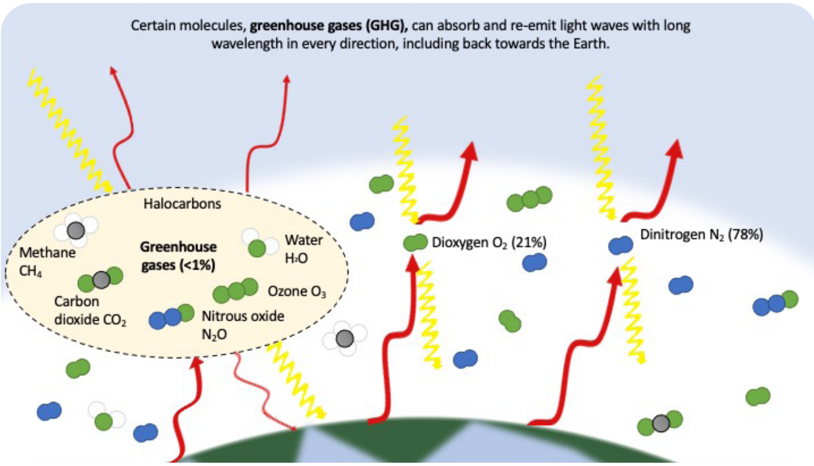
2 — https://planet-terre.ens-lyon.fr/article/effet-de-serre.xml

- methane, CH_4, current concentration 2ppm, responsible for 15% of the remaining greenhouse effect

- halocarbons:
  — These are gases of exclusively industrial origin, such as freons, which became famous for destroying the ozone layer in the atmosphere.
  — They are 16,000 times more absorbent of terrestrial light waves than CO_2, and despite a very low concentration, they account for at least 10% of the greenhouse effect, excluding H_2O.

- ozone O_3, for 10%

- nitrous oxide N_2O for 5%

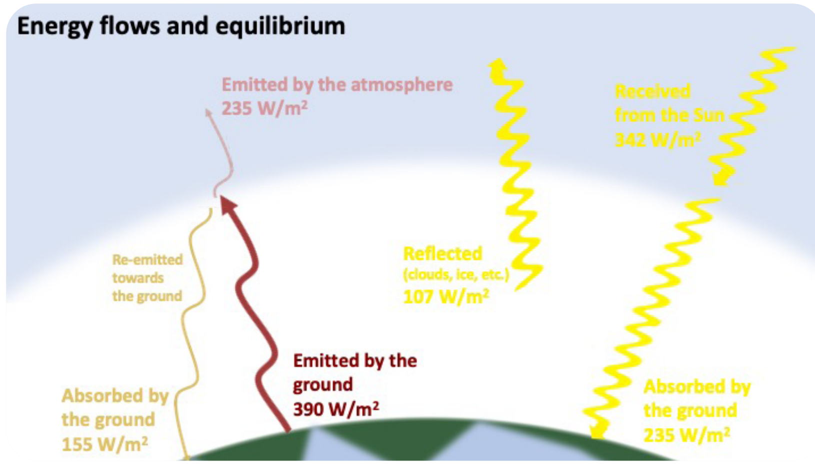


3 Radiative forcing

Water, in its gaseous form, is a greenhouse gas, however, in liquid or solid form, it produces another effect: it reflects light. Some of the solar radiation passing through the atmosphere is not absorbed by the ground, but is returned directly by snow, ice or clouds.

It is therefore necessary to slightly modify Earth's energy budget, which finally, appears as follows (unit is W/m², Watts per square metre):

- received from the Sun: 342 W/m²
- reflected: 107 W/m²
- reaches the ground: 235 W/m²
- emitted by the ground: 390 W/m²
- crosses the atmosphere: 235 W/m²



As explained, this energy budget is balanced and the temperature of the Earth is stable: 235 + 107 = 342.

These are the same flows which prevailed in 1750, in 1515, in -52 or at the times of the Pharaohs. Incoming and outgoing flows are equal.

However, since two centuries ago, the balance has been upset; the Earth is no longer able to remove all the energy it receives. The difference between energy received and energy discharged is called **radiative forcing**.

The term forcing refers to the idea that this pushes the Earth out of balance. It is expressed in Watts per square metre (W/m^2). In 2016, it was estimated at 3 W/m^2 (we will get back to energy and power measurements in one of the next chapters).

Therefore, the 'surplus' energy will mechanically heat up the Earth and we will see that the average temperatures have indeed increased since 1750. Think of lighting the fire under a saucepan: the temperature of the water increases, but that's not all: the liquid begins to agitate and evaporate. As for Earth, it is to be expected that the atmosphere will warm up, that the winds will become stronger and that precipitations will increase.

Conclusion

Greenhouse gases are atmospheric molecules composed of three or more atoms that react to long-wave radiation emitted by the Earth and re-emit part of these light waves towards the Earth. They warm up the atmosphere, even though they represent no more than 1% of its content.

For two centuries, the quantity of greenhouse gases has been increasing: mechanically, the Earth receives more energy than it sends back, and enters a warming phase. We will see in the next chapters that the story does not end there. A one-time emission of greenhouse gases is enough to create a surplus of energy and move the Earth out of thermal equilibrium, but we also add more of these gases to the atmosphere every year. The rise of temperatures then accelerates, with a whole series of cascading effects, most of which are reinforcing.

3

All living beings are interconnected: it is the biosphere and it directly contributes to the Earth's climate

Introduction

This chapter is about biology, that is, living beings, and how they fit into Earth's climate. First of all: what exactly is a living being? What differentiates us humans, toads and tulips, from stones and steel, that is, from so-called 'inert' matter?

To be clear, this is a huge issue. That's the reason why, in this chapter, we will consider a simplified definition of living beings, and realise that one of the main characteristics of living beings is that they are extremely dependent on their environment, as well as being in constant evolution. If an astronaut puts a pebble into orbit in space and returns a year later, what would she find? Unless some meteorite displaced it, she would find it perfectly intact. What if she was to replace the pebble with a fish? Or with a whole flowerbed, complete with soil and worms?

In reality, if we look at the conditions under which living beings survive, even without putting them in space, we realise that they are very fragile, since they are very dependent on each other and on external conditions. Each living being succeeds in preserving its vitality thanks to sophisticated and diverse strategies, provided that its environment does not change too much.

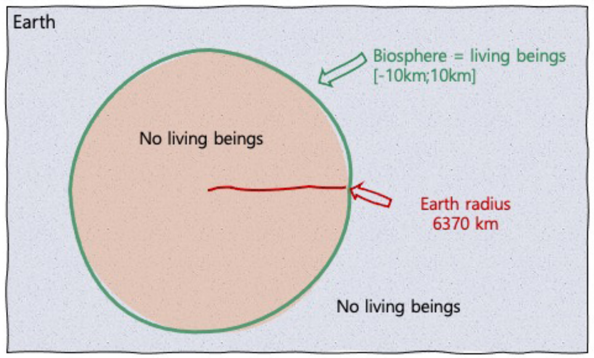
As we will also see in this chapter, and more in-depth in the next one, not only is life on Earth impacted by the climate, but the opposite is also true! Life has influenced, and continues to influence, the Earth's climate. You may think, for instance, that the dioxygen we breathe in the air has been part of the atmosphere since the origin of the world, setting the stage for human beings to appear, and before them, their living ancestors. This is not the case. Dioxygen did not exist 3 billion years ago. It appeared as a by-product of photosynthesis. It continues to be produced today, along with carbon dioxide, but its proportion in the atmosphere no longer changes, since a balance has been reached.

It's indeed this balance that is being destroyed. And as the appearance of oxygen killed thousands of living beings for whom it was toxic, we, in turn, should be concerned if the climatic conditions were to change.

1 The biosphere

1.1 Life on Earth

Despite this being a complex question, we are able to identify, in a simplified way, some big differences between living beings and inert beings: unlike inert things, living things reproduce, feed and breathe, that is, they source around them certain things which allow them to survive. Earth's radius is 6,370 km (this is the distance between your feet and the centre of the Earth). But if we focus on living beings, on all the plants, insects, plankton, fungi, animals, large and small, which feed, reproduce, and which constitute the natural environment where the human species was born, then everything takes place within a thin layer between 10 km (troposphere) and -10 km (oceans). Nothing above, nothing below! This is called **the biosphere** and, at the level of the dimensions of the Earth, you can see how insignificant we are!



Interpretation: The Earth's radius is 6370 km (on average). The thickness of the biosphere represents three thousandths of it, that is to say, in proportion, as much as three millimetres over a meter, or a millimetre over thirty centimetres. If we were to represent the globe as a circle on this whole page, this would correspond to the thickness of the line. In other words, we, together with our living companions, only occupy a very small bubble in which we find favourable conditions for our survival. There is no life anywhere else!

1.2 Interdependencies

The biosphere constitutes a single system: there is no component which can function in total independence from the rest. All living beings are connected. All the components are linked, we cannot affect one without ending up affecting all the others.

Moreover, connections are dynamic, that is to say, they evolve over time. These connection processes are also organised in multiple structures, weaving into each other and following different rules.

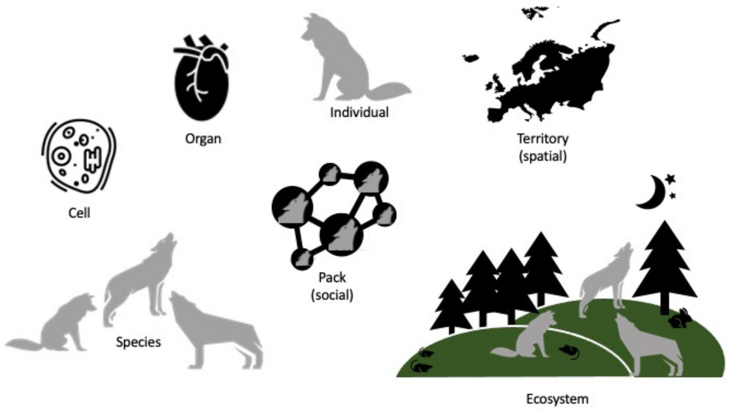
For example, let's consider the wolf to illustrate this point:

- Let's start on a small scale: we can observe a biological organisation of interconnected living beings. Cells are grouped into organs, each with its own functions. This interconnected whole constitutes an individual that we call the wolf. We can observe that all of these structures are neither completely independent (if one organ is affected, the wolf is at risk of dying, and with it all other structures disappear) nor completely dependent (some cells die and are replaced every day).

- It is the basis of another biological hierarchy: certain individuals are able to reproduce among themselves. These constitute a species.

- And it does not end there: other species live in the same environment and depend on each other, based on multiple relationships: predation, parasitism, symbiosis, etc. This interweaves the wolf within a whole interconnected system with hares and foxes, small rodents and insects, but also the large trees which offer them safe hiding places to give birth. Together, these beings constitute an ecosystem.

- This interdependence of species is often revealed by significant and sudden external disturbances. For example, the reintroduction of the wolf in Yellowstone National Park in the US has profoundly altered the ecosystem: by decreasing the deer population, wolves have modified the vegetation and allowed other animal species to thrive.[3]



3 —For more in-depth reading, please refer to: https://academic.oup.com/jmammal/article/99/5/1021/5107035

Interpretation: Biological, social, territorial... The wolf, like all living beings, is at the heart of dynamic processes on multiple temporal and spatial scales.

But that's not all! The wolf is also part of other hierarchies which superimpose on that of cells > organs > individuals > species > ecosystem that we have just described, for example:

- Social: within its own species, the individual is part of a pack, which is strictly hierarchical, providing fixed rules for hunting, sharing of prey, reproduction.

- Spatial: his pack competes with other packs, and avoids costly conflicts by remaining confined to a well-defined territory.[4]

Each of these hierarchies has its own dynamic logic:

- The main drivers shaping species are food and reproduction.

- At the ecosystem level, the Darwinian mechanisms of competition are in action: the best adapted species survive.

- For the pack, the problem is how to manage the flow of incoming members (new-borns, juveniles) and exits (those who reached the age limit). It provides for this through education and learning, teaching newcomers how to hunt, how to behave with others, how to climb the social hierarchy.

- At the individual level, each wolf has a story: it begins as a new-born, becomes juvenile, then adult, and finally reaches old age. Its position in the social hierarchy changes over time, depending on its abilities, but also on his actions: it develops a strategy.

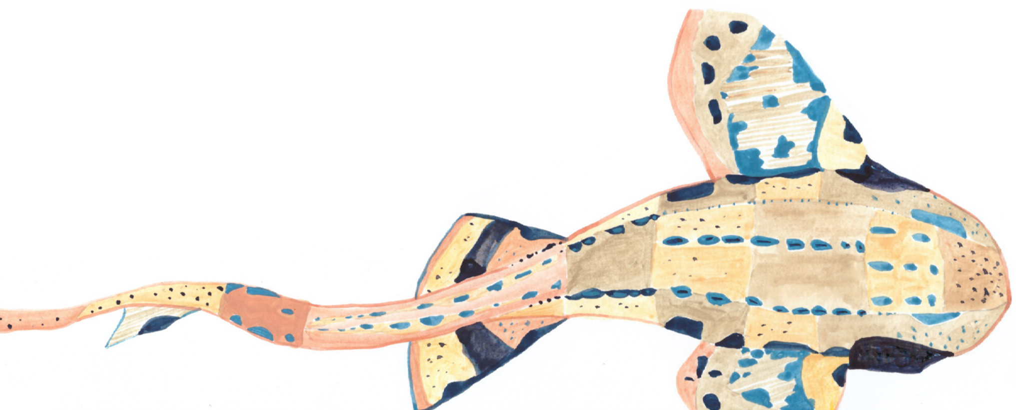
4 — To learn more and discover how the delimitation of the territory, the definition of borders, are the subject of negotiations between packs, read "The diplomats" by B. Morizot.

We can observe how the various logics can cross each other (ultimately, the rules of reproduction and hunting adopted by the pack must favour the survival of the species) and that the time scales are very different from one dynamic and one hierarchy to another (a wolf lives about fifteen years, whereas the species canis lupus has existed for fifty million years).

Finally, we can observe how the apparent stability of biological systems hides permanent flows, where inputs compensate for outputs: packs of wolves can subsist for decades in the same territory. Individuals die, leaders change, however, it's always the same pack.

Summary

- The biosphere constitutes a single system of interconnected living beings.
- It's the scene of a multitude of dynamic processes, whether stationary or not, articulated one with the other, and operating on very different scales of time and space.



2 The complexity of living things

2.1 Describing a physical system

Matter is made up of atoms, many of them, but all identical: we cannot differentiate one iron atom from another. This identity makes it possible to describe it using a few key variables: its temperature, its composition (of which atoms — "elementary bricks" — it is made), its size...

Imagine, for example, that you have to describe a piece of limestone. Its exact shape, to the nearest micron, its chemical composition (which atoms it is made of), its temperature. With only this information (and with the right instruments), a friend of yours could go and cut an exactly identical stone, in a limestone of exactly the same composition and heat it to the right temperature. When placed next to the first stone, it will become more or less impossible to distinguish. And you could wait days, maybe years, without finding any difference between the two stones.

2.2 Describing a biological system

The state of a biological system is much more difficult to define. It cannot be reduced to a few figures, as for an inert body.

Try to describe a healthy individual, for example: where would you start? Body temperature is a good index (if the temperature drops to 26 degrees or rises to 42, there would be cause for concern). Surely, we could add blood sugar levels, heart rate, muscular reaction to exercise... but that would still not be enough! For example, did you know that in your digestive system live some 150,000 bacteria which don't have the same DNA as the cells of your body, without which digestion would be impossible and which, according to new research, may also influence your mental state...

We could also obtain other figures, carry out other examinations, but it will never be sufficient to fully describe the state of a human body. And how to define the health condition of an ecosystem: a mangrove, for example, or a forest? Maybe we could count the number and size of the trees of each species? This will not be enough: for a tree species to survive in the forest, its individuals are scattered in different location within that forest, perhaps depending on their age and shape. By the way, if we only consider the trees, we would be in error, because we would miss a multitude of interactions and players that ensure the sustainability of the forest. For example, we should take into account insects (pollinators or vectors of disease), fungi living in symbiosis, with their roots providing them with nutrients, other plants such as ivy, that climbs on their trunks as well as animals, including carnivores (we have seen how the wolf changed the ecosystem at Yellowstone: it even affected trees).

2.3 What about the policies for the protection and preservation of biodiversity?

The complexity of living systems has practical consequences for all the policies aimed at the protection and preservation of biodiversity. Let's get back to the example of forests. It's easy to observe how a eucalyptus forest is very different compared to an Amazon forest. But are we able to draw a finite list of all these differences? Can we measure them, or are they purely qualitative? If we destroy one, are we able to replace it with the other? The answer is no, which represents an issue for all conservation policies.

Biodiversity itself is very difficult to define, even in a small space. We can tell that it's linked to the number of species and the quality of their interactions, but what else? And how to measure it? What should be the aim of the so-called compensation procedures? What does it mean to compensate for a Paris-Beijing plane ride by planting trees (which?) somewhere (where?)? If I destroy an ecosystem, for example, by draining a wetland in order to build an airport, I will never be able to reconstruct it identically. At best, I could build a similar ecosystem elsewhere. How is it possible to compare them, how is it possible to judge if one compensates for the other or not?

Summary

Because of this constantly evolving multiplicity of interconnections, it's very difficult to describe and reproduce a living system.

3 The fragility of living things

Living beings die. Inert physical objects don't die. If a vase is there today, there's a good chance that it will still be there tomorrow, in a year or in twenty years. If we put it into orbit around the Earth, it will revolve nicely, unless it gets hit by a meteorite. If a living thing is here today, it may be here tomorrow, but it's unlikely that it will still be there in twenty years; if it's the case, it will have changed a lot. If I were to put it into orbit around the Earth, they would die immediately.

In order to survive, living beings need a favourable environment: based on their means, they seek to establish and maintain it.

An instructive and entertaining read: “Dans la combi de Thomas Pesquet” (In Thomas Pesquet's spacesuit), a comic strip which shows the technical feats and the profusion of energy necessary to keep three astronauts alive in an orbital station. Thanks to this example, we are made aware of our direct dependence on an environment favourable to life.

In a sufficiently favourable environment, living beings have mechanisms that allow them to sustain themselves. This is called homeostasis.

For instance, the human body makes great efforts to maintain its internal temperature around 37°C. Beyond 38°C, it's fever, and if it reaches 40°C it's a major and immediate health hazard.

Sweating is another example of homeostasis in the human body. However, this mechanism of defence of the body in a hostile environment (because it's too hot) is not always possible: if the ambient temperature and humidity exceed certain limits, human beings are not able to maintain their internal temperature around 37°C and they die quickly. For example, i, when the humidity reaches 100% and the temperature 40°C the body cannot sweat and is in danger of death. Note that such lethal conditions already exist on Earth, and will become more frequent and extensive with global warming

More generally, in biology, homeostasis refers to the mechanisms by which a state is maintained around a value which is beneficial for the system considered, thanks to a regulatory process. If you stand in a steam room saturated with water, you will understand how living beings quickly reach their limits in trying to maintain themselves in a hostile environment.

This does not concern only individuals: species can die, too, or rather, disappear. This is quite logical, since individuals of the same species generally have the same limits in their ability to sustain themselves within a hostile environment. We call this an extinction.

Extinction can happen very quickly. The American pigeon, *Ectopistes Migratorius*, a gregarious bird that moved in flocks made of billions of individuals (yes! more than the number of humans on Earth), and whose colonies covered tens of square kilometres, was completely exterminated by systematic hunting in the final years of the 19th century.[5]

Source: Wikipédia

Summary

- Living beings die. Inert physical objects don't die.
- In order to survive, living beings need a favourable environment, which, they seek to establish and maintain, according to their capabilities.
- In a sufficiently favourable environment, living beings have mechanisms that allow them to sustain themselves. This is called homeostasis.

5 — For more details on the extinction of the American pigeon: https://fr.wikipedia.org/wiki/Tourte_voyageuse

4 Where does the oxygen come from?

4.1. Photosynthesis

All through their life, living beings breathe, feed and reproduce. To survive, human beings inhale dioxygen (O_2) and breath out carbon dioxide (CO_2). But then, how is it possible that animals, including humans, have not already depleted the oxygen supply on Earth?

The answer was found by Joseph Priestley in the 17th century and completed by Jan Ingenhousz in 1778. First step of the experiment: we put a lighted candle under a glass bell. The bell is airtight, no air goes through. What happens after a few seconds? The candle goes out, because it's out of dioxygen, which is necessary for its combustion. Second step: we introduce a live mouse under the bell. After a little bit more time, the mouse dies. Third step: we add a green plant. The plant does not die and if we leave it for a few days, it thrives. We add another mouse: it does not die!

This experiment shows that plants are able to "regenerate stale air". This was the first step towards the discovery of photosynthesis!

A second essential element can be deduced from this fundamental experiment. The first mouse dies because it inhales molecules of dioxygen (two oxygen atoms bonded together) and exhales carbon dioxide (one carbon atom and two oxygen atoms bonded together), which it cannot breathe in again. The plant knows how to do the opposite! How?

Go to the florist and buy a plant. Let's say the plant weighs 500 grams and the soil in the pot weighs 5kg. For one year you take care of it, water it, expose it to light. After one year, the plant weighs 1kg. And how much does the soil in the pot weigh? Except for a few grams that are not significant, it still weighs 5kg! So where did the plant get its extra 500g? From the soil? From the air? From watering? From all three at the same time?

The correct answer is both from air and watering. It's photosynthesis: the plant collects the carbon contained in the CO_2 of the atmosphere, the hydrogen and oxygen atoms from water H_2O, and fixes them in the form of organic matter. Thus, if we burn the plant, it will release the carbon trapped in this organic matter, which will return to the atmosphere in the form of CO_2.

Summary

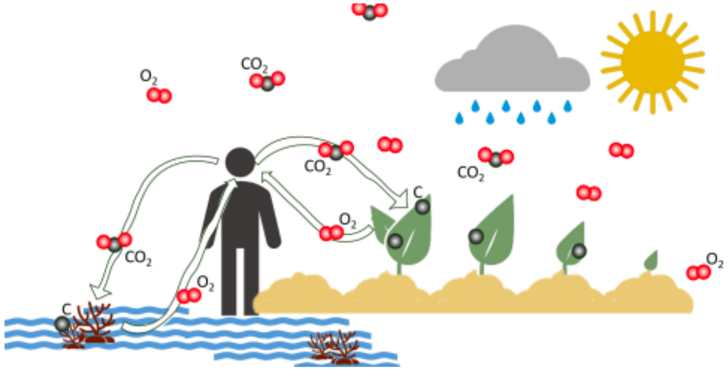
- Photosynthesis is the mechanism which is 'complementary' to animal respiration, through which plants absorb carbon dioxide (CO_2) to release oxygen (O_2).
- Animals, us included, are therefore absolutely dependent on plants and other living beings such as plankton, as they produce the oxygen we need.
- Photosynthesis is a way of storing solar radiation in chemical form. It's the process by which the plant grows, by fixing carbon atoms one after the other, recovered from the CO_2 that it 'breathes in' and that it mixes with the water that it 'drinks'.
- It is no wonder that, by cutting wood and burning it, we release... carbon into the air!

4.2. The oxygen cycle

At the very beginning of Earth's history, there was no oxygen in the atmosphere! This sounds almost unbelievable, isn't it? It's the appearance of photosynthesis by plants which provided our planet with its atmospheric oxygen, 2.3 billion years ago, and has since maintained it at the current level of 21% of the composition of the air, despite its consumption due to the respiration of living beings, as well as to the various combustions.

There is thus an oxygen cycle:

- on the one hand, it's regularly absorbed by animals and plants, for their 'breathing'
- on the other, it is emitted by plants, during photosynthesis



Interpretation: Under the effect of light, plants (terrestrial plants, algae, oceanic plankton, etc.) 'breathe in' the CO_2 exhaled by animals and return O_2.

Our survival as a species entirely depends on this 'service' carried out by plants and plankton. There is a global balance, the continents and the ocean producing, respectively, 16.5 and 13.5.10^{10} kg of oxygen per year.

Conclusion

To write the first version of this chapter, we were sitting in Ivar's office in Paris. To proofread it, we met on Zoom. In the meantime, the coronavirus came up in our lives, as an illustration of the interdependence and the fragility of the living world that this chapter describes.

Modern science is now discovering (or rediscovering) how rich, multiple and complex are the links that entangle us in this great system called biodiversity. Keeping us alive and healthy implies taking care of these links, from the bacteria in our stomachs to the pangolins in distant forests.

4

Carbon is constantly moving on Earth and in the atmosphere. What happens when human activities alter this flow?

Introduction

"Strange as it may sound, Earth's atmosphere has not always been the same as we know and breathe today. Its history is closely tied to that of living beings. Certainly, the early Earth of four or five billion years ago had an atmosphere, but it was very different from what we know today: there was no oxygen.

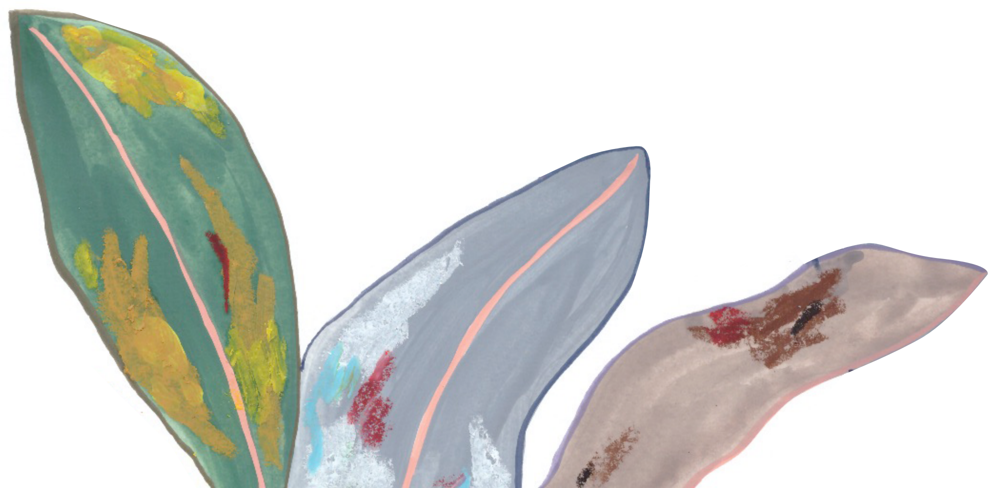
Oxygen appeared only much later, two or three billion years ago, produced by the first living organisms. For many other living beings, it was toxic, in the same way, for example, as air loaded with sulphur would be for us, and these creatures disappeared. Oxygen reached its current level, about 20% of the air, only 600 million years ago.

What do we mean when we say that "living beings produce oxygen"? Oxygen atoms have always existed on Earth, but in different forms and as components of different molecules. Some living beings have organs which 'digest' these molecules, breaking them down, and reconstituting them in other ways before releasing them into the air.

Today, dioxygen is constantly emitted by plants under the effect of sunlight: this is photosynthesis, as we saw in the previous chapter. This oxygen is constantly reabsorbed by the respiration of animals, as well as by all the phenomena involving oxidation and combustion. Thus, there is an oxygen cycle: each molecule which passes through the atmosphere only stays there temporarily, and will leave it after some time, more or less long.

This cycle pattern is not unique to oxygen. Almost all gases in the atmosphere have their own cycle: they are produced by some processes and absorbed by others. The atmosphere is a temporary storage place, before being sent back elsewhere on Earth, similarly to a bathtub connected to a reservoir from which the water would be permanently recycled. If, in the tub, the water level is constant, this is not due to the water being stagnant, it's because the inlet exactly compensates for the outlet.

After that of oxygen, the best known cycle is that of CO_2. And of course, that's the one we're interested in, in order to study the greenhouse effect and climate change. The CO_2 cycle is unique in that the 'drain hole' in the 'bathtub' is very narrow. Thus, if additional CO_2 gets discharged in the atmosphere (for example by burning wood or oil), the impact of this excess will be felt for several centuries."

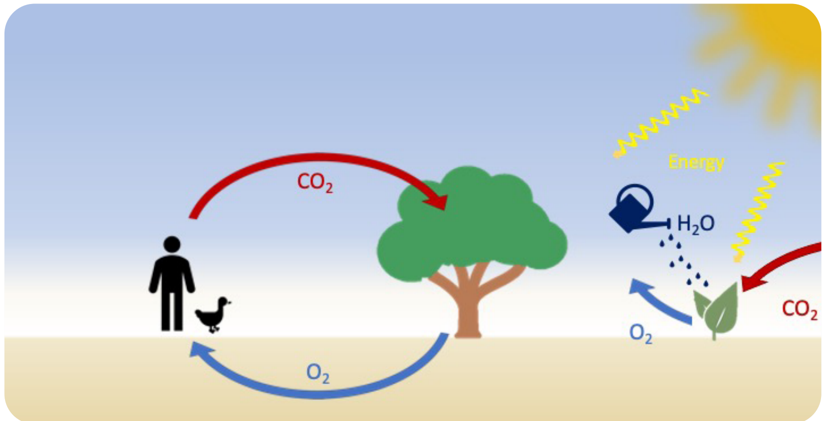


1

Plants and plankton in photosynthesis

Under the action of the Sun, and when they receive sufficient water, they are able to absorb gaseous CO_2 and, in return, produce dioxygen O_2. This is photosynthesis. If photosynthesis takes place through the energy transmitted by light waves from the Sun, what happens at night?

The circulation is reversed, because plants breathe, too!



Interpretation: During the day, plants carry out photosynthesis. At night, they breathe like animals.

Thus, our life (as well as that of all animals), depends on the capacity of plants to produce oxygen from carbon dioxide. The field of "plants" is very wide, and goes well beyond the trees and flowers of our gardens. It spans from the Amazon rainforest to the phytoplankton in the oceans. Phytoplankton are microscopic sea plants, floating on the surface of the oceans. They are not visible to the naked eye, however, their distribution throughout the oceans can be visualised by satellite, and they are crucial for feeding sea animals, either directly (whales) or by being at the base of the food chain.

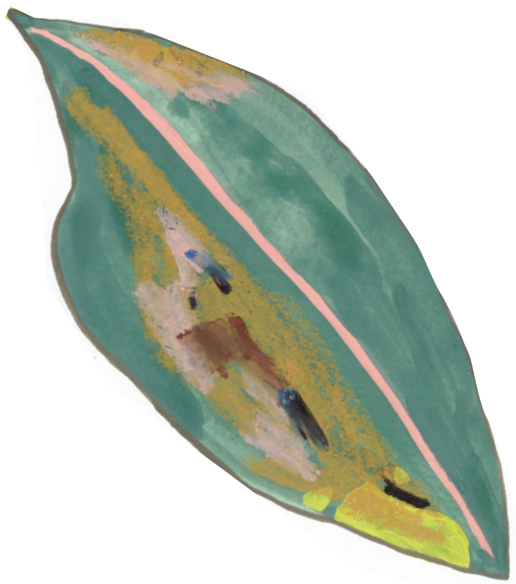
Could we perhaps call it a "lung of the planet"? We always talk about the Amazon rainforest this way. However, phytoplankton is much more efficient, considering the amount of CO_2 that it manages to permanently store on Earth.

In fact, terrestrial vegetation, even when it doesn't get cut and burned by humans, ends up dying, and decomposes in the air, absorbing oxygen and releasing CO_2 into the air, like very slow breathing. On the other hand, phytoplankton, when dying, has a good chance of falling to the bottom of the ocean, in an environment poor in oxygen. Therefore, the carbon it contained remains trapped at the bottom of the ocean. The overall balance is in its favour, to the extent that we consider more than half of the oxygen we breathe "comes" from phytoplankton. Therefore, we are like whales: our survival depends on small plants which are thousands of kilometres away from us and that we cannot even see. A perfect example of the interdependence of living species on planet Earth.[6]

6 — NASA's SeaWiFS instrument examines oceans and land to observe flora and phytoplankton. To discover the SeaWiFS instrument, you can visit: https://svs.gsfc.nasa.gov/vis/a000000/a002000/a002077/index.htm

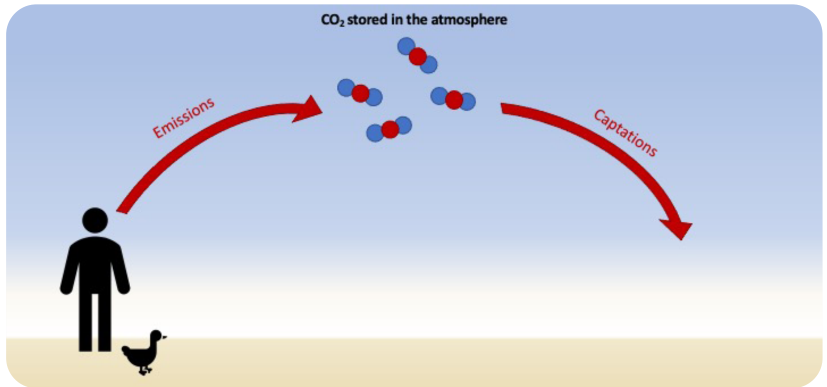
Summary

- Plants take advantage of the energy from solar radiation to 'breathe in' the CO_2 that's in the air and to synthesize molecules containing carbon.
- In doing so, they extract carbon dioxide from the atmosphere and release the oxygen that we breathe.
- In terms of "net" carbon capture on Earth, oceanic plankton is even more efficient than ordinary plants, because when it breaks down, the carbon it contains remains trapped at the bottom of the ocean.



2 | CO_2 Cycle

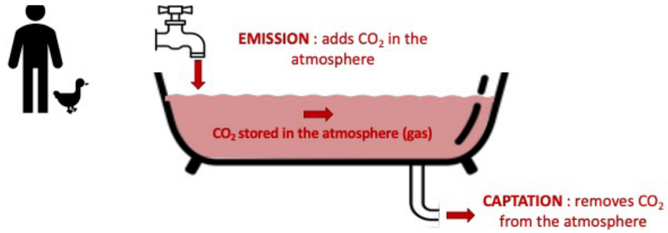
Let's get back to the central theme of this course: climate. As we saw in the first two chapters, the accumulation of CO_2 in the atmosphere was the main factor in the greenhouse effect, which heats up the Earth.



In order to understand what determines the amount of CO_2 in the atmosphere, let's focus on the previous diagram on carbon exchanges. On the one hand the emissions, on the other, the capture, and between the two: the CO_2, stored in the atmosphere.

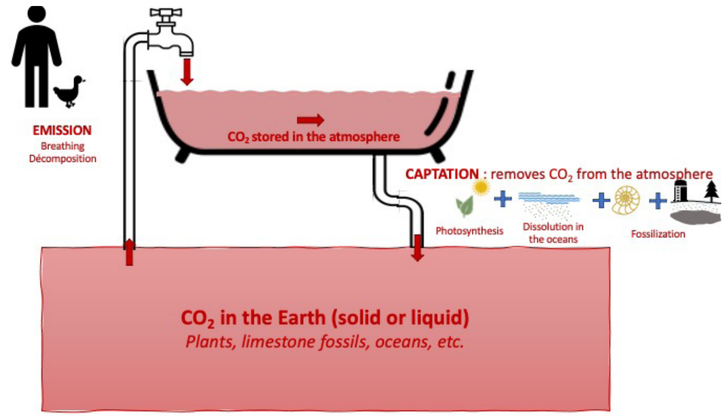
We can compare this problem to a bathtub. There are two things determining the quantity stored in the atmospheric bathtub: the quantity emitted by the tap on the one hand, and the quantity discharged by the drain, on the other hand. Where does the carbon discharged through the plug go? It's simply stored somewhere on Earth, for example within plants.

In fact, the vast majority of our planet's carbon (Earth and atmosphere) is stored in solid form on Earth, linked to calcium and oxygen: it's limestone, and the shells of animals, corals in particular. In fact, atmospheric CO_2 can dissolve in the ocean and, according to estimations, the oceans contain 50 times more carbon than the atmosphere! Part of this floating carbon is recovered by sea animals to make shells, which will be found millions of years later in the form of limestone.

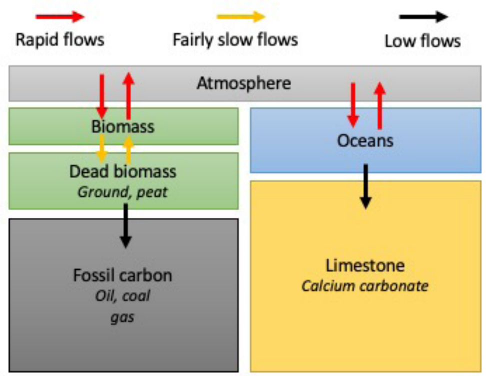


On the other hand, terrestrial carbon outside the oceans is fixed by plants and animals, to be slowly returned to the atmosphere when these decompose. However, some may escape decomposition, because of special circumstances, for example, due to the fact that they are buried in swamps, far from the oxygen in the air. This is the origin of fossil fuels: coal, gas or oil.

Aside from human intervention, as we have seen, several mechanisms ensure the capture of atmospheric CO_2 on Earth (photosynthesis, dissolution in the oceans, etc.) and conversely, several mechanisms generate new emissions into the atmosphere (respiration, decomposition, etc.).



Undoubtedly, these different forms of capture do not take place according to the same time scales. An inhalation followed by an exhalation takes place in seconds. A tree may live for several decades before decomposing. Conversely, limestone or oil pools take several hundred thousand years to form. This is what the following functional diagram shows:



Summary

- For CO_2 as well as for dioxygen, the atmosphere behaves similarly to a bathtub: molecules are only stored there temporarily, and are permanently re-captured on Earth, before being emitted again into the air.
- The carbon stock in the atmospheric bathtub is determined by the quantities emitted in relation to the quantities captured.
- The main carbon storage location on the ground is the oceans, where atmospheric carbon is photosynthesized by plankton or directly dissolved.
- Some emission or capture processes take place very quickly (respiration, decomposition, etc.) whereas others are extremely long (formation of limestone rocks, formation of oil and of other carbonaceous fossils, etc.).

3 Out of balance

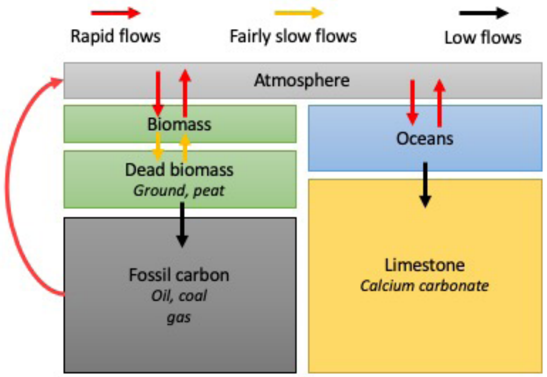
3.1 The unbalanced carbon cycle

The carbon cycle as such was in a state of balance until around 1800, that means that the emissions into the atmosphere were balanced by the capture on Earth. This way, the amount of CO_2 in the atmosphere remained stable.

Since 1800, this process has been disrupted due to the human use of fossil fuels.

We have seen that oil, coal and other fossils are nothing more than carbon slowly amalgamated with other atoms and stored on the ground or underground. By burning them, these amalgams become fractured and carbon is released in its gaseous form.

For the last two centuries we have been injecting, directly into the atmosphere, additional amounts of CO_2 that are not part of natural cycles.



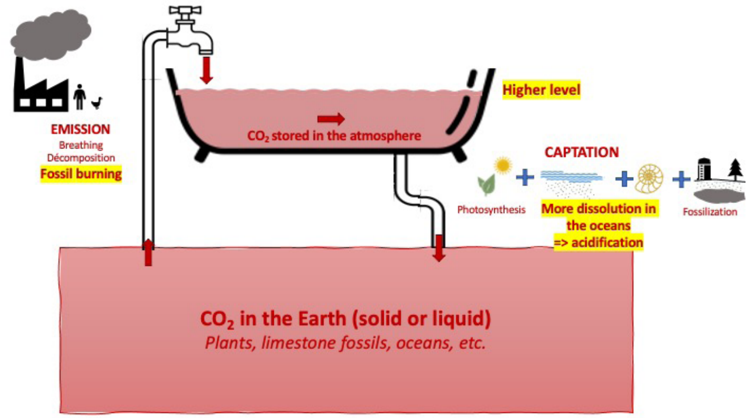
Where does this additional CO_2 end up, which the atmosphere was, so to speak, not used to receiving? About a fourth dissolves in the oceans, a third is captured through photosynthesis, and the rest stagnates in the atmosphere. This storage leads to an increase in the greenhouse effect, and therefore, to global warming. It causes the radiative forcing, which we have defined in the previous chapters.

3.2 A double issue

In fact, the issue is even double: not only does the burning of fossils increase emissions, but it also reduces the capture capacity of oceans.

It is estimated that 30-40% of excess CO_2 in the atmosphere (human-induced emissions) is absorbed by the oceans in its dissolved form. Along with the saturated atmospheric carbon cycle, therefore, there is an oceanic carbon sink, which stores some of the excess carbon. As a result of this excess storage, oceans become more acidic (this is verified by measuring their pH, and observations show that it's decreasing). This is the phenomenon of ocean acidification, to which we will get back, which is another important marker of global warming. Unfortunately, this acidification makes the ocean less capable of absorbing CO_2, and therefore, of acting as a carbon sink, as if, by asking the bathtub drain to drain more water, it would get clogged up.

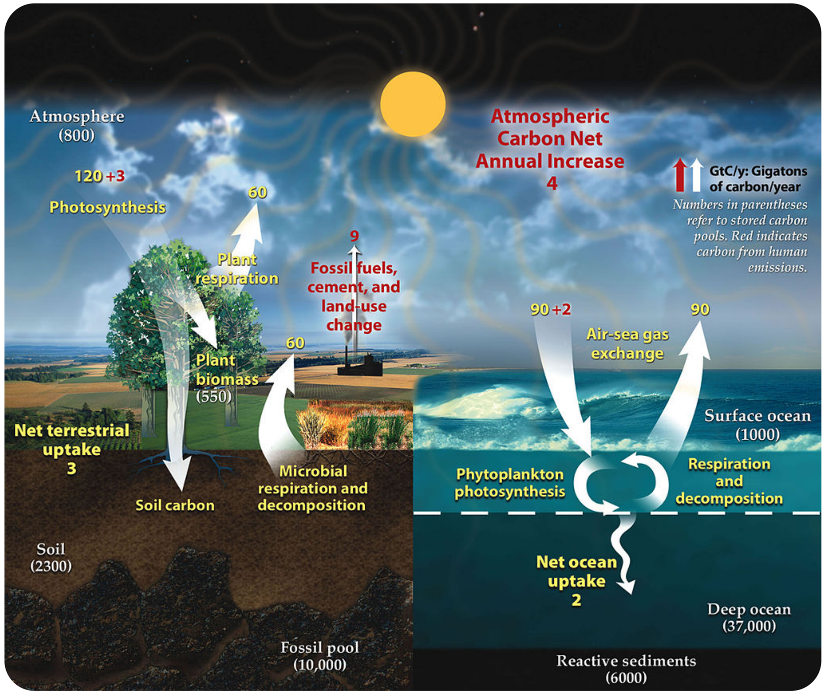
If we get back to our bathtub, then we understand how the level is increasing:



3.3 Carbon circulation in figures

The following figure shows carbon stocks (in white, in brackets) and flows (in yellow and red) in gigatons of carbon per year (one gigaton is one billion tons). Carbon thus appears in different forms and linked to different chemical elements. First of all, it should be noted that the stocks are significantly larger than the flows. The vast majority of carbon is stored in solid or liquid form. Bound to calcium and oxygen, it constitutes the limestone rocks and the shells of animals, notably corals. Buried underground, in association with hydrogen, it forms oil. The proportion of gaseous carbon in the atmosphere represents less than 1% of the total stock and appears in association with oxygen: it is carbon dioxide, the famous CO_2.

Arrows and numbers in yellow indicate the annual flows: we can see that carbon is constantly being exchanged to and from the atmosphere. In addition to natural flows (breathing, degradation, photosynthesis...), we can see human emissions (in red) that have been added for two centuries. 9 Gigatons are sent to the atmosphere, of which 3 boost the photosynthesis of plants and 2 are captured by the oceans. This surplus of emissions results in a positive balance of 4 gigatons of carbon per year in the atmosphere. Every year, about sixteen additional gigatons of CO_2 accumulate in the atmosphere. For how long?



Carbon Cycling and Biosequestration

Source: US Department of Energy, http://www.starch.dk/private/energy/img/CO₂%20 Balance.pdf

Summary

- The carbon cycle was in equilibrium until around 1850, after which, it has been disrupted due to the use of fossil fuels.
- This releases quantities of CO_2 in the atmosphere, which exceed the absorption capacities of land and oceans.
- This excess carbon is partially dissolved in the ocean, which acidifies, reducing its capacity to capture.
- Every year, therefore, four gigatonnes of additional CO_2 accumulate in the atmosphere. For how long?

4 Atmospheric lifetime

4.1 Not a recent issue

Let's get back to the image of the bathtub: the tap represents the emissions in CO_2. The drain is the absorptions. What remains in the bathtub is the stock in the atmosphere. The whole system was roughly balanced before 1800. In the 'bathtub', the same quantity of CO_2 that was coming in, was coming out, and water levels therefore, were stable. As we saw in the very first chapter, the proportion of CO_2 in the atmosphere remained at around 280 ppm during the Holocene time period.

Since then, the use of fossil fuels (coal at first, then oil, finally gas) came on top of natural CO_2 emissions. The flow rate of the 'tap' increased and therefore, the CO_2 level in the atmosphere/bath rose. The proportion of CO_2 in today's atmosphere reaches 420 ppm, not far from twice as much as in historical times!

How is it possible that the combustion of coal which took place for the first English steam engines still impacts us today? And if we stopped burning fossil fuels today, how long would it take for the atmosphere to return to its natural CO_2 levels? In other words: if we were to bring the tap flow back to its previous level, how long would it take for the bathtub to return to its previous level?

4.2 An analogy to understand the lifespan of carbon in the air

In fact, this is a question regarding the effectiveness of the drain and its capacity to evacuate more than the ordinary flow.

Imagine that you are in 2025, and your local council has put in place stricter regulations on waste collection: only one bag of 5L maximum per person per week is allowed (everyone gets rid of containers!), with a small surplus for exceptional circumstances authorised up to 0.2 L per week.

It's your birthday: you invite a bunch of friends, to have a good meal and a few bottles. But the next day, panic: your garbage bag is 9L, instead of the regular 5 which are authorised! For how long will this excess garbage end up cluttering your kitchen?

Taking advantage of the authorised weekly surplus, you will patiently get rid of 5.2L per week for several consecutive weeks. A little calculation allows us to know that it will take 20 weeks to return to the level before your birthday.

To avoid bad smell, you will of course optimise the garbage that you get rid of each week (disposing of perishable garbage first), so that the last 5.2L bag will of course no longer contain any of the beer cans of your evening.

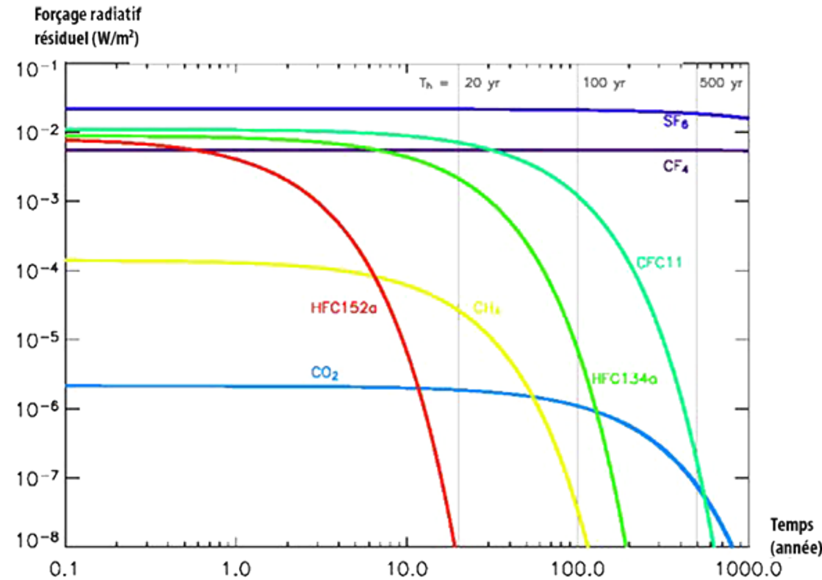
The main thing here is not your birthday junk in itself, but the lasting change in the level of junk that the one-time excess of your birthday has caused. The level of waste in your kitchen, for 20 weeks, would bear the signs of that one-time surplus.

4.3 Residual radiative forcing

This is exactly what's happening in the atmospheric bathtub with the excess CO_2 emitted over the past decades. Due to the fact that only an excess portion can be disposed of, the stock will remain for many years to come, above its usual "natural" level.

The graph below shows these "persistence" times in the atmosphere for different GHGs, also called "lifetimes". Each curve indicates the duration of the trace left by an excess unit of the gas in the atmosphere in terms of radiative forcing, that is, of reinforcement of the greenhouse effect from its emission date. Note that the horizontal axis, in years, is on a logarithmic scale, so that the marker to the left of the number 10 indicates the 9th year after emission but the one to the right marks the year 20. The vertical axis is also logarithmically scaled: we understand that CO_2 at the time of its emission is about 100 times less powerful in terms of greenhouse effect than CH_4 methane in yellow, but its effects persist 10 times longer. Indeed, look at the blue curve: we can see that the warming effect of an additional ton of CO_2 emitted today will be roughly constant for a century. It will take 1000 years for the effect to be divided by ten! This is usually expressed by saying that the CO_2 emitted today "stays" in the atmosphere for a century and only "disappears" after a thousand years. The CO_2 we emit today will therefore warm the atmosphere for several centuries!

Surprise: the black and purple curves never decrease! The radiative forcing effect persists indefinitely. Indeed, these are SF_6 and CF_4, two molecules containing fluorine and produced exclusively by industry. Fluorine is an extraordinarily reactive chemical element and is only present in nature in the form of stable minerals. Historically, it has been very difficult to isolate, but once it has been isolated, it has been used to manufacture compounds with interesting industrial properties, such as refrigerants (including the famous CFCs that destroy the ozone layer) or electrical insulators (in the case of SF_6). As they are not part of a natural cycle and are chemically stable due to the properties of fluorine, they are never reabsorbed by the continents or the oceans, and once emitted they stagnate eternally in the atmosphere. This is perhaps the purest form of "waste".



Persistence of radiative forcing after emission

Source: D. Hauglustaine, LSCE, quoted in https://jancovici.com

Summary

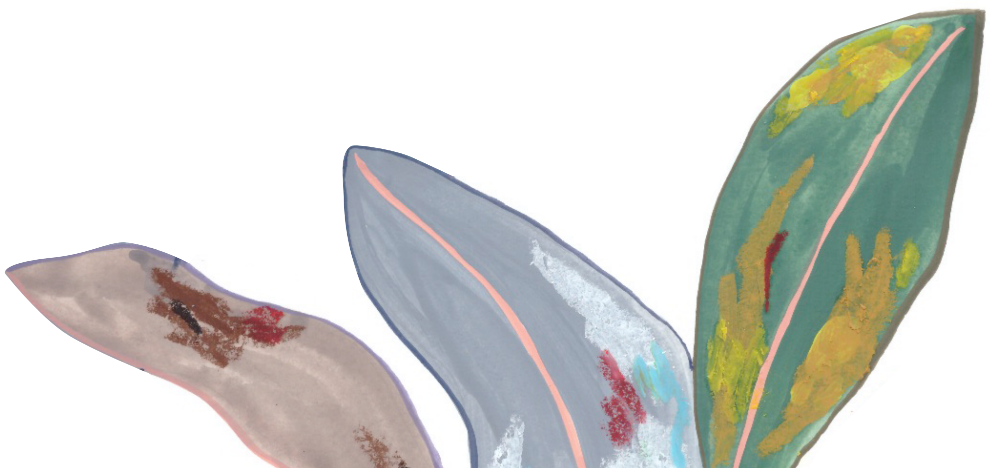
- When a gas is emitted by human activity as an "excess" into the atmosphere, the natural system will take some time to return to equilibrium.
- The time during which we continue to observe the traces of an excess is called the "lifetime" of a gas.
- For a GHG, the important thing is not its trace in terms of quantity, but its trace in terms of radiative forcing.
- The lifetime of carbon is particularly long (around 1000 years). To divide by 10 the forcing effect of an excess unit of CO_2, therefore, we must wait no less than 500 years!

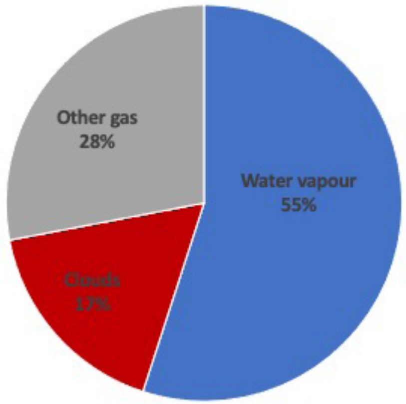
5 What about water vapour?

A question remains: why, in the previous figure, are we not talking about water vapour? Yet, as we saw in the chapter on the greenhouse effect, H_2O is a more powerful GHG than CO_2. The pie chart below shows that it's responsible, in its gaseous or condensed form (clouds), for almost three quarters of the planet's greenhouse effect.

The answer lies precisely in its lifetime, which is only a few days, and not a thousand years like CO_2.

Indeed, there is a natural cycle of water: it's present in enormous quantities in the oceans, and a little in the form of fresh water, which evaporates and falls back as rain. Human emissions do not disrupt this cycle, on the one hand, since they're tiny compared to natural emissions (like ocean evaporation), and on the other, because the atmosphere cannot accumulate water vapour indefinitely: beyond a certain limit (100% humidity) it condenses and falls back as rain. It's like if your H_2O bathtub had an escape drain, so that a maximum level of water can never be exceeded! This limit increases with temperature and creates a vicious circle: the higher the temperature in the atmosphere, the higher its capacity to store water vapor, which in turn reinforces the greenhouse effect of H_2O.





Water contribution to natural greenhouse effect

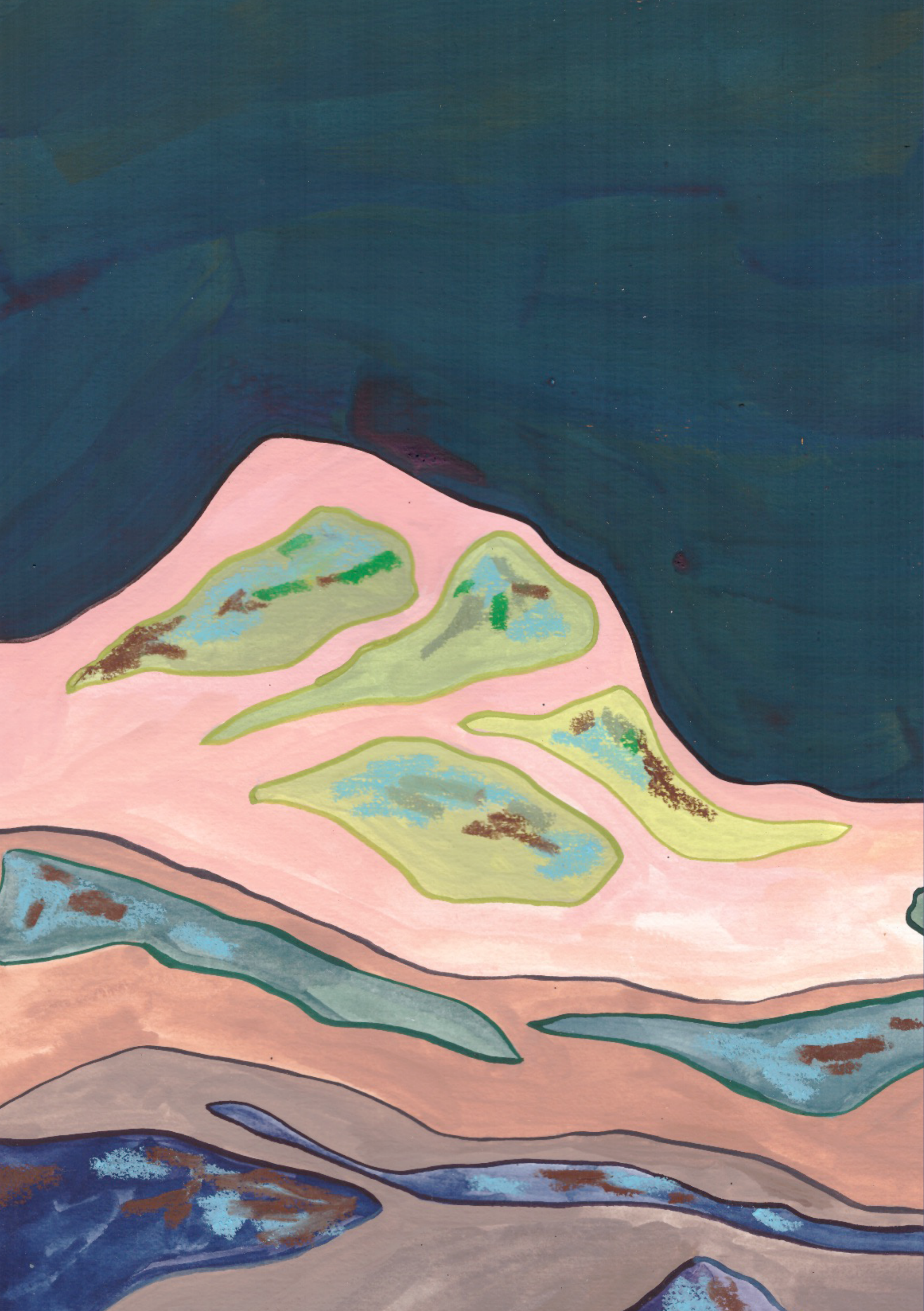
Summary

- Additional human emissions of water vapor are negligible compared to natural emissions and do not accumulate in the atmosphere. This saturation mechanism does not exist for CO_2.
- Global warming reinforces the natural greenhouse effect of H_2O.

Conclusion

The carbon atoms on Earth and in the atmosphere are distributed in a dynamic way, following natural cycles. Each plant, each of your breaths participates in these cycles, even if they represent only a tiny dust in these great movements.

However, since the Industrial Revolution, human societies have been drawing on fossil reserves, dense reservoirs of carbon built up over hundreds of millions of years. As in the Sorcerer's Apprentice scene in Fantasia, these excess emissions are creating a global imbalance that is becoming very difficult to control. The capacity of natural compensation by captation is limited, even more limited as warming increases, and the persistence of greenhouse gases in the atmosphere over several hundred years extends their impact on the greenhouse effect.



5

Observations, experiments and interpretations converge: science and climate skepticism do not go well together

Introduction

After these first four chapters on the history of Earth and its climate, we are now going to delve a little more into the thick of things.

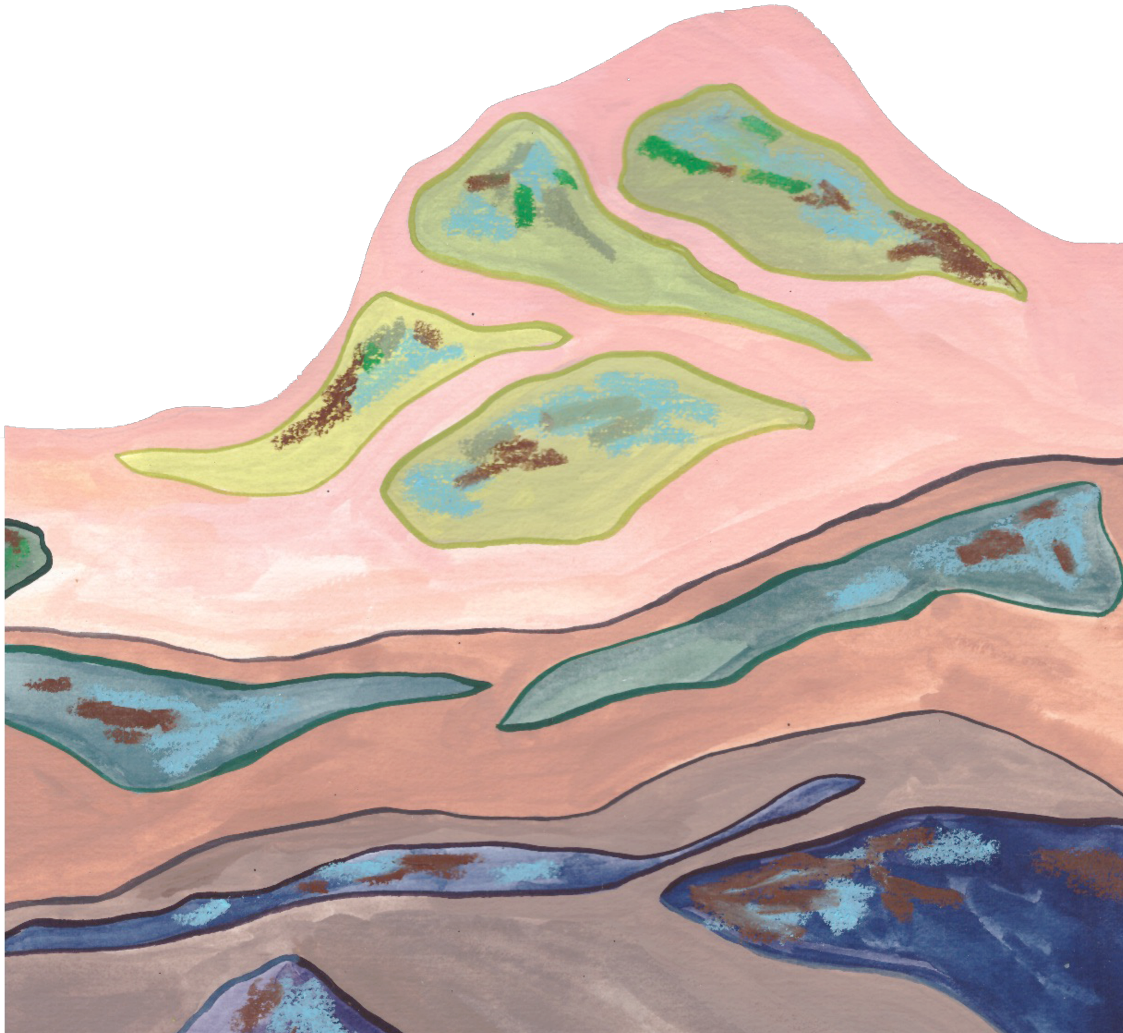
We are going to talk about climate change scepticism. It comes in many forms: some will say that nothing is happening, others that it's warmer, but not due to CO_2, and finally, there are some who say that this is not due to human activity.

In this course, we will play the debate game and review the elements which make us say, unlike climate change sceptics, that something unusual is indeed happening, and that the only reasonable explanation is the very fast increase in greenhouse gases (GHGs) in the atmosphere over the past one hundred years, especially of CO_2, and that the only identified source of these additional emissions is the human use of fossil fuels.

This is not about expressing opinions, but about providing empirical evidence. The increase in average temperature is a proven fact, as well as the decrease in biodiversity. That the CO_2 content has increased and continues to increase can be seen as a result of regular measurements.

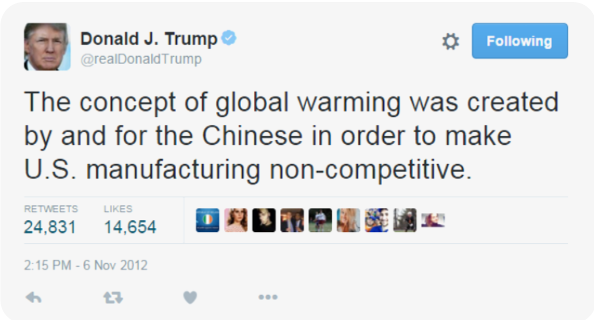
When you use a scientific approach and have all these observations available, the problem is to organise them into a consistent framework, and the only one we have is the greenhouse effect. It's a simple, straightforward conclusion which is the result of more than a century of scientific work.

Why, then, the climate change scepticism? We will focus on this issue later in this course. However, it's important to note that it results in inaction: "it's not worth the excitement, and anyway, nothing can be done about it, it's business as usual." This is the stance of many politicians and industrialists, such as Donald Trump's former administration. A stance that's truly dangerous, as if there is something that the work of scientists in the last half century has managed to establish, it's that climatic and ecological balances are shifting, and we are at a pivotal moment in the history of humanity. This is precisely the moment when it is still possible to have an impact on the future, and to make it more bearable both for us and the generations to come, and perhaps even better than today!



1 Something is definitely happening!

Not everyone agrees:



Source: Twitter

And yet...

1.1 Heat records

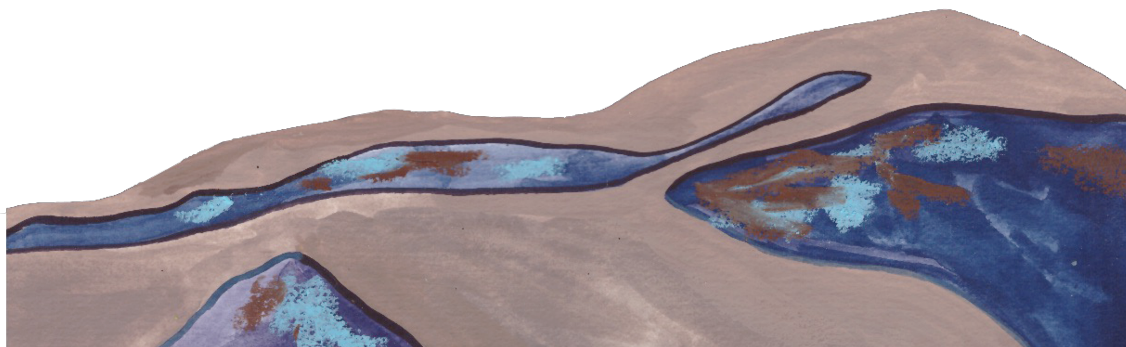
This section of the chapter needs to be rewritten every year, because every year new records are broken. As of the time of writing, April 2020, the latest numbers are:

- It was 45.9° in the Gard department on 28 June 2019, the highest temperature ever recorded in France
- It was 38.7° in Cambridge on 25 July 2019, the highest temperature ever recorded in Britain
- It was 20.75° at the Comandante Ferraz station on 9 February 2020, the highest temperature ever recorded in Antarctica
- It was 21°C in Alert, on 15 July 2019, the highest temperature ever recorded at this station located less than 900 km from the North Pole

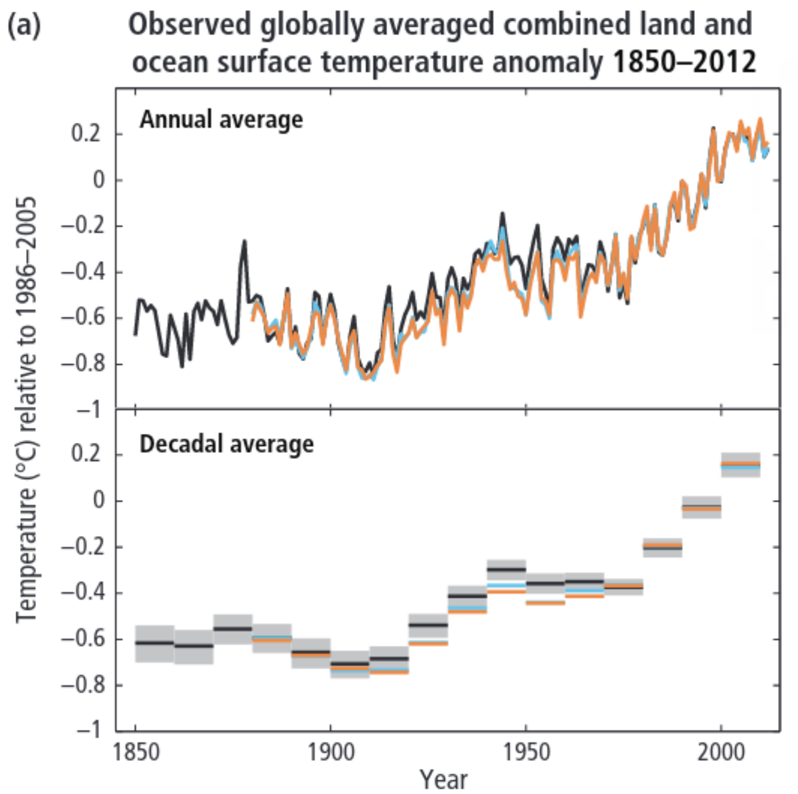
1.2 Evolution of averages

These are extreme temperatures in localised places. What about the averages on the planet?

- Between 2005 and 2019, nine months of July were the hottest on record since the beginning of measurements.
- The 2015-2019 five-year period was the hottest on record, with an average temperature 1.1°C higher than that of the 19th century.
- The graph attached, taken from the 2014 IPCC report, shows the changes since 1850. We can observe that the temperature has risen by 1°C since 1920, and that this trend has accelerated since 1980 (the different colours correspond to different series of measurements).



This graph, taken from the 2014 IPCC report, shows the average temperature changes across the globe since 1850.



Temperature evolution since 1850, according to different series of measurements

Source: IPCC 2014 Report

Interpretation: The different colours of the curves (orange, black, etc.) correspond to different series of measurements carried out by different research teams. The fact that they're almost identical confirms how reliable the results are.

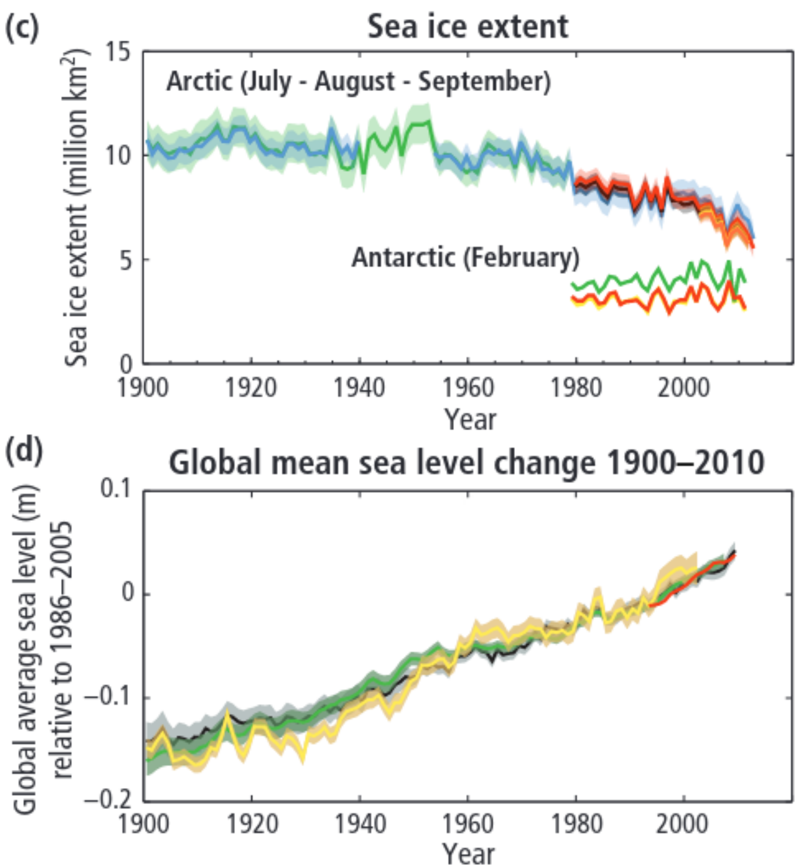
The horizontal axis corresponds to the time axis, from 1850 to 2000. The vertical axis represents the deviations from a reference temperature. The title of the vertical axis tells us what this reference temperature is: it's the average temperature over the 20 years 1986-2005. Let's take an example: in 1900, the curves are approximately at -0.6. This means that, in 1900, the average temperature was 0.6 degrees cooler than it was on average from 1986 to 2005.

Looking at the whole trend of the curves since 1850, we can see that the temperatures were globally stable until 1920 and then warmed up, ranging from -0.8 to +0.2 degrees compared to the reference temperature. The increase is particularly pronounced in the second half of the 20th century. We can observe that the temperature has risen by 1 °C since 1920, and that this trend has accelerated since 1980.

The same is visible on the bottom graph, where the average for each annual temperature over 10 consecutive years is calculated based on the top graph (that's why the curve levels off, compared to the sawtooth appearance in the top graph). Particularly noteworthy is the final acceleration.

1.3 Melting of sea ice

The increase in average temperatures results in the melting of the ice at the poles. The following graph, taken from the same report, shows the sea ice shrinking and sea levels rising over the past century (again, the different colours represent different sets of measurements, carried out by independent teams).



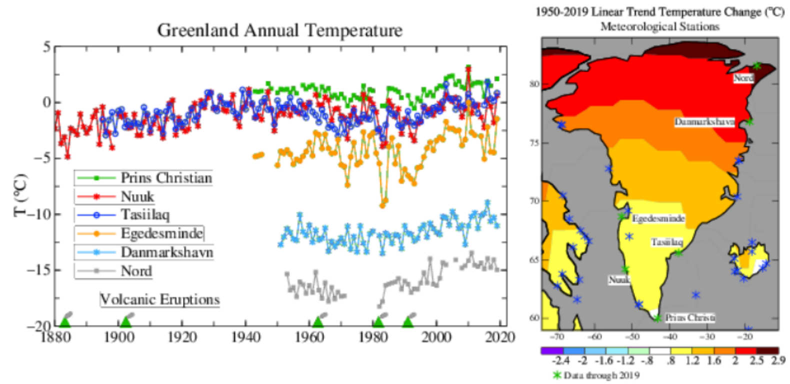
Title: Evolution of the surface covered by sea ice and of the sea level

Source: IPCC 2014 Report

We can see, for example, that sea ice in the Arctic covered approximately 10 million km^2 until 1960, then a gradual decline begins, which brings us today to around 5 million km^2. Half as much as 60 years ago.

You might be surprised not to see a similar trend in Antarctica. As we have already observed, Antarctica and the Arctic react differently: one is a continent (such as Europe or the Americas) isolated from the others by an ocean that circles the globe, the other is an inner sea between Europe, Asia and Greenland. The ice of the Antarctic is a glacier, that of the Arctic is mostly sea ice, which leads to different behaviours.

You can find regularly updated curves and much more information on the Columbia University website. In particular, we took from there the figure below, which shows that it's in the Arctic that the most significant changes in temperature have been observed, and all the more so as we go up towards the North (indicated by the red gradient on the Greenland map on the right):



Temperature evolution at different locations in Greenland

Source: Columbia University website

1.4 Can it get colder on a planet that's warming up?

Question 1: Some meteorologists say that 2012 was an exceptionally hot year in France. And yet, in February 2012, the Saône river froze in Lyon, for the first time since 1985. Is this consistent?

Answer 1: yes! If we say that 2012 was a hot year, we mean that the average temperature measured throughout the year and over the whole territory was higher compared to the previous years. However, this does not mean that, at certain times and in certain places, exceptionally low temperatures can't occur![7]

Question 2: On 26 February 2015, in a now famous incident,[8] US Senator Inhofe brought to the Senate a snowball which he had just picked up outside, pointing out that it was very cold, and that you had to be crazy to claim that 2014 had been particularly hot. After which, he threw the snowball against the chairperson. It's true that, that day, it had been very cold in Washington. Is this an admissible argument against global warming?

Answer 2: No, as above: we can have a high average with certain low measurements. Moreover, as stated by the journalist who wrote the article, that same day in February, while in Washington it was particularly cold, it was actually particularly warm in Florida (30°C)! Hence, the importance, in science, not to judge situations based only on anecdotal evidence.

Summary

- The planet is warming up, meaning that temperatures have been rising steadily since 1850.
- This is true both for seasonal averages as well as extreme temperatures, and the trend is accelerating.
- This trend is also visible through the significant melting of Arctic sea ice.

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7 — For further details (and some nice pictures), see https://planet-terre.ens-lyon.fr/image-de-la-semaine/Img378-2012-02-27.xml

8 — You can find this incident reported here https://time.com/3725994/inhofe-snowball-climate/

2 This has an impact on living beings

2.1 Disruption of the living world

When you heat water in a pot, currents form to spread the heat throughout the liquid (this is called convection), then the water agitates in a disorderly fashion before it begins to boil. We're not there, yet, but this is a general rule: as the atmosphere gets warmer, it becomes more and more turbulent, which means that extreme events, temperatures (chilly weather or heatwaves) or precipitation (cyclones, droughts) are more frequent and more pronounced.

These changes will have a dramatic impact on living beings. In 2019, a Martian would have been able to see the fires devastating three continents: America (in the Amazon), Asia (in Siberia) and Australia (in the Southeast). In the latter, fires destroyed flora and fauna over 186,000 km² (for the sake of comparison, Great Britain has an area of 230,000 km²), burning down trees and animals. The few survivors are bound to disappear, due to lack of habitat and food.

Source: https://www.theguardian.com/australia-news/2019/dec/31/australia-bush-fires-towns-devastated-and-lives-lost-as-blazes-turn-the-sky-red

These fires caught the imagination of people, along with the images of surviving koalas, for whom nothing could be done since their habitat had disappeared. However, more often, these changes go unnoticed, due to the loss of memory between human generations. This is called the "ratchet effect": we consider as "normal" the situation we experienced in our youth. Those who drove in the 1960s remember when they had to stop every one or two hundred kilometres to clean their windshield, covered in a mush of flying insects. Cyclists in the countryside in the summer had to close their mouths so as not to swallow insects. People driving today don't have this memory, and don't wonder where these clouds of flies, mosquitoes, beetles, ants, bees or wasps have gone. In the meantime, reality has changed.

2.2 Measuring the living

©David Liittschwager. Source: https://www.nationalgeographic.com /magazine/2010/02/life-ecosystems-one-cubic-foot/

How can we become aware of this, beyond our individual subjective experiences on a bicycle or in a car? Quantifying "biodiversity" is a much more difficult exercise compared to measuring air temperature or pressure. This should remind you of the third chapter of this course, on biology.

An interesting experiment was attempted by a photographer named Liittschwager.[9] He carried out the following experiment in different environments: placing a cubic metal structure, consisting of only six 30 cm edges (see the image below among the corals), and photographing everything that passes through the cage, which is more than a millimetre long, continuously, for 24 hours. Afterwards, the artist brought together all the images of these living organisms in a series of photographs — stunning in their richness and diversity.

Could these plates be enough to give a complete idea of the biodiversity in a given spot? We can see an incredible multitude of living beings... And yet there are still many missing! First of all, because it is only a snapshot on a given day: according to the weather and the seasons, the populations change, and we must also think about the migratory ones. The soil is full of life, with earthworms and fungi. By construction, everything that is less than a millimeter is also missing: bacteria for example. Last but not least, it misses all the relationships that link the different species: they all have a role in the ecosystem, and they need the other species to survive.

The richness of the fauna and flora will always escape any measurement. However, if the purpose is to give an idea in just a few figures, maybe in order to communicate with some bureaucrats, and to provide evidence, in an objective way, on the losses or gains, the following is most often used:

- The number of species present, by category (mammals, insects, plants, trees)
- The surface area occupied by the species and the number of individuals
- The total weight of the individuals constituting the species (this is what we call the biomass)

We should always remember that these figures are seasonal: some plants or insects may appear as absent in certain years, because they exist in the form of seeds or eggs. Despite being inadequate, these

9 — The book was published by Chicago University Press, and you can find some photos of the process on the web.

indicators are very useful. They show, for example, that the Amazonian forest, swarming with life on all levels, from underground up to the canopy, is infinitely richer than a eucalyptus forest, with its sparse foliage and arid soil. It's not possible to replace one with the other.

2.3 Declining biodiversity

What can we learn from these measurement tools? A 2017 study[10] shows that in Germany the biomass of flying insects was a quarter of that of 1990. According to the ratchet effect, what for our generation represents a real loss, does not for the next one, which will look at what's around it without imagining that reality could have been very different.

Globally, a comparative analysis of historical data[11] shows that 40% of insect species are threatened with extinction. As regards mammals, a study[12] carried out over 177 species shows that all have lost at least 30% of their habitat, and that 40% have lost 80% or more of their population. Finally, the Great Barrier Reef has just suffered a massive bleaching episode, the third in five years.[13] Corals live in symbiosis with algae, and bleaching means that they separate from them, which ultimately leads to their death, and with them, to the disappearance of the entire coral reef ecosystem, one of the richest and most spectacular in the world.

The current situation is shown below, as it appears in the 2019 report of IPBES, the body corresponding to the IPCC but focusing on biodiversity. To see the summing-up figures, focus on the right half of the image below.

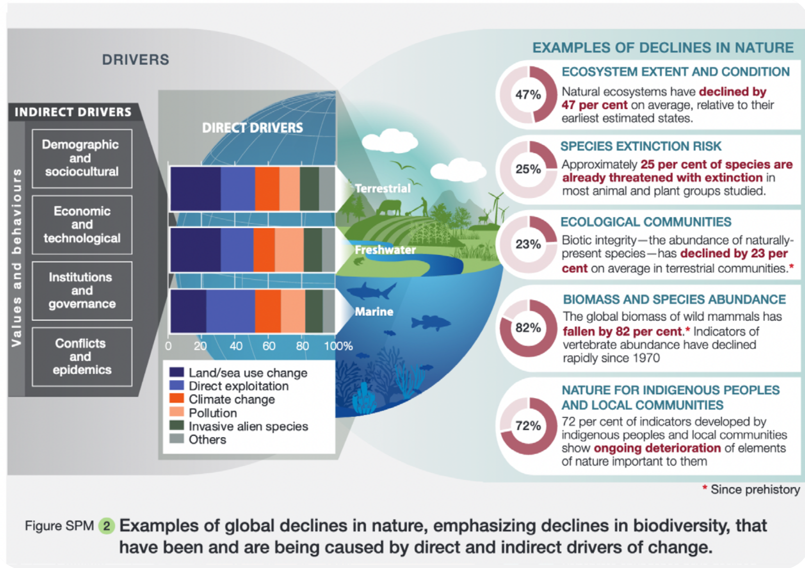


Figure SPM 2 Examples of global declines in nature, emphasizing declines in biodiversity, that have been and are being caused by direct and indirect drivers of change.

Examples of declines observed in nature

Source: 2019 IPBES report

2.4 Climate… or pollution?

These changes are not due exclusively to the increase in temperatures. In general, they are due to a first, more direct effect connected to human activities: pollution, and the destruction of living environments. It is estimated that 75% of the terrestrial environment and 65% of the marine environment has been "seriously altered" by human activities, which is not so surprising if we consider that livestock and agriculture

10 — https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0185809

11 — https://doi.org/10.1016/j.biocon.2019.01.020

12 — https://www.pnas.org/content/114/30/E6089

13 — https://www.theguardian.com/environment/2020/mar/25/great-barrier-reef-suffers-third-mass-coral-bleaching-event-in-five-years occupy more than a third of the surface of the continents and use three quarters of freshwater resources.[14]

The rate of destruction of animal and plant species is unprecedented since the disappearance of dinosaurs, so that specialists now even speak of a “sixth extinction”.

We may think that this is good for the human species, as we'll have the planet all to ourselves. However, the COVID-19 pandemic shows us that it's not the case! The biosphere nourishes us and protects us in many ways. Viruses were on this planet long before us, and found their hosts as evolution was taking place. If the virus from a bat or pangolin sees its host disappear, either because it's being hunted or because its habitat is shrinking, it will mutate to find another host. As humankind has become the most abounding and least endangered species, then it is obviously the ideal host.

Summary

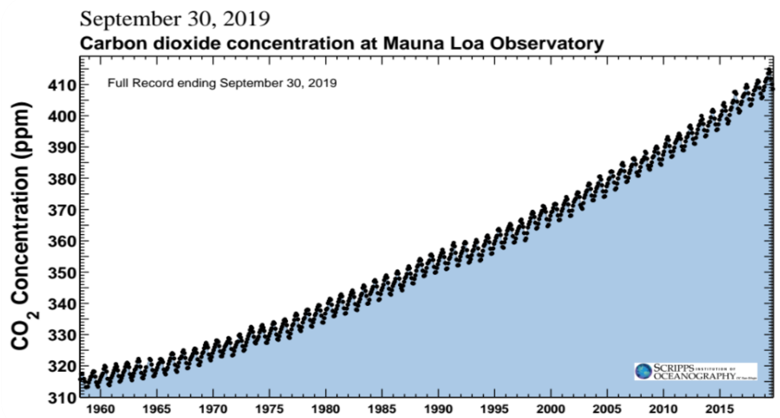
- Global warming is accompanied by a biological collapse: many species have disappeared, and those that remain are becoming rare.
- The main direct cause is pollution, and the destruction of their living environments.
- We measure this decline in the biosphere mainly by counting the number of existing species, the number of individuals per species and their biomass.

14 — 2019 IPBES Report

3 The link with CO_2

3.1 The Keeling curve

In 1958, Charles Keeling set up a meteorological observatory in Hawaii to measure the concentration of CO_2 in the air. The location, the volcanic island of Mauna Loa, was chosen due to its isolation and lack of vegetation. Records have been collected continuously until today, which makes it a particularly valuable and intelligible database.

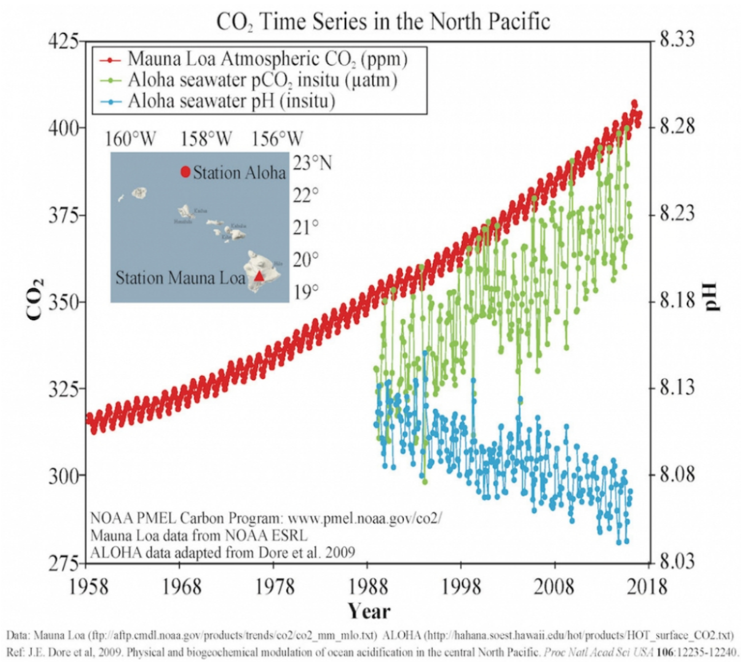


Keeling curve

Source: Website of Mauna Loa Observatory

In the graph, we can see that at the start of the experiment the CO_2 concentration was 314 ppm. It is now 420 ppm, there has therefore been an increase of 32% over the entire period, that is 0.56% per year for 50 years. Moreover, why is the curve not perfectly smooth but instead has this jagged appearance? In fact, these are the seasonal fluctuations over the course of a year, due to the carbon cycle: plants are more active in summer than in winter! The two hemispheres take turns during the year, but since there is less land in the South than in the North, the contribution of the latter is more important.

You can visit the observatory website to find the updated observations. You can also find information on other GHGs, such as methane, as well as ocean acidification. This has also been measured around Mauna Loa, although only from 1990, and the results are the following:



Joint evolution of CO_2 concentration in the air and in water, and water acidity

Source: Mauna Loa Observatory's website

You may recognise the red curve: it's the CO_2 levels in the air, the green curve is CO_2 levels in water, and the blue curve is the pH (the lower it is, the more acidic the water, the more corals suffer). It's clear from this graph that these three variables seem to evolve in a "connected" manner. This is called a correlation.

3.2 Correlation and causality

We come across correlations between variables every day, and inevitably, when we read the press. A detour through an example will show us how we can use them.

Does smoking cause lung cancer? Without denying that people smoking were more frequently affected by lung cancer compared to non-smokers, the great statistician Irving Fisher, a smoker himself, claimed, more precisely, that one was not the cause of the other, but that there was a yet unidentified cause, probably a gene, which caused a predisposition to both lung cancer and smoking. Thus, one was not the cause of the other, and Fisher concluded that preventing cancer patients from smoking was a double punishment, because it was withdrawing from them the little consolation they had left. What are your thoughts about it?

Conversely, hikers have sprains more often than swimmers, and they also eat salami more often. Does this mean that the salami is a determining factor for sprains?

As you understand, in the case of lung cancer, smoking is a direct cause, while in the case of salami and sprains, there is a hidden causal factor which explains the two observations: the practice of hiking.

Now let's get back to our question: is it CO_2 that causes rising temperature and the acidification of oceans? One could claim it's not, and that, in fact, both are the consequence of a common cause, today unknown. In theory, this could be possible, similarly to the case of sprains and salami. However, we have simulation experiments carried out in the lab that show that CO_2 creates a greenhouse effect. As early as the 20th century, well before global warming's effects could be felt, some scientists (Fourier (1824), Tyndall (1861), Arrhenius (1896)) had predicted that the CO_2 levels in the atmosphere would affect temperature (ironic: they were more interested in cooling than warming, as they were interested in explaining the ice ages!). Briefly, the fact that CO_2 is a GHG is no longer in doubt and therefore, we know that the more there is in the atmosphere, the more heat it will retain.

We can also test and prove experimentally that CO_2 dissolves in water, and acidifies it.

In addition to these observable facts and concurring simulation experiments, the accumulation of CO_2 provides a simple explanation for global warming and we currently don't have any alternative explanation. Astronomical phenomena such as those we discussed in the first chapter, for example, take place much more slowly, and the orbit of Earth has not had enough time to be able to change in fifty years. One could try to connect this body of evidence in a more convoluted way, or by invoking an unknown hidden power. However, this is an old rule in science (and besides, also very useful in everyday life!): if you have a choice between several explanations, the simplest is deemed the most probable (which is called, oddly enough, Occam's razor). Until we find another explanation which makes our observations and experiences consistent and which is simpler (this may happen after all!), we must accept that CO_2 (along with other GHGs) is the cause of global warming and ocean acidification.

Summary

- The available measurements, including the famous Keeling curve, provide evidence of the correlation between temperature, CO_2 and ocean acidity.
- Beyond a simple correlation, the model describing the greenhouse effect through the accumulation of CO_2 in the atmosphere makes lab simulation experiments and observations consistent.
- Therefore, according to the scientific approach, this model is to be adopted, as long as there's nothing more conclusive.

4 The link with human activities

The proportion of CO_2 in the air was 280 ppm before 1850, while today it's 417 ppm. Where does the CO_2 that has accumulated in the atmosphere come from? This, in itself, is not a simple question. Volcanic eruptions, for example, release CO_2. We also saw together in the first chapter that the concentration of CO_2 and temperature used to vary long before Homo sapiens appeared. However, let's remember the first chapter: these prehistoric changes reflected changes in geological factors and therefore, took place along much slower timescales compared to what we are experiencing today. As we saw in the previous chapter: in the last two centuries, the only difference in the filling and emptying of the carbon bathtub is the use of **fossil fuels**. In theory, it would also be possible to envisage another biological disruption of the carbon cycle. However, there's no trace of it, and we don't have any reason to believe that there is one.

The following graph shows human emissions by source since 1880.[15] We can observe that these are gigatons (Gt) of CO_2 molecules, and not carbon atoms alone. To know the equivalent in gigatonnes of carbon atoms, you need to roughly divide by four (3.67, more precisely). The 40 Gt of CO_2 reached in 2017 correspond to around 10 Gt of carbon atoms. We can then compare this graph to that of the previous chapter (the carbon cycle).

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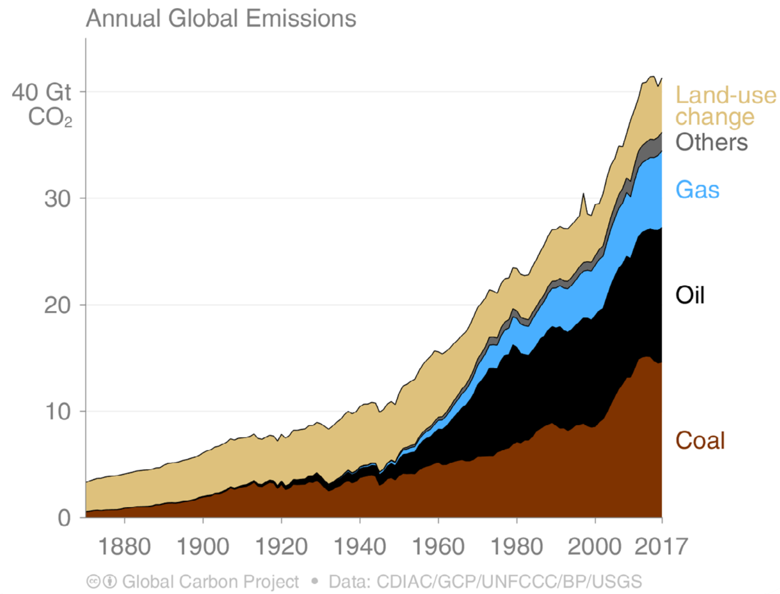
15 — Other graphs, detailed and updated, can be found on the Global Carbon Project website https://ane4bf-datap1.s3-eu-west-1.amazonaws.com/wmocms/s3fs-public/ckeditor/files/2019_COP25_GCP_CarbonBudget_gpeters.pdf?gRkQ71BSsg8JYWP_2LFGg6zKKfHeTHEj



Evolution of annual CO_2 emissions

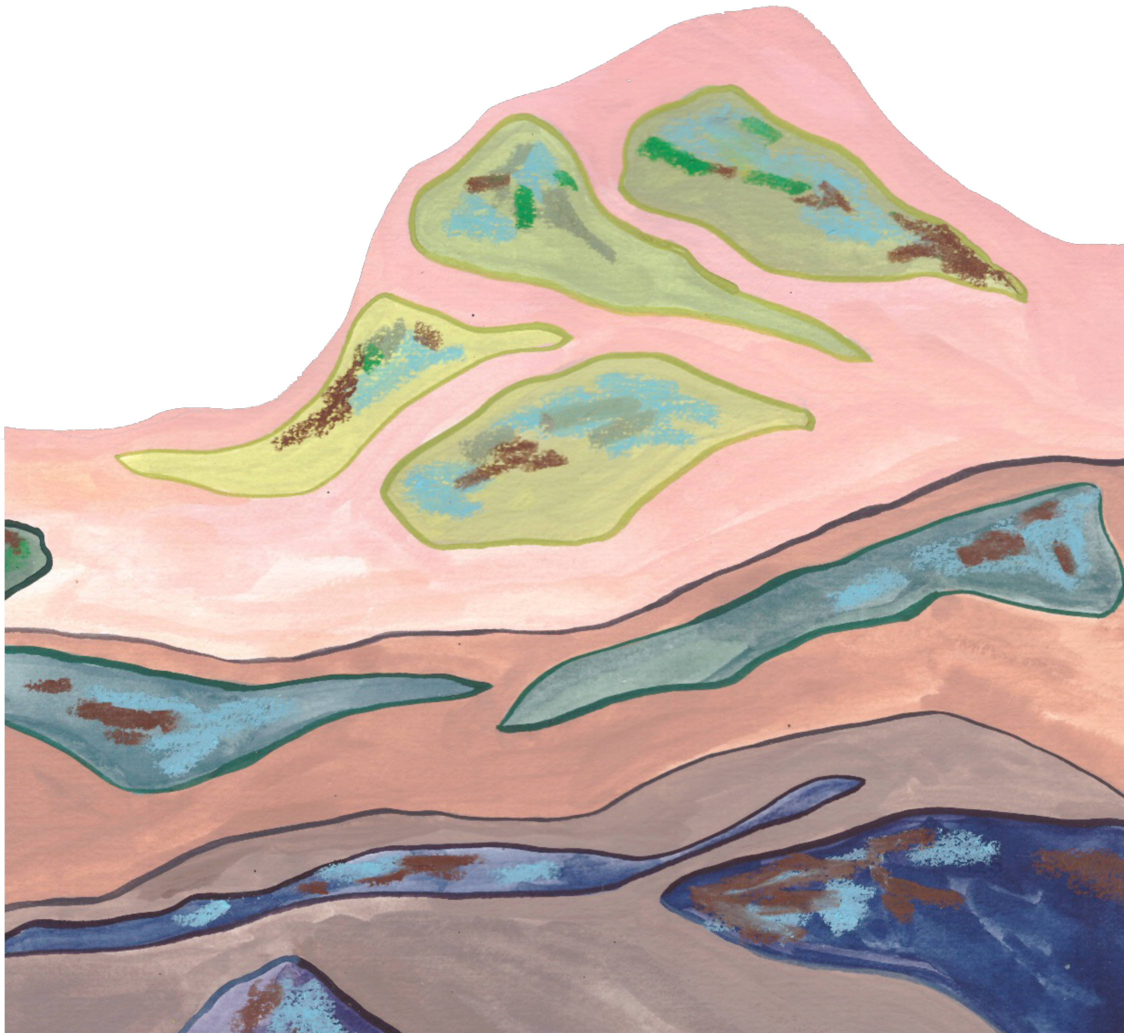
Source: Global Carbon Project

Until 1950, the use of the land (agriculture, deforestation, wood) was the main cause for the emissions. These emissions take place, for example, when a forest is cleared to burn wood as a fuel for heating, or when swamps are drained to build cities. Since the end of the 19th century, there has been a slow rise in fossil fuels: first coal, then oil. After 1950, the world economy was entirely dominated by fossil fuels, gas appeared, and emissions really took off: they quadrupled in 70 years!

Is this enough to unbalance atmospheric carbon stocks at a global level? Yes. In the natural cycle of carbon emissions, emissions are 210 Gt of carbon (120 for the continents and 90 for the oceans). By reading the previous graph, we can see that human activity injects 9 to 10 Gt of additional carbon atoms per year. This is not negligible! And in fact, this is sufficient to disrupt the natural cycle. Getting back to the comparison of the bathtub, we open the tap more and more and over several years. The water is flowing harder and it's no wonder that levels are rising.

Summary

- The only change in carbon emissions over the past two centuries is the use of fossil fuels.
- These emissions are not negligible and are of a sufficient magnitude to disrupt the cycle on a planetary scale.

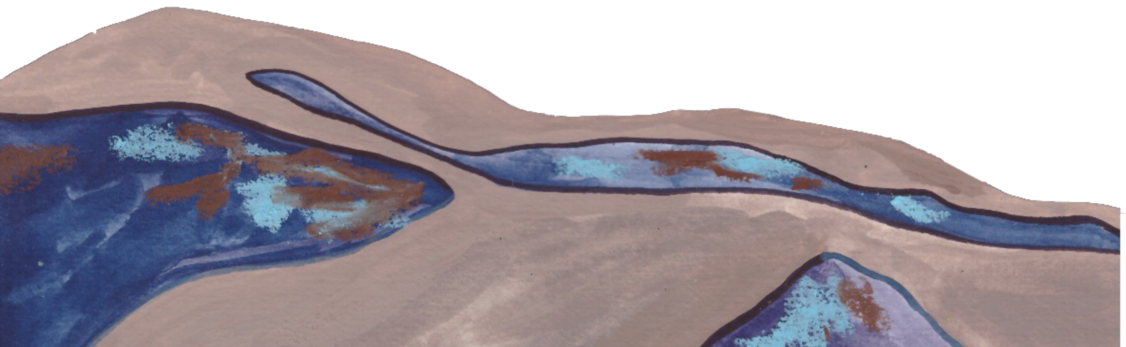


Conclusion

If we follow a scientific approach, we can say that global warming is proven and that it's due to human CO_2 emissions caused by the combustion of fossils. No other possible cause can be observed for such a rapid increase in the CO_2 content of the atmosphere. Moreover, we are also witnessing the accelerated disappearance of many living species, today mainly due to the destruction and pollution of their living environments, but which tomorrow will certainly be amplified by the consequences of global warming.

Although this could be seen as excellent news, this warming, as we will see, may have catastrophic consequences if it persists. If we didn't know about CO_2, we would be at the mercy of a cause that we don't know and over which we may not have much control.

But since it's CO_2, we have the possibility to act: if we manage to reduce the quantity present in the atmosphere, we can certainly bring down temperatures. It is crucial to understand that we are not powerless, and that's the reason why we're racking our brains to do science: to find ways to act.



6

Now what? And where to? Understanding the IPCC scenarios

Introduction

Now that we know how climate works and how close we are to tipping points, we can think about where this may lead us, and whether we can have any impact on the trajectory ahead.

In order to answer these questions, we might find it useful to know, for any possible choice of society, the climate to expect — to project ourselves into our potential futures. This is what we will discuss in thischapter.

The Paris Agreement, signed in 2015, asks all signatory States to act in order for the average level of global warming, compared to pre-industrial times, to be less than 2°C in 2100, and preferably closer to 1.5°C. So how did we reach this consensus, and how did we set this objective, knowing that we are already at 1.1°C? Considering that it is difficult to predict the weather accurately a week or two from now, are we really able to make serious predictions about the climate in a hundred years? We will now see how this is possible.

The organisation dedicated to collecting and gathering the work of the various research centres working on climate is called the IPCC, the Intergovernmental Panel on Climate Change. It regularly publishes reports which take stock of our knowledge and of what the future will look like, based on our actions both today and tomorrow. These reports are available online and available to everyone. They constitute an essential working basis for communities and companies trying to plan their development in the medium or long term.

Warm-up questions

- Question: The quantities of CO_2 emitted into the atmosphere by human activities soared with the industrial revolution. Of the entire quantity emitted over two centuries, what proportion has been emitted in the last thirty years: 1/8, 1/4 or 1/2? *Answer: 1/2*

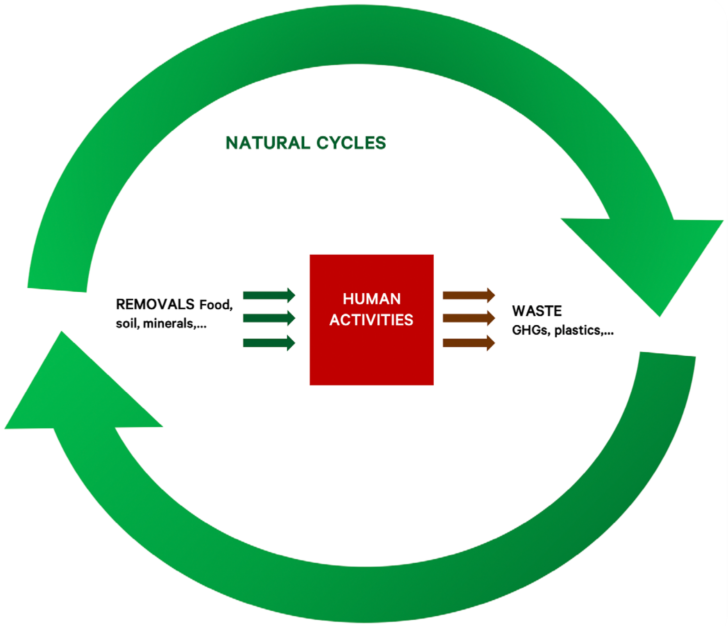
- Question: Based on the current 'business as usual' trajectory, the IPCC forecasts global warming of 4°C or more by 2100. This is the average warming of the planet. As regards just the Arctic, how much would the average warming be: 2°C, 6°C or 13°C? *Answer: 13°C*

- Question: Based on the current 'business as usual' trajectory, the IPCC forecasts a sea level rise of 1 to 2 cm per year until 2100. According to the same study, if emissions stopped as of that date, sea levels during the 22nd century (1) would fall by 1 to 2 cm per year (2) would remain stable (3) would rise by 4 to 10 cm per year. *Answer: (3) - they would rise by 4-10 cm per year*

- Question: When an ice cube melts in a glass of water, the water does not overflow. Thus, why should anyone be worried that melting sea ice should increase the sea level ? *Answer: In fact, the melting of sea ice should not be linked to sea level rises, even if both are consequences of global warming. The rise in sea levels is due to the thermal expansion of the oceans (because of its higher temperature, seawater expands) and the melting of ice caps, such as the glaciers in the Alps, and also, in particular, in Greenland or Antarctica (90% of the world's ice is in Antarctica!). All the ice stored there is resting on a continental plate: if this ice melts, its water will be discharged, joining that of the oceans.*

1 How to make forecasts

The climate is a product of the biosphere, that is, the climate would not be what it is without the interactions with living beings. The biosphere is characterised by natural, physical and biological cycles, disrupted by mankind removing resources (animals and plants for food, minerals for industry) and discharging waste, especially GHGs, and in particular, CO_2. This can be summarised through the following diagram:



Therefore, climate is the combined effect of two causes: natural cycles on the one hand; human activities (and GHG emissions in particular) on the other. We consider macroscopic natural cycles to be independent of human will, and physicists and biologists know how to characterise them using evolutionary equations. However, human activities result from individual or collective decisions that we can sometimes direct, but for which nothing, or almost nothing, can be determined in advance. Cycles can be predicted, future human activities can only be the subject of speculation.

This would not be a problem for predicting the climate for decades to come if humans were contributing just the equivalent of a drop to the great natural mechanics of climate. But, as we have seen, for two centuries, human activities are no longer negligible compared to the great natural cycles, and have a significant impact on the climate. So, how can we predict the climate if it's the result of both predictable macroscopic cycles and uncertain human actions?

The solution adopted by the scientific community is to split the problem into two. We begin by setting a certain number of potential scenarios for human activities. Then, for each of these scenarios, calculations are made on how the major cycles will behave. Therefore, the results of climate projections depend on the scenario adopted and are not, strictly speaking, forecasts, since they don't predict the scenario, but take it into account, instead, as an input, in their calculations. To mark this difference, we speak of projections rather than forecasts.

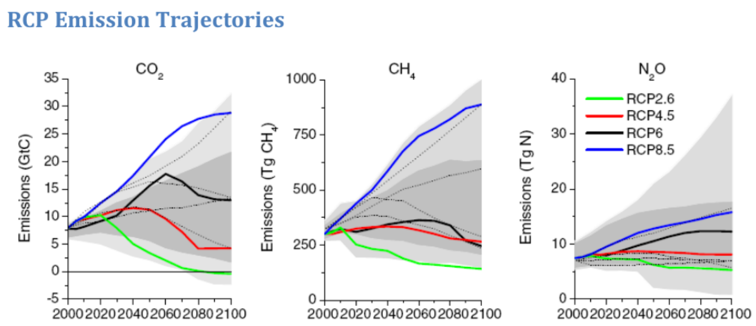
1.1. The scenarios

As you can imagine, the number of imaginable scenarios is endless. Fortunately, not all the details are significant when we investigate the evolution of the climate. The most determinative parameter for the climate, as you should now know by now, is the quantity of greenhouse gases (GHGs) released into the atmosphere. Thus, our problem can be significantly simplified by considering each of the scenarios only according to the amount of associated GHG emissions.

These emission scenarios are now standardised. They are called *Representative Concentration Pathways*, abbreviated by RCP, each characterised by a potential evolution in the amount of GHGs present in the atmosphere by the end of the century. There are four in total, from the most pessimistic, RCP 8.5, to the most optimistic, RCP 2.6, with RCP 4.5 and RCP 6 in between.

What do the figures 8.5 or 2.6 refer to? The figure indicates the radiative forcing reached by 2100 according to each scenario, for example 8.5 Watt/m^2 according to the RCP 8.5 scenario, that is, the imbalance between the energy received by the Earth and the energy returned into space.

They are shown below:



Projected changes in CO_2 emissions, and CH_4 and N_2O emissions according to the different scenarios studied

Source: IPCC 2014 Report

Interpretation: The four scenarios are represented by coloured curves and the three graphs represent three greenhouse gases, with the best known, CO_2, far left. RCP 8.5 corresponds to the warmest climate, since the greater the forcing, the warmer the planet becomes. This is consistent with what we can see on the three graphs: the blue curve is the highest for the 3 greenhouse gases represented.

The decision to consider only four scenarios is recent. Researchers have previously explored a wide variety of scenarios, and the graphs show where the RCPs lie in relation to the previous literature: 95% is within the dark grey, and 5% within the light grey. We can see how representative they are: RCP 8.5 represents the 'business as usual' (BAU) approach, without any climate policy. Meanwhile, RCP 2.6 corresponds to a policy of drastic reduction in emissions beginning today.

Summary

- The climate is the combined effect of two causes: natural, predictable cycles; and human activities, which are not predictable.
- Therefore, climatologists proceed by setting a number of possible scenarios for human activities, in which they simulate natural phenomena.
- The 4 reference scenarios (RCP) are indexed in terms of total emissions, up to the RCP 8.5 scenario, corresponding to the extension of the current trends.
- The figure indicates the radiative forcing reached in 2100. The higher the number, the greater the global warming.

1.2 The calculations

The advantage of fixed standard scenarios is that these can then be handed over to mathematicians, physicists, biologists and other scientists, who are able to do their calculations without worrying about where the emissions come from and how they are produced. Knowing the quantities of GHGs emitted by human activities at any point in time, they will calculate the weather accordingly, using usual meteorological equations.

However, you might point out that everyone knows that weather forecasts are hardly reliable beyond a week or two. Thus, how can we trust climate forecasts which extend to the end of the century?

The answer is that meteorologists on the radio must announce the exact weather at a specific point and date. Conversely, a climatologist presents average predictions over several years to come and in a probabilistic manner. This should remind you of the very first chapter, where we made the distinction between weather and climate.

The situation is similar to when you throw a die. At each throw, at the moment when the die leaves the hand of the gambler, its trajectory is perfectly determined, and can be calculated by applying the usual laws of physics. You can imagine the meteorologist as the person who calculates the trajectory before the die hits the carpet, and the climatologist as the person responsible for stating, on average, the sides on which the die will land most often. The first one can predict the position, let's say, for example, where the die will hit the mat, the other can provide the probabilities of obtaining a particular result. Both provide precise answers, both follow a scientific approach, both use physical equations related to wind movement, precipitation, etc., but the second one does not seek to obtain an actual prediction, but a probabilistic description of possible futures.

How useful is such a statistical response, when it does not say what will happen but merely states the potential outcomes, providing a probability for each of them? Of course it's useful! If you have to choose between two dice, it's better to play with the one which has a 50% chance of getting a 6 rather than the one which only has a 10% chance.

Briefly, if we apply this to the topic of global warming:

	The meteorologists	The climatologists
They try to predict	The exact temperature and precipitation for the place and future date considered	The most probable average temperature and precipitation over the region and future period considered
Their answer is	Exact: only one weather forecast is predicted for each date	Probabilistic: it presents the different possibilities over periods of several years, as well as the probabilities associated with each possibility
They don't try to predict	The scenario of GHG emissions due to human activities. It is assumed in their calculations, like the type of throw of the die.	The scenario of GHG emissions due to human activities. It is assumed in their calculations, like the type of throw of the die.
They perform their calculations	Just once, with maximum accuracy	Many times, each time slightly modifying the initial conditions to account for possible errors, in order to identify the most frequent results.
They use equations	Relating to climate physics	Relating to climate physics

For each of the scenarios, climatologists provide the probabilities that the average global warming will be 1, 2, 3, 4°C or even more. Choosing a policy and sticking to it, is like choosing one of the dice. Doing nothing (business as usual) means choosing the die stamped with RCP 8.5. The climatologist will not provide you with the climate that will prevail in

2100, but with the list of possible climates, along with the probability for each of them.

1.3 Accelerating towards 2100

As we have seen on several occasions, the excess CO_2 emitted today does not begin to be eliminated naturally in less than one thousand years. Even if we were to put a stop to all our emissions today, the stock of CO_2 present in the atmosphere would remain substantially unchanged for ten centuries, and the entire third millennium will have to deal with the atmosphere we leave them.

However, even in this case, this does not mean that the climate would remain unchanged during this period. There are several reasons for this. First, as we understood in chapter 2, the 'padding' of the Earth's atmospheric ‘sleeping bag’ over recent decades has created a structural imbalance between energy received and the energy returned. Earth's climate, therefore, is naturally evolving towards a new point of equilibrium, a warmer one, which we have not yet reached.

In addition, global warming is accelerating. This is due to the fact that certain mechanisms, sometimes very slow ones, end up triggering others, which, in return, impact on the earlier ones, making them more powerful. For example, global warming in century 1 melts part of the sea ice, which will no longer be there in century 2. Now, the ice reflects sunlight, and this is as much energy that was sent back to space without being intercepted by the GHGs (these are not infrared). Therefore, in century 2, there will be less reflected sunlight, and more light absorbed by the surface and reflected back as infrared radiation. This radiation will be intercepted by the GHGs and will end up heating the atmosphere even more, and melting even more sea ice. Thus, global warming is accelerating each year. In the case of the polar ice cap, its complete melting may take place over several centuries, causing the sea level to rise by several tens of meters.

We know of several such natural mechanisms, all of which may accelerate global warming beyond 2100. We don't know of any that would slow it down. This is why the IPCC reports, according to the RCP 8.5 scenario, talk of a sea level rise of 1.5 to 2 cm per year until 2100, then of several centimetres per year beyond that. No more is said, since we don't know how quickly the ice will melt. The complete melting of the Antarctic ice, on its own, would raise sea levels by 70 metres (luckily not in the short term).

1.4. The threshold effects

In essence, the current calculations incorporate all the mechanisms that the scientific community believes have influenced or will influence the climate in the next two or three centuries. However, they don't incorporate well-identified mechanisms on which we don't yet have enough information to be able to make predictions (the fall of an asteroid to Earth, a new world war). There is one exception, though: all the scenarios assume that by 2100 we will have invented some industrial processes to extract CO_2 from the atmosphere and store it, and that these processes will be deployed on the necessary scale. At present, we are long way from this indeed, and in reality, it's almost impossible to see how we will get there. Nonetheless, this hypothetical industry plays a fundamental role in the reduction of emissions anticipated in RCPs 2.5 to 6.

Among the physical or biological mechanisms, which, in theory, are well understood, but on which we don't have enough information to be able to make predictions with certainty, we must finally mention the threshold effects. We also speak of tipping points. This is the same principle as when loading a boat progressively: it sinks a little more each time but it still floats, and then all of a sudden, a small additional load causes it to sink. Passing some thresholds may lead to brutal and colossal changes at the level of an entire continent. In relation to global warming, scientists who produced the following map have identified nine:

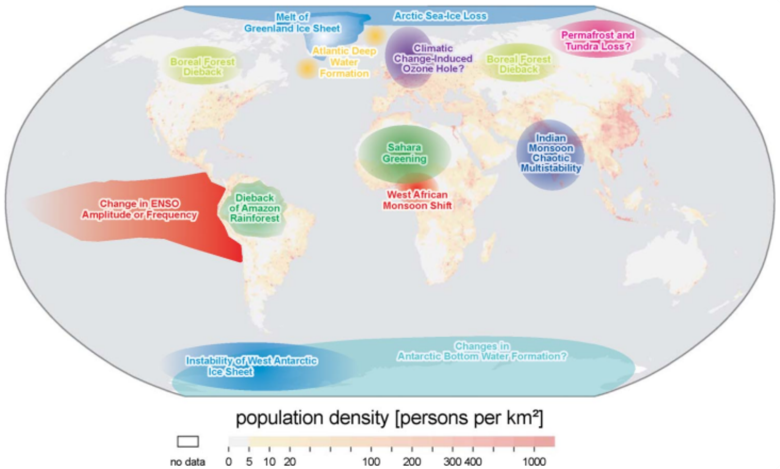


Fig. 1. Map of potential policy-relevant tipping elements in the climate system, updated from ref. 5 and overlain on global population density. Subsystems indicated could exhibit threshold-type behavior in response to anthropogenic climate forcing, where a small perturbation at a critical point qualitatively alters the future fate of the system. They could be triggered this century and would undergo a qualitative change within this millennium. We exclude from the map systems in which any threshold appears inaccessible this century (e.g., East Antarctic Ice Sheet) or the qualitative change would appear beyond this millennium (e.g., marine methane hydrates). Question marks indicate systems whose status as tipping elements is particularly uncertain.

Nine Potential Tipping Elements Impacting Global Climate

Source: *"Tipping elements in the Earth's climate system", article published by the United States National Academy of Sciences (PNAS journal)*[16]

Let's consider the case of the monsoon. As you know, it's a pattern where significant rainfall takes place during part of the year, while the rest of the year remains dry: it regulates the alternance between the dry and the rainy season around the equator, West Africa and India. According to the article, there's a risk that these patterns will disappear with global warming. For India, this would lead to widespread drought, with all the consequences in terms of food and survival which you can imagine.

However, note that not all these threshold effects lead to more drought: in Africa, for example, this could lead to the greening of the Sahara, which would receive more rain. This would be one of the rare positive consequences of global warming! You can read more about it in the original article.

1.5 Why 2100?

So why has the date 2100 been retained? The idea is to find a compromise between showing, on the one hand, the scale of the changes to come (the most dramatic will not happen in ten years but in fifty to sixty years) and, on the other hand, remaining close enough so that people living today can feel concerned.

Unlike the generations which have the decision-making power over our economic and social systems today, those born after 2000 will live their entire working lives in a climate that's warming up, with a good chance of spending their old age, towards the end of the century, under the conditions described by the IPCC reports.

16 — https://www.pnas.org/content/pnas/105/6/1786.full.pdf?wptouch_preview_theme

Summary

- For each human emissions scenario, climatologists have presented a statistical projection, which indicates the possible trajectories alongside their associated probabilities.
- This uncertainty is partly due to the difficulty of calculating all of the parameters affecting the climate, but also to some reinforcing processes, which increase the magnitude of the changes, and even more to threshold effects, which have the potential of disrupting the entire system.
- The projections point to 2100, which is a horizon both close enough to feel concerned and far enough to appreciate the extent of the changes to come.

2 The IPCC

There are many climate research centres, such as the ISPL (Institut Pierre-Simon de Laplace) in Paris, along with many institutions doing forecasting, such as NASA in the United States.[17] However, the IPCC, the Intergovernmental Panel on Climate Change, is unique in that it represents an international scientific and political consensus.

It was founded by the United Nations and the World Meteorological Organization in 1988, under the English name "IPCC", for Intergovernmental Panel on Climate Change,[18] with the aim of "assessing on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation".

It's not a research centre, but an intergovernmental organisation with 195 member states. To fulfil its mandate, it relies on scientists, however, their conclusions are always submitted to the Member States, which alone, have the power to validate them. It publishes a report every six years (each of which is divided into several sub-reports), in addition to reports on specific topics. There have been five reports, in 1990, 1995, 2001, 2007 and 2014, and the last one is expected by 2022 (you can already read its first volume, published in August 2021).

17 — These organisations have very interesting websites on the subject, such as: https://www.climat-en-questions.fr/ or https://climate.nasa.gov/

18 — Its website is https://www.ipcc.ch/ and a section is in French: https://www.ipcc.ch/languages-2/francais/

Researchers collaborate on the reports on a voluntary basis and are not remunerated. They represent all disciplines, all the regions of the world and great importance is given to turnover.[19]

Their task is to gather the different results obtained by different research teams around the world, and to extract the relevant information. The validation process is long and complex, involving the authors of the report and the researchers whose results are reported, then the authors of the report and the politicians who represent their governments and defend their interests (you just need to think of the example of Saudi Arabia, which, economically speaking, has no real interest in questioning the emissions linked to the consumption of hydrocarbons). Other scientists can also read the reports and submit observations to which the authors must respond. Thus, each report is the result of a scientific and political agreement: all the information published has been validated by the scientific community as a whole as well as by the political authorities of the countries concerned at the end of an open and transparent process, operating without private funding. This is a huge advantage, as it provides authoritativeness, even if one may fear that such a consensus could be obtained by minimising the risks involved.

Summary

- The IPCC is an intergovernmental institution representing 195 member states.
- Its mandate is to offer a synthesis of the scientific studies available on climate change.
- The IPCC issues reports approximately every six years, on which there is scientific and political consensus, providing authoritativeness on the international stage.

19 — https://medialab.sciencespo.fr/en/news/cartographier-les-auteurs-du-giec/

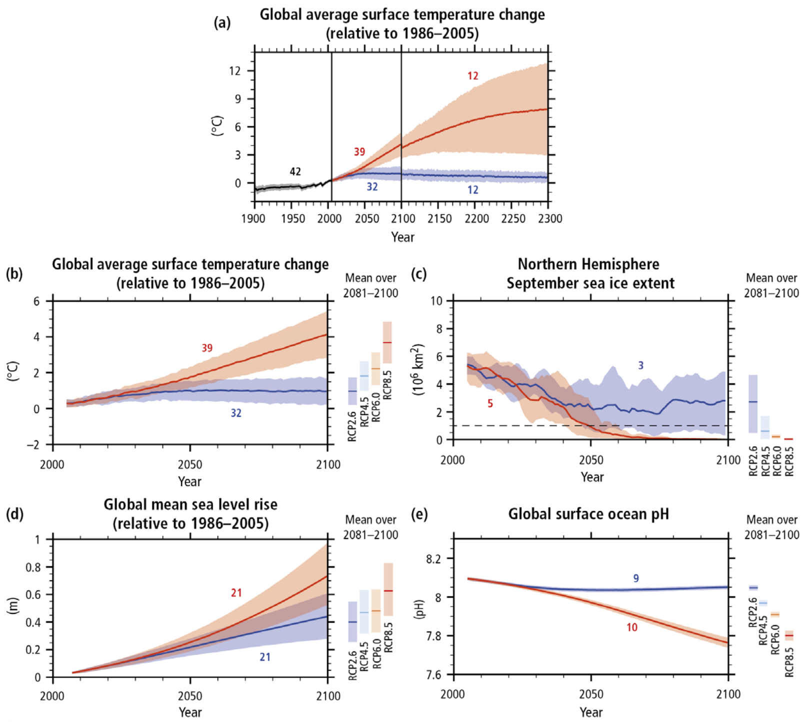
3 Reading IPCC reports

3.1 Maps of the expected global warming

The reports are available online, on the IPCC website. The 2014 report, for example, actually includes four sub-reports: one presenting the projections, that is, the course of global warming until 2100 according to the four scenarios selected, another, the way in which human activities could adapt to it, the third, on how it could be mitigated, as well as a summary report. Each of these four reports begins with a "summary for decision-makers", which provides the basics, and ends with the technical annexes.

As regards the projections, they are always probabilistic, as previously explained, and therefore, they are presented with their probability of occurrence.

Page 59 of the summary report presents the projections in terms of average temperature, sea ice extent, sea level rise and ocean pH. You can find it below:

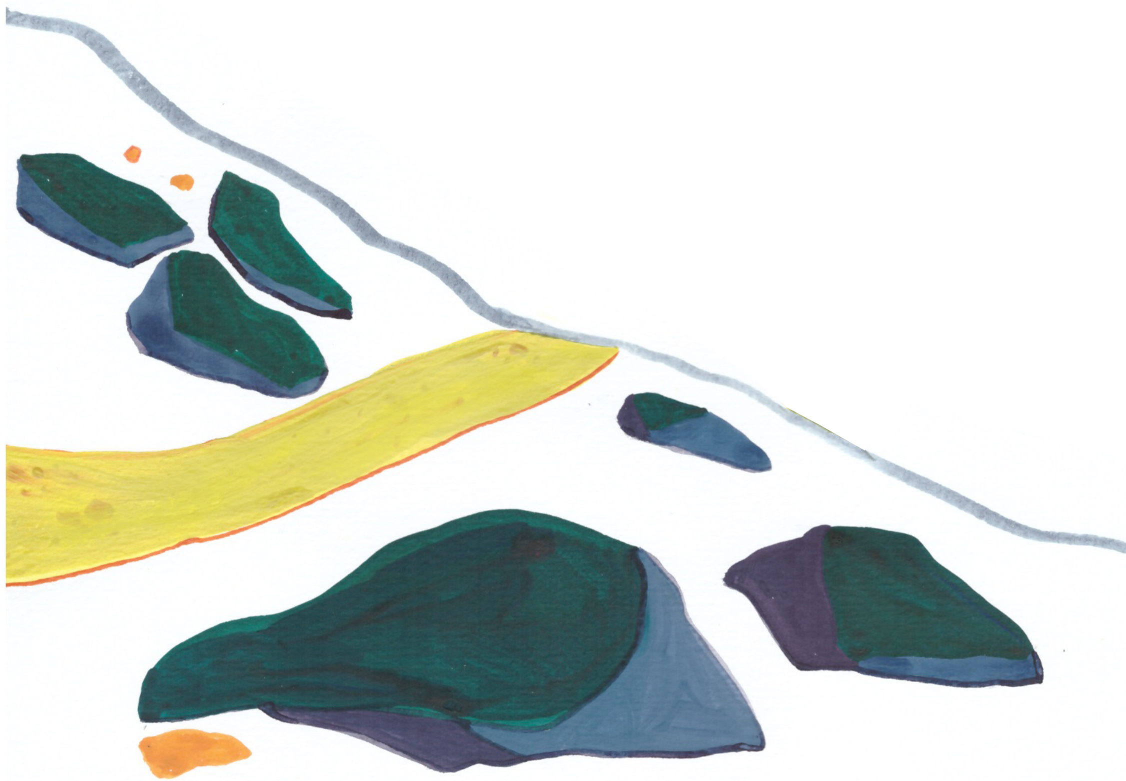


Evolution of different markers of global warming within two extreme scenarios

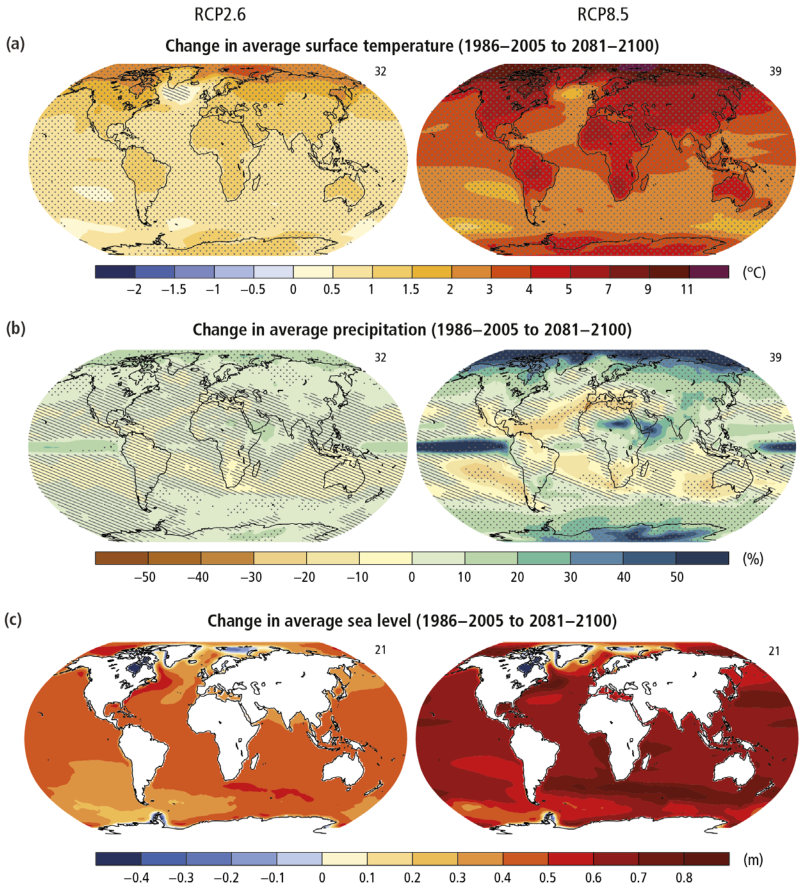
Source: Page 59 of the 2014 IPCC Report

As showed in the legend, the red curves correspond to scenario 8.5, the blue ones to scenario 2.6. Not surprisingly, temperatures or sea levels will be significantly higher in the first scenario. We can also see that the surface of the Arctic ice pack and the pH level of the seas and oceans are lower in this first scenario (i.e., the acidity of the seas increases by absorption of excess atmospheric carbon, as we saw in Chapter 4).

As in any statistical exercise, forecasts come with uncertainty: this is shown by the light red and light blue areas around the mean curves. These are 90% confidence zones, i.e. we estimate that in a given scenario there is a 90% chance that we end up in the light-coloured zone. This is why we see this zone widening with time on all the graphs: the more we advance in time, the less certain we are, and the wider the "90% probability" zone is. You can also notice that the 8.5 scenario has generally wider confidence zones. This is because it corresponds to a climate evolution in much more unusual areas, with for example threshold effects with multiple consequences that are very difficult to anticipate.



These global projections are detailed geographically. Let's take, for example, page 61:

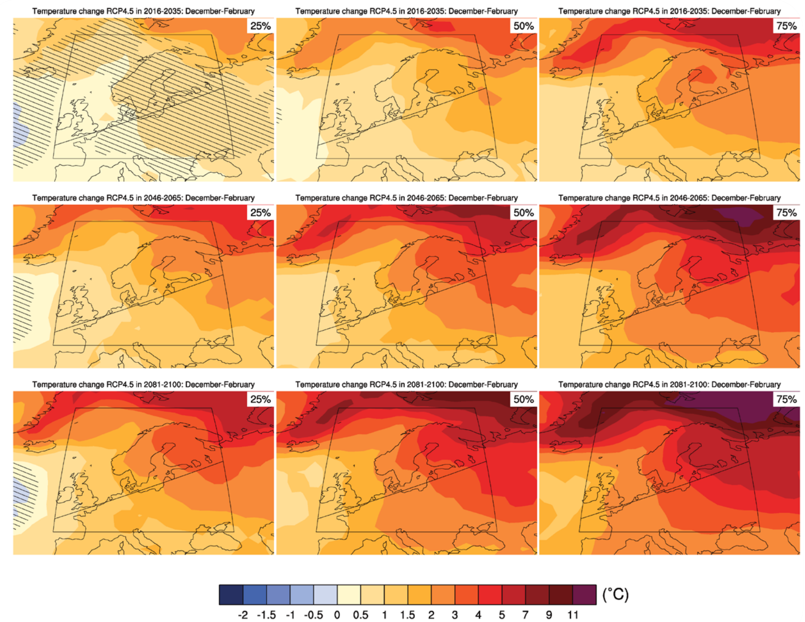


Regional climate changes according to two extreme scenarios

Source: Page 61 of the 2014 IPCC Report

We can immediately see the regional disparities. According to scenario 8.5, the forecast for the average global temperature rise is 4°C, however, in the Arctic, temperature will rise by 13°C. And curiously, south of Greenland, there is a region where the average temperature will be stable, and might even drop, according to the RCP 2.6 scenario, as part of global warming! Also interesting is the very last figure: try to locate New York, London, Kolkata and Tokyo on the map...

In the report on the physics of climate change, you can find detailed maps for large regions of the world. If, for example, you are interested in Europe, below you can find the forecast, in terms of winter temperatures in Northern Europe, according to an optimistic scenario, based on efforts being made to limit GHG emissions, the RPC 4.5:



Temperature changes in Europe according to the RCP 4.5 scenario

Source: IPCC 2014 Report

To avoid getting lost among all the red and orange gradients, first scan the titles: they indicate the dates. The first line shows three projections for the winter of years 2016-2035; the second line for 2046-2065; the last for 2081-2100. Unsurprisingly: the maps become more and more red as you go down. So, even according to this optimistic scenario, it will be warmer every year.

As usual, the results of these projections are based on statistics: thus, a median projection is presented, along with a "confidence interval" around such an average, where we expect the results to be. Thus, the expected median values are represented in the central column, where 50% is indicated on the three maps. What do the maps with 25% on the left and those with 75% on the right represent? They indicate the extent of the confidence interval around the expected mean. More precisely, a 25% map means that the IPCC estimates that there is a 25% probability of having lower warming than that shown on the map. Similarly, a 75% map means that the IPCC estimates that there is a 75% probability of having lower warming than that shown on the map. Thus, these three maps allow us to draw a confidence interval around what we expect the outcome to be.

Warming figures are provided in relation to the end of the 20th century, so we need to add 0.6°C to find the warming values in relation to the pre-industrial era. We can see that, even according to this optimistic scenario, while the average warming is 4°C over the region, the Arctic winter has one in two chances of warming by at least 9°C by the end of the century.

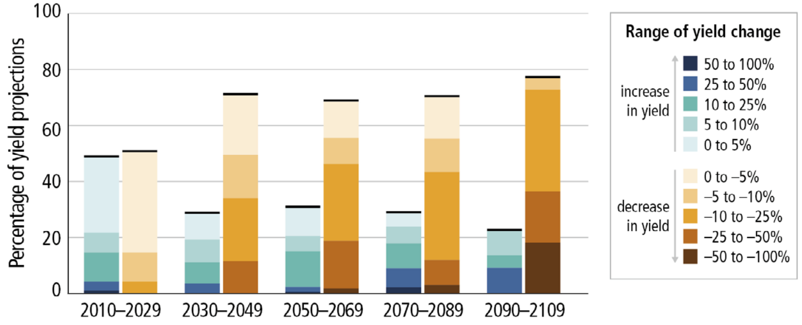
On the IPCC website you can find the evolution of summer temperatures in Northern Europe, as well as the evolution of precipitation. It's an atlas of projections, where you can find similar maps for all the regions of the world.

3.2 Consequences of global warming for human societies

Global warming is not without consequences. Below you can see, for example, from page 69 of the summary report, the projections for the changes in cereal crop yields during the 21st century, compared to those in 2000. The table gathers the results of some thousand research programs carried out under various hypotheses, providing the progression or, conversely, the decline in yields every twenty years. Some studies conclude with a progression (in blue), others with a regression (in ochre-brown), and the table indicates the proportion of each one, along with their conclusions. We can see how the vast majority are pessimistic, even very pessimistic:

- While about half of the studies expect an increase in yields over the period 2010-2029 (the blue bar is almost at the same level as the ochre bar), only just about more than 20% expect an increase over the 2090-2109 time period.

- Among the many studies expecting yield declines after 2030, nearly 20% conclude that yields will drop by more than half at the very end of the century (see the darkest brown share over the 2090 -2109 time period), and nearly 40% to a drop of more than 25% (if we add the two darkest ochre-browns over this period).

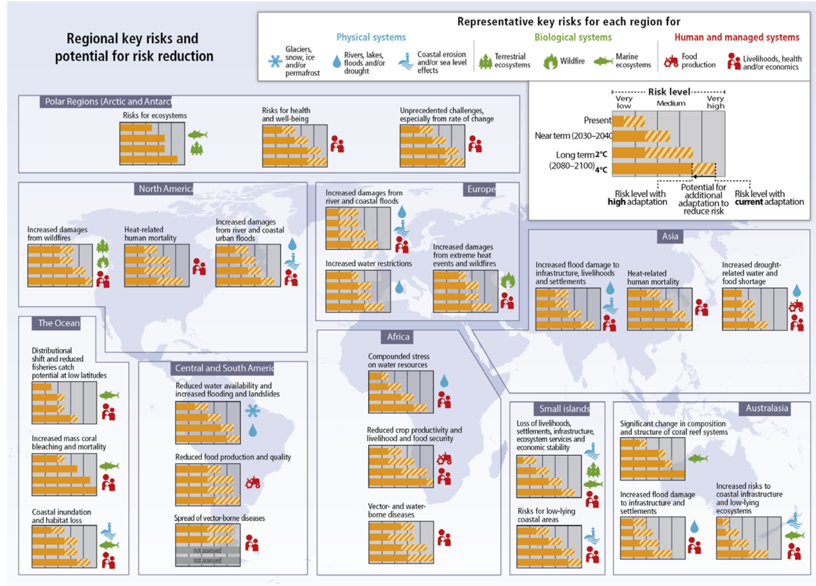


Distribution of agricultural yield projections according to different scientific studies

Source: Page 69 of the 2014 IPCC Report

Furthermore, the maps we have seen represent the averages, and don't contain all the information. As the average rises, extreme events become more frequent. There is a succession of heatwaves, each breaking the record set by the previous one. In the tropics, more and more violent cyclones are generated, and years of drought become increasingly long in other places. Heat and drought combined produce massive fires, like those that ravaged Australia in 2019 and 2020.

The IPCC has attempted to list the different risks which accompany global warming: fires and floods are just the most visible. The results are included in the two reports on mitigation and adaptation. They can be summarised according to the following overview, which is explained on page 65 of the summary report:



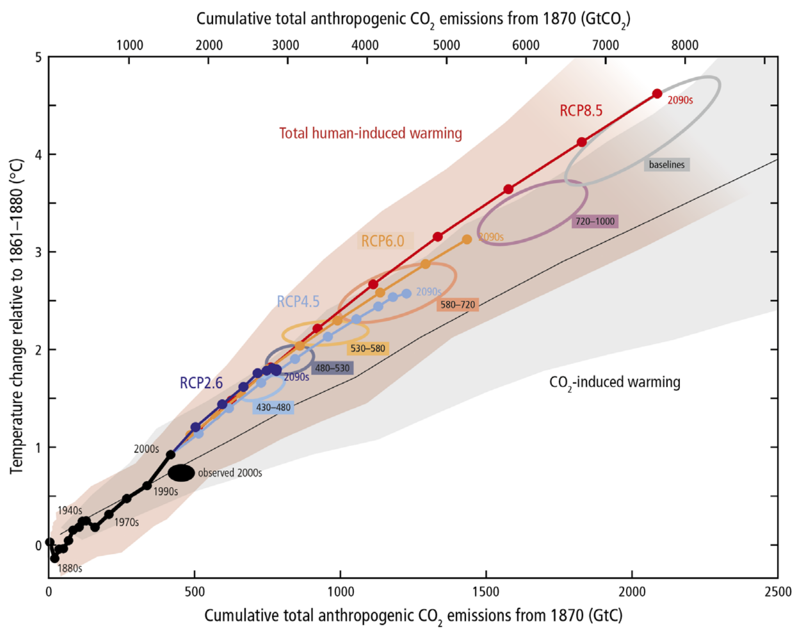
Risk projections by region

Source: Page 65 of the 2014 IPCC Report

The risks are evaluated according to two assumptions, a warming of 2°C compared to 1985 at the end of the century, and a warming of 4°C. For each of them, it provides the short-term risk (2030-2040) as well as the long-term risk (2080-2100). This is explained in the section at the top right. Just above, you can find the classification of risks by type. We can see, for example, that Asia will be particularly affected (food shortage due to drought, destruction of cities and infrastructure due to floods, and direct mortality due to the combination of heat and humidity, as we pointed out in the chapter on biology). North America won't be spared, being struck in particular by direct mortality.

Conclusion

To conclude this chapter, it's useful to recall the assumptions corresponding to the four scenarios selected, RCP 2.6, 4.5, 6 and 8.5. Essentially, these are scenarios linked to GHG emissions, and they are represented by the following graph, along with the corresponding warming figures:



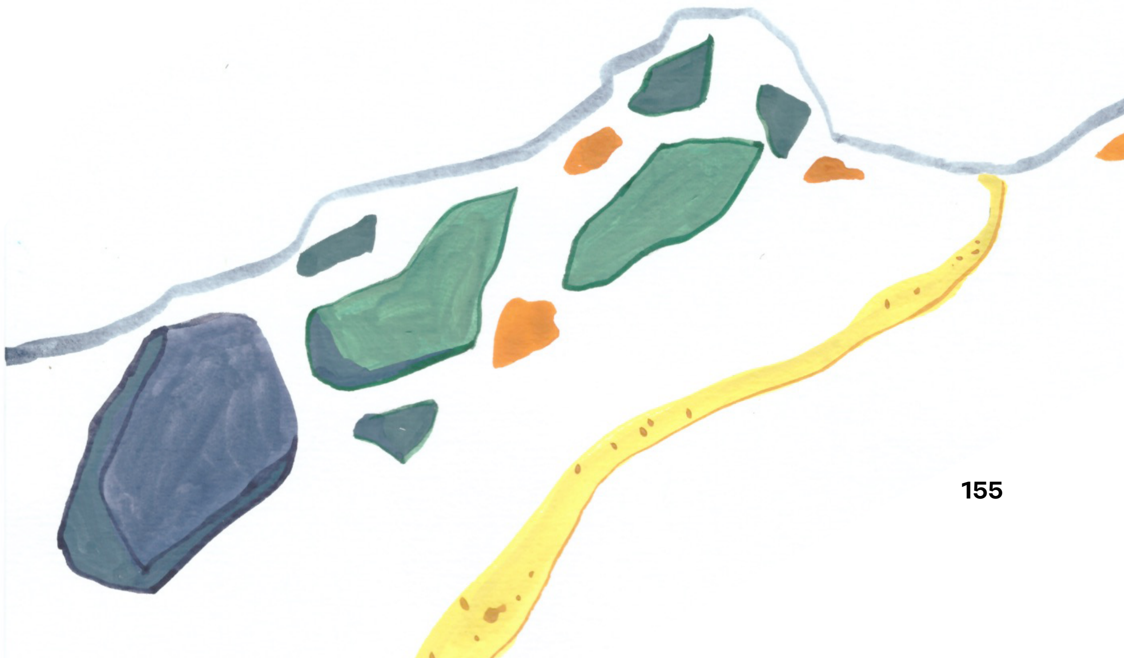
Cumulative emissions of CO_2 and average temperature rise by scenario

Source: IPCC 2014 Report

On the horizontal axis (at the top of the graph) we can read the total amount of CO_2 emitted by human activities since 1870, and on the vertical axix, the corresponding warming figure. The dates are indicated directly in the figure. For example, we can see that according to scenario 8.5, BAU, mankind is supposed to have emitted in 2090 more than 7500 Gigatonnes of CO_2, whereas today we're still only at 2000 Gigatonnes. Perhaps you would think 7500 will be hard to reach.

At the same time, you can observe that the carbon stock has doubled between 1970 and 2000. In other words, we have emitted as much CO_2 in 30 years as during all previous centuries combined! Therefore, the question could be reformulated as follows: is it realistic to think that this trend will be reversed spontaneously? And if not, we will need to think about ways to embark on a different trajectory. Without doubting our adaptation capacities, this chapter should have made clear that the consequences of global warming will be much more favorable to decent human life in a scenario like 2.6 than 8.5.

How can our social and economic systems get transformed to get there? That’s the topic of the second volume of this course!



7

From Fossil Fuels to Energy Transition

Part I — An introduction to energy

This part was co-written with Jacques Treiner, physicist and professor, chairman of the *Shift Project*.

Introduction

There are now nearly 8 billion of us on this planet. The majority live better and longer than our ancestors. Progress began with the industrial revolution, and accelerated around 1950. But greenhouse gas (GHG) emissions, as well as biodiversity loss, have followed the same path, to the point where they now risk jeopardizing all the hard-won achievements of the previous two centuries. We are like a driver, who is on a long journey, and who suddenly sees the engine temperature indicator entering the red zone. Let's stop the car on the roadside, open the hood and check the engine. What's wrong with it? What tools do we have to fix it? After the diagnosis, it will be time to decide what to do.

This chapter consists of two stages. Firstly, we will introduce key concepts about energy, such as power and energy efficiency. We will then review the various sources of energy and their characteristics: stock or flow, concentrated or diluted, controllable or intermittent, and finally we will show their distribution on the planet. This information is crucial to understand the historical development of modern societies and the current issues of global warming.

A few questions to warm up

- There are 7.8 billion people on the planet today, compared to 1 billion in 1800. On what date had the population reached half that number, i.e. 4 billion? (a) 1902 (b) 1953 (c) 1974

Answer: (c)

- A correspondent once wrote to Ivar: "Why don't we generalise the use of electricity? This would allow the economy to function without emitting GHGs, and it would solve the problem of global warming." What would have been your answer?

Answer: And how does one produce this electricity?

- A barrel of oil is 42 US gallons (160 liters). How many barrels of oil are consumed in the world per day? (a) 1 million (b) 10 million (c) 100 million (d) 1 billion

Answer: (c)

- Cows emit CH_4 (methane), they even emit a lot. In what way? (a) they burp (b) they fart (c) the methane comes from their dung

Answer: (a)

1 Energy

1.1. What is energy, really?

In everyday language, we speak about energy as if it were something tangible, a commodity like any other: we buy it at the pump, we pay it to the electricity provider, we produce it in power plants, and we can even read the "energy content" of food on the package. As if energy could be produced, then consumed and finally would disappear.

This is a mistake: we do not produce or consume energy . We consume fuel or food and certain physical transformations then enable us to run on a soccer field or to drive a car. Energy is a form of accounting that allows us to track physical transformations. In any transformation of matter, the energy of the final state is equal to the energy of the initial state: this is known as the law of energy conservation.

Let us explain this. Humans live by transforming matter: they clear the land, cultivate, build (and incidentally emit GHG!). A garment, a vegetable, a house, a computer, a car, a factory: all this is matter transformed by human work, helped by machines, which themselves are matter transformed. In the course of history, humans have discovered increasingly ingenious ways to turn the transformations of matter to their advantage. The industrial revolution, for example, is the result of the invention, and the later improvement, of machines burning coal.

We do not need to use the concept of energy to tell this story. On the other hand, it becomes very useful when it comes to scaling these transformations. Can we perform the same amount of work with a liter of gasoline, a kilo of coal, or a horse lent for an hour? How many liters of gasoline are needed for a given task? Energy is a common denominator, a kind of currency, which allows us to answer these questions.

Thus, with a single liter of gasoline, one can do the same work as with 1.5 kg of coal or 15 horses lent for an hour. In everyday life, we say that one liter of gasoline "contains" as much energy as 1.5 kg of coal or 15 horses for one hour.

Of course, in practice, this quantitative equivalence is not enough. There must be physical transformations capable of transforming this energy into useful work! Drinking petroleum will not help us run, and putting carrots in the car's tank will not carry us far. However, in what follows, as in everyday language, we shall speak of "production", "consumption" or "transfer" of energy, and we may even liken it to matter itself (we eat "energy bars" before a marathon, don't we?). Keep in mind, however, that energy is but a mode of accounting which links the successive states of matter in a physical transformation.

For any transformation, whether it is done by an animal or a machine, we distinguish the quantity of incoming energy (associated with the initial state of the matter, the gasoline in the tank for instance) from the quantity of energy that will actually be used, called usable energy (related to what in the final state of the matter interests us: the movement of the car for example). Note that the latter is always less than the amount of incoming energy: the difference comes from a part of the transformation that is "useless" to us, i.e. that does not contribute to the intended objective. For a car that we want to drive, the incoming energy measures everything that the fuel in the tank can do. Most of it will allow the car to move forward (usable energy) but some of the fuel burned will heat the engine, which is not "useful" to us. This is often referred to as "dissipated" energy. In reality, it is not (heating is a transformation that "serves" us in many other contexts!), but in this case, it does not contribute to the intended objective. If we had taken into account all the outgoing energy, useful and useless, it would always be equal to the incoming energy.

Summary

- Humans live by transforming matter.
- Energy is a quantity that allows us to scale the transformations of matter.
- In any transformation, there is conservation of energy: the incoming energy associated with the initial state of the matter is equal to the sum of the outgoing energy, usable and useless, associated with the final state of the matter.
- We often speak of "dissipated energy" to describe the "useless" outgoing energy.

For readers who like physics and mathematics:

Let's drop a mass m from a height *h*. It will gain speed as it loses altitude. There is a quantitative relationship between the height of fall h and the acquired velocity v on reaching the ground, namely:

$$9{,}81mh = \frac{1}{2} mv^2$$

This equation expresses the energy balance of the transformation: the immobile mass located at a height *h* has become a moving mass impacting the ground with a speed *v*. The incoming energy 9.81*mh* (called "potential energy", which is the multiplication of the mass by the height and a "gravitational constant" approximately equal to 9.81) is equal to the outgoing energy (called "kinetic energy"): $\frac{1}{2} mv^2$.

It is very useful to have such an energy balance! Try to answer the following questions:

- If I double the mass *m*, will I increase the impact speed? *No*
- If I double the mass *m*, will I increase the kinetic energy? Yes*, it's doubled*
- If I double the drop height *h*, by how much will I increase the kinetic energy? *By 2*
- To double the speed *v*, by how much do I need to increase the height *h* from which I drop? *By 4*

This principle is the basis of hydroelectric energy, which is used in dams and hydroelectric power plants: water is retained at a high altitude by a dam, then dropped from a height *h* through penstocks, and the kinetic energy acquired is used to drive turbines. Alternators and other pieces of machinery will transform the turbines' rotation into electricity, i.e. a movement of electrons in a conducting circuit).

1.2 What's energy efficiency?

The energy efficiency of a machine, and more generally of a physical transformation, is the ratio between the usable energy and the incoming energy. In practice, as we have seen, there is always some energy dissipation, i.e. a more or less important part of the incoming energy is used for other purposes than the one for which the machine is designed, and the energy efficiency is therefore less than 1.

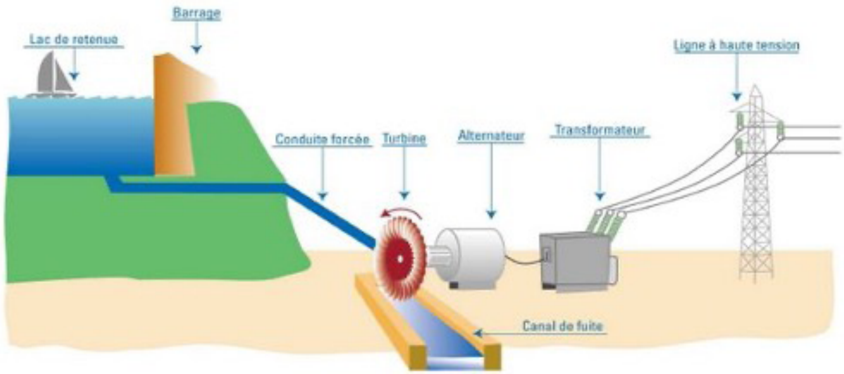
For a combustion engine, powering a car for instance, the energy efficiency is therefore obtained by dividing the usable energy propelling the car by the initial energy supplied by the combustion of the gasoline. The difference between the two comes from the heat absorbed by the radiator or rejected into the atmosphere with the exhaust gases. The energy efficiency is about 30-40% for modern machines. The higher it is, the less fuel the car consumes for a given distance.

In a thermal power plant, the initial heat source can be coal, gas or uranium, and the result appears as electrical energy, i.e. the process creates a global movement of electrons in a conducting metal. The overall energy efficiency is about 35-40%. The residual heat is rejected into the environment (atmosphere, waterways, sea). If one is ingenious enough, it can also be recovered in another network and used to heat homes, which increases the overall energy efficiency of the plant.

The most important of all physical transformations, the one that allows life on this planet, is photosynthesis: it stores the energy of solar rays (incoming energy) in chemical form, namely organic matter, which has been formed and stored in the plant. Its energy efficiency, i.e. the proportion of radiation that is actually stored, is very low: it is between 1 and 6% depending on the plant.

For readers who like physics and mathematics:

Generally, physicists distinguish several types of energy transfers: work and heat. Work corresponds to a displacement or a deformation.



If you lift your arm, you are performing work, and if the car is running, the combustion of the gasoline is performing work. Heat corresponds to a disordered agitation on a microscopic scale: if you heat water, you increase the speed of the molecules in the liquid, without any macroscopic change.

You can't produce work without producing heat. In a combustion engine, we start by burning gasoline, which increases the temperature in the cylinders, and by a very clever mechanical design, we convert this heat into work that propels the vehicle. But not all the energy goes into work: some of it is converted into heat, which increases the temperature of the tires and the engine, and even of the ambient air!

1.3 Energy efficiency and financial yield

The concept of "yield" is very commonly used, and for very different things. This can be confusing. In agriculture, for example, the term "crop yield" or "agricultural yield" is used to refer to the weight of food produced per hectare cultivated. It has increased significantly over the past fifty years: in France, it has gone from 3 tons per hectare in 1961 to 7.8 in 2015.[1]

This does not mean an increase in the energy efficiency of farms! During the past fifty years, there has been a considerable increase in energy input, in the form of mechanical work (farm machinery) and chemical fertilizers (nitrates): between 1948 and 1998, the total amount of mechanical work in agriculture has increased 44-fold,[2] while the quantity produced per surface was multiplied by 2 or 3. It is clear that the energy output (energy recovered in the form of food calories) does not increase in the same proportion as the energy input, i.e. the energy efficiency actually decreases.

However, from an economic point of view, the farmer is concerned neither with the energy efficiency nor the agricultural yield. He is interested in the "financial return". Specifically, if he sells his crop for P, and it has cost him C (to buy seeds, pay for wages, fertilizer and pesticides, machinery use, and fuel), his profit is P-C and the financial return (P-C)/C. If C is greater than P, the operation generates net losses, which is not sustainable. As soon as P is greater than C, he makes a profit. The higher P is compared to C (e.g. tomatoes are very expensive and inputs are cheap), the higher the financial return. If the prices of fuel and fertilizer are low enough, it will be financially optimal for the farmer to industrialize his production system, even though the energy efficiency will be deplorable.

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1 — https://ourworldindata.org/crop-yields

2 — Mathieu Calame, « Enraciner l'agriculture », PUF 2020, p.160

What is the overall energy efficiency of an agricultural production system? On the output side, we have the energy stored in the crop. On the input side, the energy provided by fertilizers and the energy used by agricultural machinery and human labor. But there is more! There is also the solar energy captured by the photosynthesis of the cultivated plants, and the energy provided by the natural processes that take place in the soil (e.g. networks of fungi and bacteria providing nutrients to the roots). These additional sources of energy captured by the plants are not accounted for but allow the farmer to recover more energy in the form of food than that which he has provided in the form of work and fertilizers. This is how mankind has survived since the early days of hunter-gatherers!

Summary

- The energy efficiency of a machine (and more generally of a physical transformation) is the ratio between the usable energy (in the case of a car: its motion) and the incoming energy (in the case of a heat engine: the energy released by combustion of the gasoline in the engine).
- The energy efficiency of a machine is always less than 1 because no energy transfer process can take place without some energy being "dispersed".
- Energy efficiency is neither the only factor, nor the main one, for deciding on production technologies.

1.4 What is power?

Let's go back to the analysis of an hydroelectric plant. The upper lake is a water reservoir. The water flow through the pipes is expressed in cubic meters per second, m^3/s. This flow of water will produce a flow of energy, the electrical energy delivered per second.

This is obviously an important quantity: we can have a large water reserve, but if the flow is low, we will not be able to put out a fire. Similarly, I can be very wealthy, but if I can only spend one euro per day, I will not be able to do much with my fortune. In physics, the flow of energy is called power. If we denote by P the power of a device, by E the energy it provides when it works for a period of time T, we have the relation $P = E/T$, or equivalently $E = P \times T$. In other words, the power is the quantity of energy available per unit of time.

Summary

- Power is the energy flow, i.e. the amount of energy provided per unit of time.

1.5 Units and orders of magnitude

The unit of energy is the *Joule* (J). A mass of 1kg falling from a height of 1 meter provides 9.8J (which is often rounded to 10J to facilitate calculations). With this convention, it takes 10J to lift a mass of 1kg from 1m. The unit of power is the *Watt* (W). A device that produces or consumes 1J per second has a power of 1W. These are the basic units for expressing quantities of energy and power, just as the meter or gram are the basic units for distance and weight.

The food that a human being consumes in one day, once digested, provides 10 to 12 million Joules. This energy transfer takes place during one day, that is 86,400 seconds. We can therefore say that the power of the digestive system is about 120W on average (we divide 11 million by 86,400). This energy serves three functions: to keep our body temperature at 37°C, i.e. to compensate for heat loss through our skin; to create new cells and replace our dead cells; and of course to activate our muscles (heart, breathing, exercise).

Let's go for a hike in the mountains. If you go up 300m and weigh 70kg, you will use 205,800J, or about 200,000J (you can calculate the potential energy using the formula above). If you do this in one hour, you will develop a power of 57W (3,600 seconds in 1 hour). If she trains, a sportswoman can increase her power during the effort and reach several hundred Watts. Is this a lot? How much can we do with our physical strength alone? To find out, let's put our athlete on a bike that converts mechanical energy into electrical energy. Well, with this hundred Watts delivered after a good hour of effort and sweat, she will be able to... barely toast a slice of bread![3]

Yes! One slice of bread only! And our sportswoman will probably be exhausted and hungry. By comparison, the combustion of one liter of gasoline alone transfers nearly 36 million joules. With an engine with a standard energy efficiency of 30%, that would be about 10 million joules of usable energy, i.e. 6 times more than what a human being can provide in a day of effort. And all this for 2€ without sweating... We start to understand that drawing from other sources of energy is essential for us to live comfortably and to carry out all the transformations that we depend on.

Given the orders of magnitude involved in daily life and a fortiori on a large scale, we most often express power in kiloWatts (kW, 1000 Watts), MegaWatts (MW, 1 million Watts), GigaWatts (GW, 1 billion Watts) or even TeraWatts (TW, 1000 billion Watts). Rather than in joules, we express energy in Watt x hours (Wh) and its multiples kWh, GWh, TWh. A Wh is the energy supplied by a power of 1W operating for one hour. Finally, when it comes to measuring large quantities of energy, we use the *ton of oil equivalent, or toe*, and its multiples ktoe, Mtoe, Gtoe. One toe is the energy obtained by burning one ton of oil, or 42 billion joules.

Here are other examples to get this major difference of energy and power between machines using fossil energy sources, and humans with only their muscular force:

Tractor	60 kW = 600 humans
Excavator	100 kW = 1,000 humans
Truck	400 kW = 4,000 humans

3 — Watch the video of Olympic medalist Robert Föstermann using all his energy to toast (barely) a slice of bread: https://www.youtube.com/watch?v=S4O5voOCqAQ

One should not infer that an excavator does the work of 1,000 workers: workers need to rest! The excavator can work 24 hours a day without getting tired: it does the work of 1000 teams of 2 or 3 people.

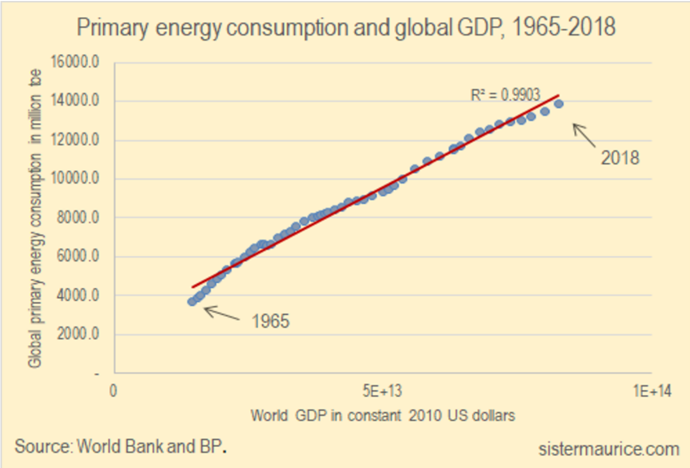
Humanity as a whole (7.8 billion inhabitants) consumes nearly 14 Gtoe today, which is an average of 1.8 toe per capita.[4] As there are about $3x10^7$ seconds in a year, this results in a power per capita of $1.8 \times 42 \times 10^9 / (3 \times 10^7) = 2500$ W. We have seen that the average human power from physical force is about 100 W. On average, each of us therefore has access to energy resources about 25 times greater than what a single human is capable of! For an inhabitant of a rich OECD country, this is 2.2 times more, i.e. "55 individuals", and even 4.5 times more for an American, i.e. "112 individuals". It is as if every European had 55 tireless energy "servants"[5] in the form of various machines that manufacture the goods and services he consumes every day, just to ensure the standards of living he enjoys.

It should come as no surprise to you that GDP is very closely related to primary energy consumption. For over sixty years, it has taken about 1.6 kWh to generate $1 of GDP.[6] This is something crucial to consider — yet it is almost never discussed in modern economics courses.

4 — This average hides a great disparity: 4 toe/capita for OECD countries, 8 toe/capita for an American, 0.5 toe/capita for an inhabitant of a poor country. As energy measures the capacity to transform matter to produce goods and services, these disparities in energy consumption are strongly correlated to inequalities in living standards.

5 — Jean-Marc Jancovici talks about energy "slaves", see: https://jancovici.com/en/energy-transition/energy-and-us/how-much-of-a-slave-master-am-i/

6 — Jacques Treiner, « Fil conducteur pour une introduction à l'Anthropocène en début d'études supérieures », Janvier 2020



World GDP and primary energy consumption since 1965

Summary

- Usual power quantities are expressed in W, kW or GW. Energy quantities are expressed in Joules, but more frequently in kWh or GWh.
- An individual can use his physical force to exert a power of about 100 W, i.e. a usable energy of 100 Wh if the effort lasts one hour.
- The combustion of one liter of gasoline alone transfers 10 kWh, a hundred times more than an individual's physical force during one hour.
- On average, a person in the OECD has 55 times more energy resources than his or her physical capacity alone

For readers who like physics and mathematics:

Let's go back to your mountain hike. If you climb 300 meters in one hour and your mass is 70 kg, how much energy do you use? According to the formula 9.8*mh*, your movement requires 9.8 x 70 x 300 = 205,800 J.

The duration of the hike in seconds is 3600s. The power of this exercise is therefore 205,800 / 3,600 = 57W. Eight hours of hiking at this pace requires 1,646,400 J, which is equivalent to about 0.5 kWh. If you work out, you may be able to reach 200 W and maintain it for eight hours, which will be 2 kWh.

In comparison, burning a single liter of gasoline releases about 10 kWh...

2 Primary sources of energy

There are a few exploitable sources of energy on Earth. Some of them correspond to simple physical processes: the energy of a mass at a height (for example a dam, which releases into pipes water, which will action turbines downstream in hydroelectric power plants) or the energy of a mass launched with a certain speed v which strikes something (this is the mechanism of mills where the moving fluid, water or wind, makes a wheel or a wing turn).

Radiation is also an exploitable source of energy, whether it is the visible radiation emitted by the sun which is used for photosynthesis, or the infrared radiation of the stove from which we warm ourselves during the winter. Living beings, humans or animals, once fed, can also be mobilized as sources of energy, and have been widely used. If we go back to find out where living beings get their own energy from, we ultimately come across photosynthesis, which stores the energy of solar radiation in chemical form.

The energy sources that can be exploited on Earth are called primary energy. Hydrogen, for example, the most abundant element in the universe, is not available in free state on our planet: it exists only bound with other elements in molecules like H2O. One can therefore not directly exploit it: it is not a primary energy. One can extract it, for example by cracking methane CH4, and then use it as a source of energy: it is then said to be a secondary energy (primary energy was needed to crack the methane). Electricity is in the same case: it is not available directly (unless some way could be found to harness lightning) but it can be produced by using primary energy.

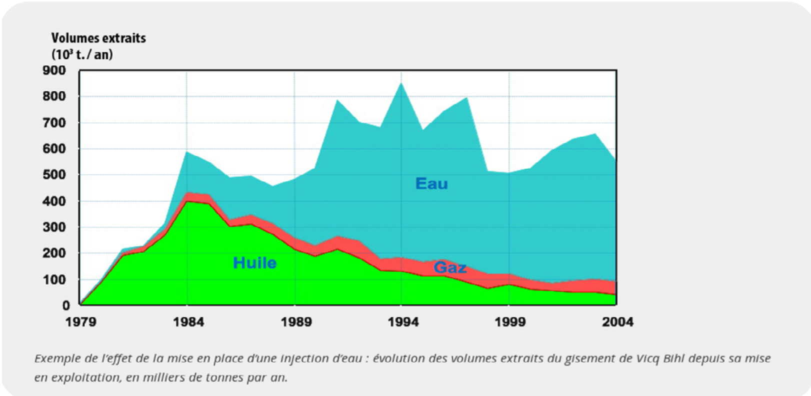
To know which energy sources to use, you can compare them according to three important characteristics:

- available in the form of flows or stocks;
- controllable or intermittent;
- concentrated or diluted.

2.1 Flows or stocks

Coal, oil, natural gas and uranium are *stocks* of energy: they are found in reserves (oil fields, coal or uranium mines) that have to be located, from which they have to be extracted from and which eventually will run out. They can be transported elsewhere, used whenever and however much is needed, as long as there is enough left. From an energy supply point of view, their limit is that they are not renewable (it took hundreds of millions of years to make coal or oil; as for uranium, it does not renew itself and it naturally disintegrates) so they will necessarily run out one day.

The pattern of exploitation of a deposit is always the same, whether it is of coal, oil, gas, or ore: after exploitation, production increases rapidly, then slowly declines until the deposit is abandoned. Rather than being totally depleted, the deposit will be abandoned because what is left in it becomes too difficult or expensive to extract. As an example, here is a typical oil well development scheme. At the beginning, the oil spurts out without any problem. Then, as the deposit gets depleted, water under pressure must be injected to bring out the remaining liquid. A mixture of oil, gas, and water comes out, and eventually the well is shut down when the amount of oil and gas to extract becomes too small to offset the operating costs.



The exploitation of an oil deposit

Source: https://jancovici.com/transition-energetique/petrole/a-quoi-doit-ressembler-lexploitation-dun-gisement-de-petrole/

On the contrary, wind, sea or river currents, or solar radiation are constantly renewed, and can potentially be used indefinitely: they are *flow* energies. The same is true of living beings, whether it be the plants or animals we eat or the wood we burn, provided we make sure that they are renewed. The advantage of flow energies is that they are renewable. But, as opposed to stock energies, they are not available anywhere and anytime: the wind blows where it wants, when it wants and how it wants.

2.2. Concentrated or diluted

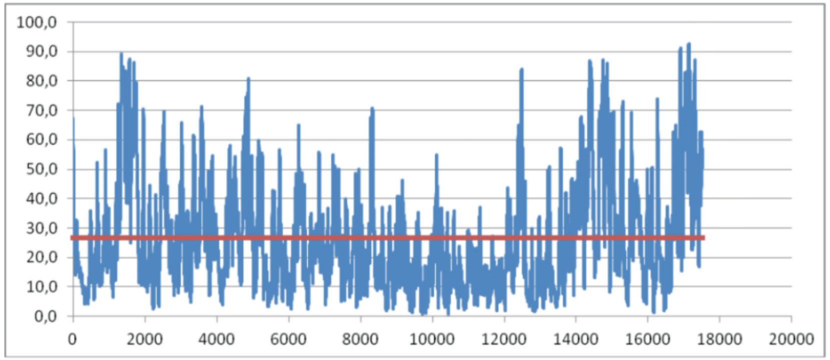
A stock energy is said to be *concentrated* if it can provide a lot of energy per unit of weight or volume. We have seen that oil is an extraordinarily concentrated source of energy: the combustion of one liter of gasoline provides about 10kWh. Anthracite, the highest quality coal, also provides 10kWh per kg, but the lowest quality coal, lignite, provides half that amount. This makes it economically not profitable to transport brown coal over long distances. Lignite-fired power plants are therefore usually located near the mine, or in the ports, close to ship deliveries.

A nuclear reactor provides a power of about 1GW continuously. To obtain the same power, you can either use 100 to 300 tons of fossil fuel per hour, or recover 1200 tons of water falling from a height of 100m per second, or install 1000 wind turbines of 5MW, or finally deploy 30km2 of solar panels. As you can see, to decide what source to use, it is important that you know its concentration, and therefore the weight or volume of the energy equipment you will need.

2.3 Controllable or intermittent

An energy source is *controllable* if it can be used at any time and its flow can be regulated. This is true for stock energies, but not for flow energies: the wind can blow anytime, and when the sky is cloudy, solar panels hardly deliver. If an energy source is not controllable, there are two possibilities: either we know when it will be available (e.g. tides, where we may install tidal power plants) or we do not know at all (e.g. wind power) or only partially (e.g. solar power: we know that there will be no sunlight at night). This is called *intermittency*.

As an example, here is a graph that gives the power supplied by the French wind network, every half-hour, during the year 2013, as a percentage of the installed power (i.e. the power that would be supplied if all the wind turbines were operating simultaneously at maximum power). We can see that at most, we draw 90% of the installed power (it is apparently never windy simultaneously everywhere). It also happens that we draw nothing (e.g. in the middle of summer, when there isn't any wind anywhere). All in all, we recover 26.7% of the installed power over the year, i.e. a little more than a quarter. It is still necessary to be able to store the excess electricity received during periods of high wind, which brings us to our next point.



Instantaneous power from all wind turbines in France over the year 2013
Interpretation: The graph shows the instantaneous wind power in France throughout 2013, every half-hour, renormalized to 100 GW. At the end of the year, i.e. during winter, we observe that the power can reach a maximum of more than 90% of 100 GW, i.e. 90 GW. The red horizontal line indicates the average power over the year, of 26.7 GW.

Source: Jacques Treiner, « Stockage de l'énergie, comment le dimensionner ? » Les Focus, Techniques de l'Ingénieur, mars 2017.

2.4 Storing flow energies

It is obviously very inconvenient not to have energy when and where it is needed. The challenge is therefore to try to store flow energy. For a long time,one has retained water with a dam in order to release it at the right moment, as in the example of the hydroelectric power station. This idea has been used by water and wind mills in the past, and it is used today to store the energy produced by wind turbines or photo-voltaic panels. Wind turbines and photovoltaic panels are designed to induce an electric current (some from the mechanical energy of the wind, others from solar radiation). Pumped-storage power plants use this electricity to lift water from a lower reservoir to an upper reservoir (the exact opposite movement of the fall in the turbines discussed earlier). Through misuse of language, we sometimes say that we "store electricity".

We can also store it in other ways: by using it to make hydrogen for fuel, to compress air to drive turbines, or to charge batteries that store energy in chemical form. But it is important to understand the limits of these techniques: all the energy contained in all the electrochemical batteries in the world is currently a few TWh, less than an average day of French consumption! We are far from being able to make up for the intermittency of production by storing it in batteries. In practice, hydroelectricity is not used to store.

Summary

- Some energy sources can be used directly from stocks, but these stocks are non-renewable (oil, coal, gas, uranium).
- On the contrary, other sources are indefinitely available on the human life scale (wind, solar radiation, tides) but they are intermittent, more or less controllable, and difficult to store.
- We have to draw on all these sources to meet our needs, and the difficulty of storing energy from renewable sources is an obstacle to their use.

3 Energy throughout the world

3.1 Energy sources

It is easy to list all primary energy sources on our planet. We can present them in chronological order:

- first, biomass, notably wood (used for heating), plants (used directly for food, and indirectly, by eating those who feed on them or by using them as draught animals);
- wind, used for some works (with mills), for propulsion (like sailboats), and more recently to produce electricity (wind turbines)
- running water, for some works (with mills), for transportation (as with barges, boats without sail), and more recently to produce electricity (dams, tidal plants)
- coal, mostly used nowadays in thermal power plants, to produce electricity, and for the manufacture of steel (coke)
- petroleum, everywhere in transportation (gasoline, diesel, kerosene) and heating (fuel oil)
- gas, used in thermal power plants to produce electricity and for heating
- uranium, used in nuclear power plants to produce electricity
- solar radiation, used directly (photovoltaic) and indirectly (by exploiting the outputs of photosynthesis).

All power plants are based on the same principle: something rotates an alternator, which sends out electricity. To rotate the alternator, we can use an engine (as in gas power plants) or a turbine (a kind of mill whose blades are pushed by a blast). The blast is obtained by heating a gas (air or water vapor) which expands (increases in volume) and drives the turbine. The necessary heat is obtained either by burning coal (coal-fired power plants) or by using the heat released by the controlled fission of a rare isotope of the uranium atom (^{235}U, representing only 0.7% of natural uranium stocks).

3.2 How much energy do we use?

On the next page is a figure that shows global energy consumption since 1820.[7]

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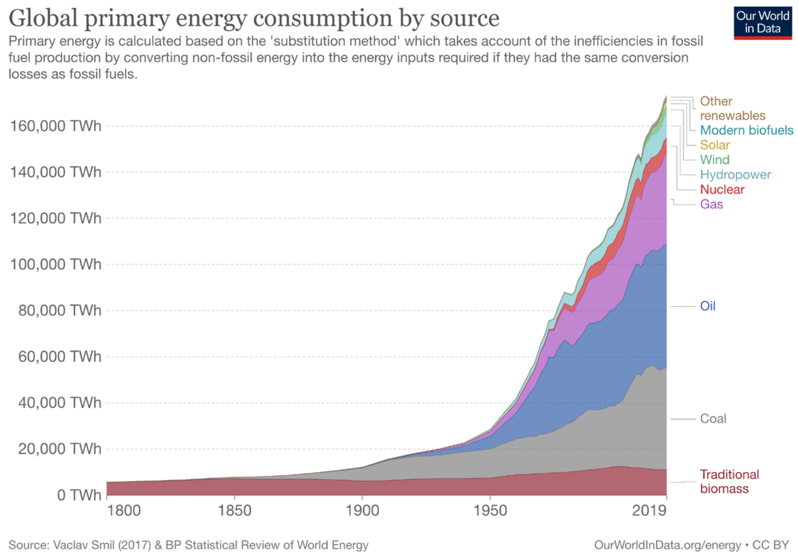
7 — Source : OWID https://ourworldindata.org/energy-production-consumption



Global yearly energy consumption from 1820 to 2010

Try responding to these questions:

- What lies on the horizontal axis? the vertical ? What units are used?
- What is the general pattern of the curves?
- By how much was global energy consumption multiplied between 1820 and 1950? And between 1950 and 2000?

Then, take a look at the different sources of energy:

- In 1820, what was the main energy source? And in2000?
- Take any source you want: what does its consumption over time look like? Is the same true for other sources?
- When a new source appears and starts getting used, do older sources get less used?

The figure shows the time axis on the x-axis and the annual energy consumption in TeraWatt-hours (TWh, 10^9 kWh, or 862,000 toe) on the y-axis. We note an explosion of total consumption after 1950: it is first multiplied by 4 between 1820 and 1950 then... by 5 in 50 years between 1950 and 2000! In 2019, world consumption was 171,240 TWh, or almost 15 billion tons of oil equivalent, 40 million toe per day!

Something crucial to note here: 80% of the energy used in the world today comes from the combustion of fossil fuels, coal, oil and gas. In 1950 the proportion was 70%. It has only increased since then.

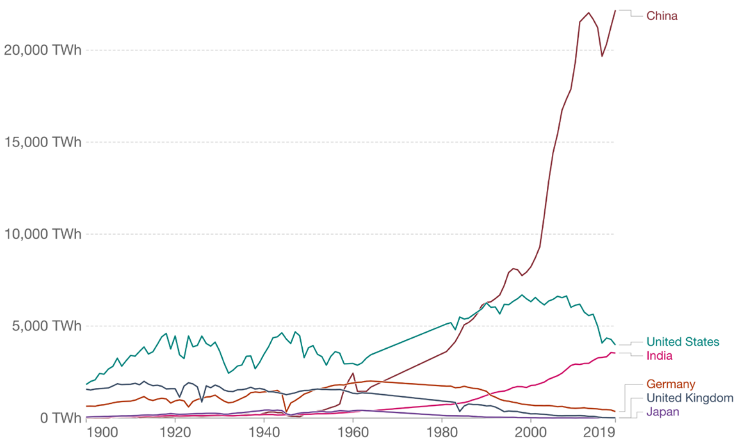
This is because new energy sources do not replace old ones! They pile up, and each layer thickens with time. In other words, there has never been an "energy transition": there were technology transitions, as when emails replaced fax or computers replaced typewriters, but no energy transitions. Coal dates back to the first industrial revolution, and it is not surprising that its use increased until the early days of oil in the 1930s. But when oil consumption exploded, coal consumption continued to grow at a good pace, even accelerating over the last 10 years. It has found different uses: no longer to fuel stoves in houses or boilers in ships, but to produce electricity.

3.3 Where are these sources?

Primary energy sources are very unevenly distributed around the world. Moreover, there is a problem of renewal: as known deposits are depleted, others must be discovered (until no more is left) and then exploited. World geopolitics cannot be understood without taking into account these disparities, the desire of developed countries to preserve their supply, and of developing countries to get access to it.

See below the production of coal, oil and gas by region since 1900. These graphs are all taken from *Our World in Data* (OWID) https://ourworldindata.org/fossil-fuels. There are many more, they are interactive and come with maps: go take a look!

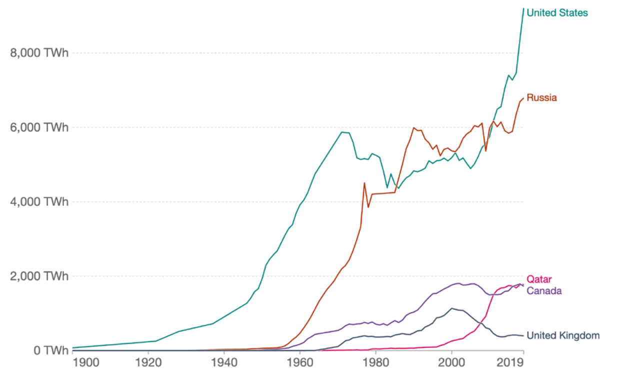
Coal production



Source: BP Statistical Review of World Energy; and Shift Data Portal

OurWorldInData.org/fossil-fuels/ • CC BY

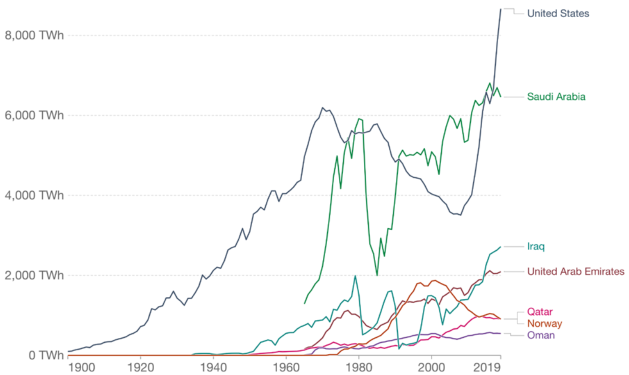
Gas production



Source: BP Statistical Review of World Energy; the SHIFT Project

OurWorldInData.org/fossil-fuels/ • CC BY

Oil production



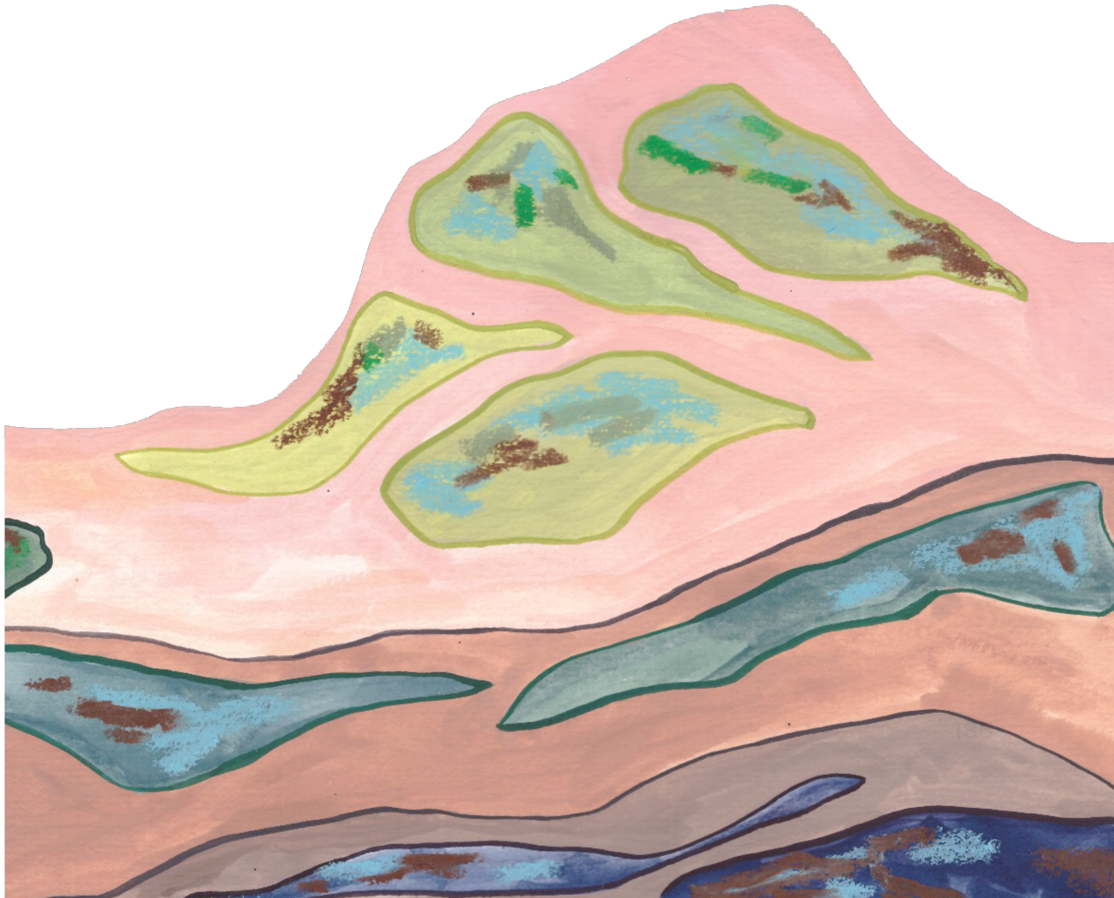
Source: BP Statistical Review of World Energy; the Shift Project

OurWorldInData.org/fossil-fuels/ • CC BY

Conclusion

One cannot produce energy, although this is what we often say and hear, by misuse or convenience of language: energy is taken from sources. There are several sources of energy on our planet, with very different characteristics. Wind, water and the sun are flow energies, while fossil fuels and uranium are stock energies.

Because these stock energy sources have an immense potential and very interesting use characteristics, world energy consumption has multiplied by more than 6 since 1950 and today and 80% of world energy consumption now comes from the combustion of fossil fuels, coal, oil and gas. Reducing their use will therefore not be easy. Especially since historically, when a new source of energy has been found, it has been added to the others and has not replaced them. There has never been an energy transition.



8

From Fossil Fuels to Energy Transition

Part II —
Acting on GHG emissions

Introduction

In the previous chapter, we opened the hood of the car. We also identified the main characteristics of the engine: energy, power, efficiency. Now it's time to think about how we can reduce its emissions.

In this chapter, we'll take stock of GHG emissions and look at possible ways to reduce them. You will see that there are many options: we can change the way we produce, and we can change the way we consume. The challenge is to choose the right mix

Of course, each of the possible options (nuclear power for instance, or, agricultural transition) is a topic of its own, and we cannot do them justice in the scope of a chapter. Our aim is rather to give you an overview of the various options, so that you can get an idea of their advantages and their limits, and make up your own mind.

This is a particularly long chapter, so feel free to read it in two parts, for example by taking a break after the section on energy transition.

A few questions to warm up

- Households in France eat less fruit and vegetables than the WHO recommends, and surveys show that they find the prices too high. Will reducing these prices (e.g. through subsidies) definitely increase the consumption of fruits and vegetables?

Perhaps not: it may just free up some budget to buy other foods, like meat for example.

- To meet the goals of the Paris Agreement (keeping the increase in average temperatures below 2°C by 2100), accumulated human-induced CO_2 emissions since 1850 would need to be less than 2,900 billion tons of carbon. We were at 2,260 in 2020, and emissions that year were 40 Gt.[1] If they stabilize at this level, in what year will this budget be exhausted?

In 2036.

- Annual CO_2 emissions were 11 Gt in 1950 and 40 Gt in 2020. If they continue to increase at this rate, in what year will this budget be exhausted?

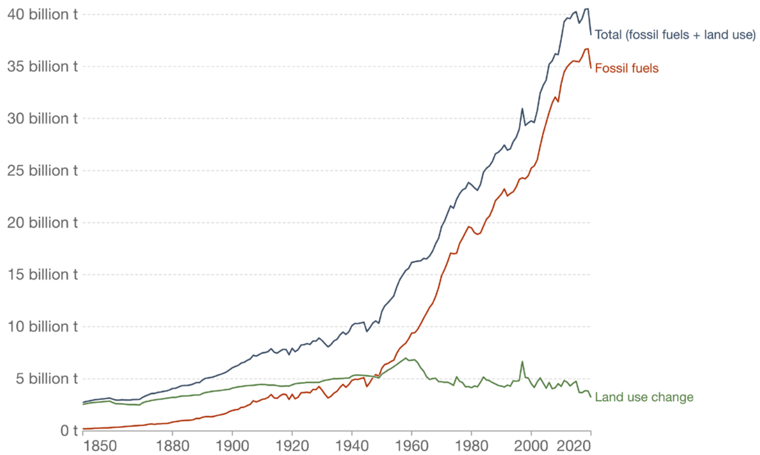
That's 1.9% per year, and the budget will be exhausted two years earlier, in 2034.

1 — Source: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

1 Carbon budget

1.1. Emissions over time

Let's go back to the history of man-made CO_2 emissions. As far as CO_2 is concerned, we must distinguish between emissions due to the combustion of fossil fuels and emissions due to land use, i.e. agriculture (livestock, fertilizers, soil degradation) and deforestation. The latter are designated by the acronym AFOLU (Agriculture, FOrestry and Land Use). They are shown in the following graph, where you will see that today, annual global CO_2 emissions are about 40 Gigatonnes (Gt), of which 35 are directly attributable to fossil fuels.



Global emissions of CO_2 from fossil fuels combustion or land use
Source: OWID

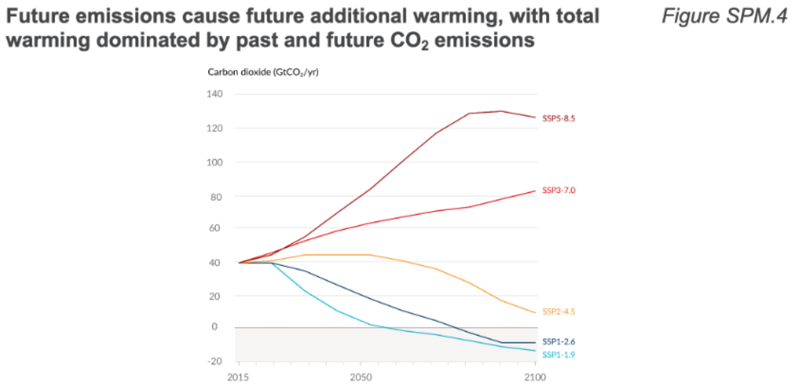
Methane CH_4 and nitrous oxide NO_2 as well as several other gases contribute to greenhouse effect and they have very different life cycles (as discussed in chapter 4). In 2016, they represented 10Gt of CO2 equivalent, which were to be added to the 40Gt of CO_2 emissions from human activities.

Nonetheless, most of the emissions, 35Gt out of 40 for CO_2, or 50 if we take into account all GHGs, are due to fossil fuels: coal, oil and gas. Unfortunately, we saw in the previous chapter that these same fuels provide 80% of the energy used in the world! This means we cannot reduce emissions without weaning the economy out of fossil fuels.

1.2 Future scenarios

The 2015 Paris Agreement sets the goal of keeping global warming "well below 2°C compared to pre-industrial levels and to act to limit the rise in temperature to 1.5°C."

Is that feasible? Since we started writing the first chapters of this course, largely based on the 2014 IPCC report, the first section of the 2022 report was released, with updated projections:



5 scenarios in the 6th IPCC report
Interpretation: The IPCC model includes 5 scenarios, starting in 2015, whose index, from 1.9 to 8.5, corresponds to the radiative forcing reached in 2100. See the IPCC website https://www.ipcc.ch/report/ar6/wg1/ for other forecasts associated with these scenarios, especially in terms of temperature increases.

The scenario at the top of the figure represents Business as Usual, where CO_2 emissions continue to grow as they have so far, reaching 130Gt annually by the end of the century! This would lead to a temperature increase well above 4°C.

The two lower scenarios meet the objectives of the Paris Agreement. Note that they cap emissions around 2025. In the second half of the century emissions become negative, i.e. carbon is removed from the atmosphere (using capture techniques that do not yet exist, at least not on an industrial scale).

1.3. Deciding on a climate strategy

A simplistic but useful way to remember the constraints is to think in terms of a "carbon budget". In order to have two chances out of three to meet the objectives of the Paris Agreement, i.e. to keep the increase in average temperatures below 2°C, we would need to have less than 2,900 billion tons of carbon emissions from human activities accumulated since 1870. We were at 2,260 in 2020, which means that we have a global carbon budget of 640 billion tons to last until 2100. If we continue at the current rate of 40 per year, this budget will be exhausted in 2036. If we continue to accelerate, it will be exhausted sooner.

The amount of carbon in fossil fuel reserves that are still available underground is much higher than the allowed budget. If we want to meet the 2°C target, we will have to leave two thirds of the fossil carbon in the ground! This means that we cannot rely on nature to restrain us. The challenge is therefore to voluntarily adopt a new strategy that reduces emissions and puts us on the right climate trajectory.

Given the trends, you may think that this is unrealistic. You may wonder why the IPCC is seriously considering 2°C scenarios, and why governments continue to assert this objective when the "business as usual" scenario is so far from it. As we just mentioned, this is because the IPCC includes in its scenarios negative emissions, that is, industrial processes which will extract CO_2 from the atmosphere and store the carbon on land or underground.

A growing number of research programs look at these options, but for now, neither the "technical" nor the "biological" solutions are well advanced. Capturing carbon is expensive, storing it is difficult, there is not much room left for planting forests, and existing forests are already difficult to preserve. Rather than discussing these solutions, that address the problem downstream, we will therefore focus in this chapter on upstream solutions. Where do the emissions come from? Is it possible to reduce them or even eliminate them entirely?

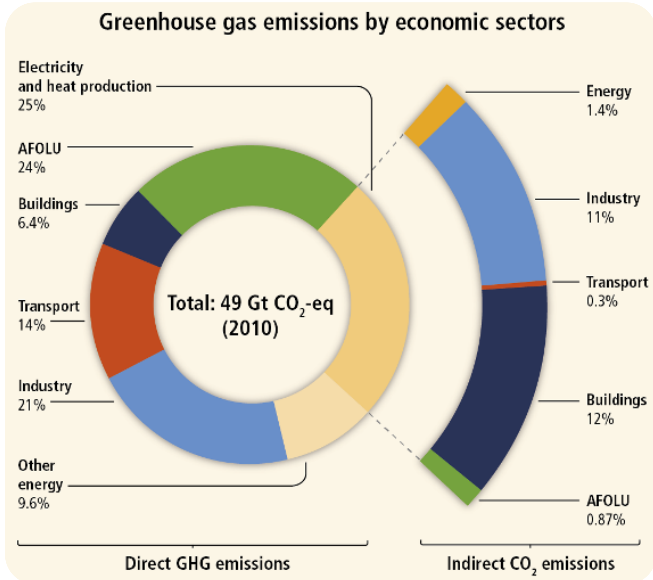
Summary

- If CO_2 emissions are stabilized at current levels, the carbon budget to respect the Paris Agreements will be exhausted in 2036.
- The depletion of fossil fuel reserves will not be sufficient to keep global warming below 2°C in 2100.
- The IPCC's optimistic scenarios are based on carbon capture techniques that are not operational at large scale today.

2 Where we stand: emissions by sector

2.1 Distribution by sector

Here is the breakdown of GHG emissions by sector of activity, from the 2014 IPCC report. All GHGs are included, but the sum is in CO_2 equivalent.



Which sectors emit the most?

- **AFOLU** (24%), i.e., as we have seen, land use: this is not only direct emissions, due to agriculture and livestock, but also the destruction of carbon sinks, through deforestation and degradation of agricultural land that releases carbon.

- **Electricity and heating** (25%). Heating and cooling are listed in one or the other of the two sides of the graph, depending on whether or not they are electric. As we saw in the previous chapter, electricity always comes from an upstream process such as coal combustion or the capture of solar radiation by photovoltaic panels. This explains why it is counted as "indirect" GHG emissions. In the different uses of electricity, we can see that at least 10% of GHG emissions come from heating or cooling, hence the importance of insulating buildings.

We also see a somewhat puzzling sector that is responsible for 10% of emissions: "other energy". On second look, it is actually called "energy production, excluding electricity". These are the many industrial processes which transform primary energy sources into usable energy. It is not petroleum that we put in our engines: it is gasoline, diesel, fuel oil or kerosene.

Between the energy source (primary energy) and the energy available to the user (usable energy), there is an industry, which is itself very important and highly emissive. In modern economies, it represents about 7% of GDP.

Between oil and the pump, there is the oil industry, which is in charge of exploration, extraction, transportation (by oil tanker or pipeline), refining and distribution.

Between coal and the thermal power plant, there is the extraction in the mine (the time of the galleries where the miners crawled is over, today there are huge open-air mines), and transportation by train.

Between gas and heating systems, there is transportation by gas pipelines where the gas circulates under pressure or by LNG carrier ships which carry the gas in liquefied form. This means that one must have plants which pressurize and depressurize the gas (pipe lines) or liquefy and evaporate the gas (ships).

To get a concrete idea of the power of these industries, and of the size of their installations, you should take a look at the pictures of Edward Burtynski[2] (see the "Oil" section). You can also have a look at the "Mines", "Quarries" and "Tailings" sections (tailings are the artificial lakes that contain the chemical residues that were used to extract the metal from the ore). These pictures also give an idea of the impact of these industries on their local environment.

What about hydrogen as a non-electric energy? Hydrogen can be used as a fuel and it is often considered as "green fuel" (when burning, it produces water vapor and not CO_2). Yet, unfortunately it does not exist in a free state on the planet Earth. In other words, it is not a primary source of energy. It has to be produced from something else, and today it is mainly from methane CH_4. By combining one molecule of methane CH_4 and two molecules of water H_2O, we obtain four molecules of hydrogen H_2... and one molecule of carbon dioxide CO_2! If hydrogen is produced by cracking methane, as it is, it cannot be considered a “green” fuel, because the end-to-end process emits CO_2.

2 — See: https://www.edwardburtynsky.com/projects/photographs

Summary

- GHG emissions, expressed in CO_2 equivalent, can be grouped by emission sectors.
- The first two emission sectors are electricity and heat production, and land use.
- The production (extraction, transformation, transport) of secondary energy, excluding electricity, from primary energies alone accounts for 10% of total emissions.

3 How do we reduce GHG emissions?

We have now reached the central question: is it possible to reduce our GHG emissions? Where should we focus our efforts? We can break it down into five sub-questions:

1. Is it possible to replace fossil fuels with other energy sources? This is the question of the **energy transition**.

2. Is it possible to make better use of fossil fuels? This is the question of improving **energy efficiency**.

3. Is it possible to reduce GHG emissions from sources other than fossil fuel use? This is essentially about AFOLU, so it is the issue of deforestation and **agricultural transition**.

4. Is it possible to better use energy? This would mean producing for alternative uses, instead of producing differently for the same uses. This is the question of the **"green" economy**, of consuming less or better.

5. Is it possible to capture carbon when it is emitted, or to have **negative emissions**, i.e. to extract and sequester carbon from the atmosphere? There is a lot of research on this topic, and the IPCC scenarios do rely on it, but we won't say anything about it here because these techniques are still at a very early stage of development.

4 The energy transition

4.1. Alternative sources of energy

This is about replacing fossil fuels with other energy sources that do not emit GHGs or emit less. Let's now take a look at energies that could be alternatives to fossil fuels and discuss their limits[3]

- biomass
- wind
- running water
- solar radiation
- uranium.

Let's start with the **nuclear industry**. It provides about 10% of the world's electricity production, but 75% in France.[4] It is an extractive industry, like the coal, oil or gas industry, and it relies on the exploitation of a finite resource: a rare isotope[5] of uranium, called U 235. Its depletion is expected in the next 50 to 100 years. There are technical solutions that make it possible to use the most common isotope, U 238, which represents 99% of terrestrial uranium, in"breeder reactors" that have been built in France (Superphénix) and in other countries (Russia, China) but these projects have not proved to be very successful so far.

The advantage of nuclear energy is that nuclear plants do not emit CO_2 during operation. But on the other hand, it entails considerable risks, particularly related to the possible consequences of an accident and the storage of radioactive waste. These risks can be reduced by appropriate safety measures, but the more they are reduced, the more it increases the production costs. The whole debate on nuclear power revolves around the question of whether there is an acceptable level of risk, and whether nuclear power is profitable at that level. For example, Germany decided in 2011 to close all its nuclear power plants by 2022. In 2022, only six remain in operation. At the same time, France will commission a new generation EPR-type reactor in 2024. The debate is therefore still open and active.

Let's turn to **biomass**. It continues to be used in the form of wood, which is used for heating and cooking in many places in the world. More recently, biofuels have entered the market. Whether you burn ethanol or gasoline, you emit about the same amount of GHGs. So how can one claim that replacing gasoline with ethanol would reduce emissions? The answer is not obvious and seems questionable. The argument is that the ethanol is produced from sugar cane, oil palm or corn, i.e. plants that have first removed carbon from the air while doing photosynthesis. If they are not harvested, their decay would return the carbon to the atmosphere anyway, and if they are harvested for human or animal consumption, the carbon would also return to the atmosphere, as living bodies do not store carbon permanently. Thus, using plants as fuel takes advantage of the natural plant carbon cycle.

The problem is that biofuels substitute for other uses of plants, such as food, unless additional land is cultivated, i.e. deforested. In fact, the advent of biofuels at the beginning of the century had a considerable

3 — See Jean-Marc Jancovici's website https://jancovici.com/category/transition-energetique/ for an in-depth analysis.

4 — The other European countries that use the most nuclear power in their electricity mix are Slovakia (54% of the mix), Belgium (52%), Hungary (51%) and Sweden (40%). The average among European countries is 26%. Source: https://www.forumnucleaire.be/theme/dans-le-monde/lunion-europeenne

5 — An isotope is a "version" of an atom. Atoms are all made up of three types of elementary particles: positrons and neutrons in the nucleus, and electrons that "gravitate" around it. The hydrogen atom is the atom that has exactly 1 electron and 1 proton. Oxygen has 8 protons, 8 neutrons and 8 electrons. But there are also other, rarer "versions" of oxygen that have 9 or even 10 neutrons. These different versions are called "isotopes" of oxygen.

impact on the prices of soybeans, corn and sugar, pushing them up by 10 to 20%.[6]

Hydraulic energy has been known and used for a long time. In the Middle Ages, all rivers were equipped with mills. More recently, dams have been built to produce electricity. Today, 12.5% of the electricity produced in France is of hydraulic origin. As discussed in the previous chapter, dams are used to store electricity: when there is too much electricity generated, pumps are activated to draw water from below and bring it up to the dam. That being said, many sites are already equipped in most countries. Moreover, the installation of dams creates problems of water management downstream, particularly for agriculture. These tensions are on the increase because of the effects of climate change.

4.2 The challenges of wind and solar energy

Hope therefore rests heavily on **wind and solar power**. These energies derive from an inexhaustible flow: wind in one case and solar radiation in the other, as opposed to coal, oil, gas and uranium, which derive from finite stocks, produced over hundreds of millions of years which will be exhausted some day. A flow energy has the advantage of being illimited, but is it available where we want it and when we want it? And can we regulate its power?

Wind and solar energy are used to produce electricity. These sources of energy are:

- intermittent: they are not available all the time. Solar energy is of course unavailable at night so we know for sure that it will work half the time, at best.

- not controllable: we don't know when they will be available.

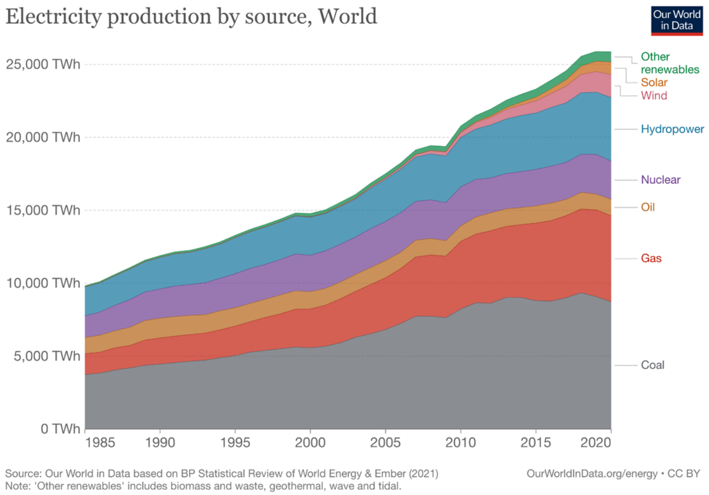
- not adjustable: when they deliver some electricity, there can be too much of it or not enough.

Integrating them into the electrical grid creates problems that greatly restrict their efficiency. As intermittent and non-pilotable energies, it is perfectly conceivable that they could fail together at the worst possible moment. What do we do if, for example, there is no wind in Europe on Christmas Eve?

We know of only two solutions for now: either keeping thermal or nuclear power plants in operation to supplement the electricity supplied by wind or solar power when there is not enough, or storing the electricity produced when there is too much of it. There are therefore two technological challenges: improving renewable electricity production methods on the one hand, and storage capacities on the other.

The technology of wind turbines and photovoltaics has made rapid progress, and the electricity produced is becoming less expensive. The following graph shows the growth of renewables in electricity production. Wind and solar now account for 10% of global electricity production, whereas they made their first appearance around 2005. Nuclear power went down from 15% to 10% during the same period. Finally, note that the most important renewable energy, by far, remains hydroelectric, which, today as in 2005, represents 16% of global production.

6 — Source : https://www.federalreserve.gov/pubs/ifdp/2009/967/ifdp967.htm

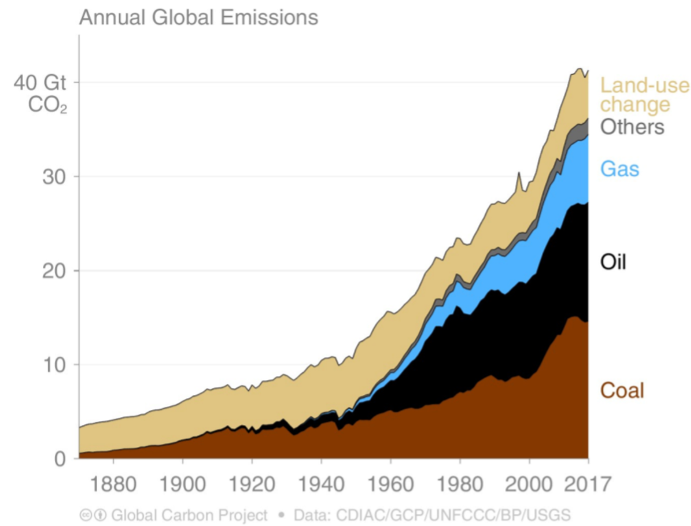


4.3 Replacing or adding?

Even if all the technical problems related to the use of renewable energies were to be solved, there would be one last major issue, which is partly an economic and political question: would renewable energies replace fossil energies, or would they just complement them?

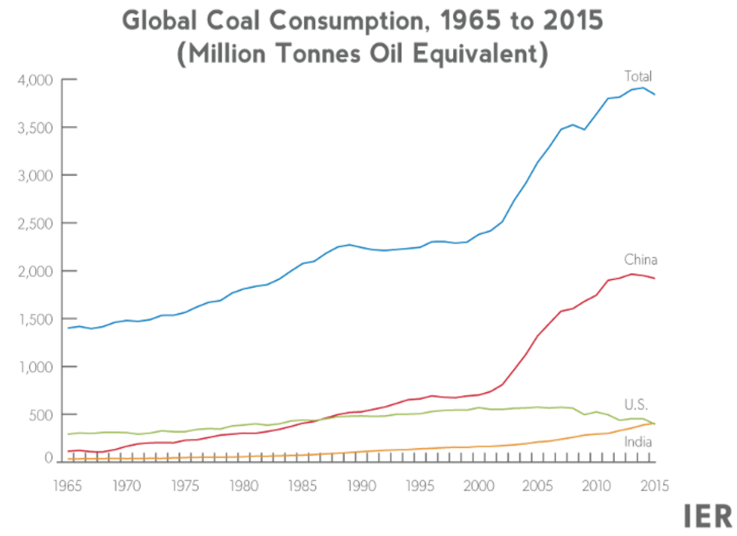
The underlying idea, of course, is that they would replace them, and that GHG emissions would be reduced accordingly. But this is definitely not something we can take for granted! Throughout history, every time a new energy source has been discovered and exploited, the old ones have expanded along the new ones. This is an example of Jevons' paradox that we will see later: new energy sources create new energy needs!

To illustrate this, let's go back to a graph we have already seen: GHG emissions in the world since 1850, broken down by source.



Forget about history and warming, and look at this graph: what period would you call the golden age of coal? That is, during which decades were there more GHGs emitted from coal? What about oil and natural gas? The three answers are the same: 2000-2017!

We can see that oil does not replace coal, and that gas does not replace oil. On the contrary, we could say that coal (used mainly for electricity production) is the fuel of the future! Its consumption has more than doubled in the last fifty years, as confirmed by this other graph from IER, the Institute for Energy Research.



We can see that while coal is in moderate decline in the United States, it is far from being so on a global scale, where it is fuelling the rise of Chinese and Indian industries. Although our European representations associate it naturally with the first industrial revolution, coal is a very modern energy!

The technological challenge is not so much to produce electricity from renewable sources as to draw less from old sources. The goal is not to produce more electricity, but to burn less fossil fuel, and renewable electricity must replace fossil fuels wherever they are used.

Summary

- Most of the energy used in the world still comes from fossil fuels.
- Several energy sources are less emissive alternatives to fossil fuels, but they all have limitations.
- Nuclear power raises problems of radioactive waste management, sustainable uranium mining and large-scale accidents.
- Hydropower is an important source, but it is difficult to build new dams and it interferes with other water uses.
- Biofuels have a questionable carbon impact and increase food prices.
- Wind and solar are intermittent, they can't be controlled, and we don't yet have scalable storage solutions.
- It is not enough to produce more electricity from renewable sources, we need to decrease the use of fossil fuels.

5 Improving energy efficiency

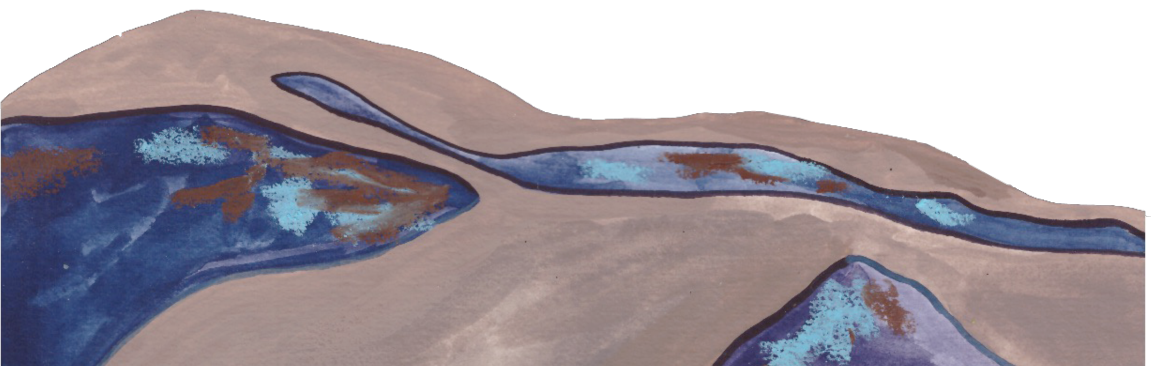
5.1 Is it such a good idea?

We must reduce the use of fossil fuels? Let's improve engine efficiency! It's a solution that seems obvious. A car which travels 30 miles per gallon consumes less than a car which travels 20 miles per gallon. If we could, with a wave of a magic wand, replace all the current cars by less fuel-consuming cars without changing anything in the way they are used, we would reduce the emissions of the transportation sector.

Unfortunately, in practice this is not true because other effects come into play. From the user's point of view, a fuel-efficient car is also a cheaper car to use. If the price of fuel is $4 per gallon, a car which travels 20 miles per gallon costs 20 cents per mile, while a car which travels 30 miles per gallon costs only 13 cents. The owner will therefore be encouraged to use her car more frequently, and she will probably do so with a clear conscience, since she has a "clean" car.

Moreover, improvements in fuel efficiency often go hand in hand with improvements in the manufacture of cars: the purchase price falls, and we have cars that are cheaper to use and less expensive to buy, therefore winning over a wider range of customers.

In the end, we have more drivers driving their cars more often, and overall consumption increases.



5.2 Rebound effect

This is called the rebound effect (also known as the take-back effect), and historically it is well documented. The first steam engines consumed so much coal that they could only be installed in coal mines. How many were there? A few dozen or a few hundred, and they were used exclusively to pump out water. Decades later, steam engines were powering the entire British textile industry, locomotives were running in the thousands, and steamships were crossing the oceans. Efficiency improved, each machine consumed much less, but overall coal consumption exploded.

Locomotives ran on railroads and had to carry along their coal in a special wagon, but the discovery of petroleum made automobiles possible. This is now a huge industry. It is estimated that there are 1.5 billion vehicles in the world, 19% of which are in the US.[7] In France alone, in 2020, there were 38.2 million private cars in circulation. On a global scale, private cars alone consume a quarter of all oil produced. And improvements in energy efficiency do not always lead to a reduction in consumption, as shown by the success of SUVs: larger and heavier than ordinary cars, they ultimately consume more.[8]

Let's take another example. One of the consequences of the industrial revolution was the lighting revolution. Before 1800, there was no public lighting: whoever ventured into the streets of Paris or London at night did so at his own risk, carrying his torch with him (or escorted by manservants). At the turn of the century, gas was distilled from coal, and used for lighting: street lamps were installed in the cities, with lamplighters passing by every morning and evening. Brussels, in 1833, was the first large city to inaugurate this system. Afterwards, of course,

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7 — Source: https://hedgescompany.com/blog/2021/06/how-many-cars-are-there-in-the-world/

8 — Source: https://www.iea.org/commentaries/growing-preference-for-suvs-challenges-emissions-reductions-in-passenger-car-market there was electricity, the incandescent bulb, then neon lights and today's LEDs. Energy efficiency exploded, and consequently, prices fell dramatically. Between 1800 and 2000, the price of one unit of light (one lumen) was divided by 3000, but the consumption was multiplied by 40 000.

A lamplighter in Paris, 1905

Source: https://i.pinimg.com/originals/fd/58/62/fd58622d88978addbc-fa6fb83508a8eb.jpg

The fact that improved efficiency, and technical progress in general, increases energy consumption rather than decreases it, is also known as Jevons' paradox, named after a British economist, William Jevons (1836-1882), who first demonstrated it in a seminal book, *The coal question*, published in 1865, right in the middle of the industrial revolution.

Summary

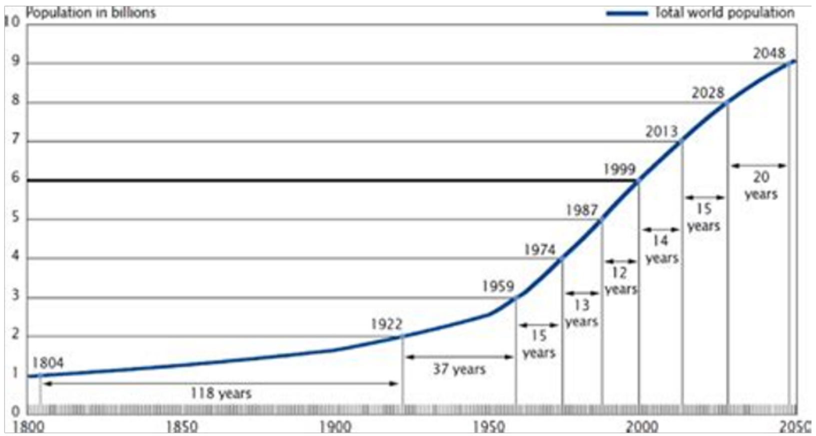
- Improving the energy efficiency of a machine does not guarantee that the global energy consumption related to the use of this machine will decrease.
- In practice, two rebound effects are frequently observed: better efficiency encourages greater use by existing users and attracts more users.

6 Land use

6.1 Meeting exponentially growing food needs

In 1800, the world's population reached one billion people. It took tens of thousands of years to reach this figure. But from then on, the evolution accelerated: the second billion was reached 120 years later, and in 2020 we were 7.8 billion on this planet. As demographic trends tend to be long-term and slow-moving (birth and death rates vary very slowly), we can extrapolate and assert that, barring a major catastrophe, we will be 9 billion by the middle of the century.

The industrial revolution is undoubtedly the cause of this population explosion, thanks to the progress of medicine of course, but also to the improvement of living conditions (access to running water, public hygiene). But how did the food supply meet this growth?



6.2 The industrialization of agriculture

The answer is twofold: on the one hand, there is the expansion of agricultural land, and on the other, the industrialization of agriculture. The prairies of North America and Australia were transformed into grain fields as settlement spread inland. This process reached its limits around 1900, and industrialization took over. The First World War gave a boost to the mechanical industry (production of trucks and tanks) and to the chemical industry (production of explosives and combat gas). Mechanical work in the fields was henceforth carried out by agricultural machines, organic fertilizers provided by livestock were replaced by industrial fertilizers, predatory insects and parasitic fungi were exterminated by pesticides. This was the birth of the agri-food industry, an economic and technical system which supplies farmers with machines, seeds, fertilizers, pesticides, and which buys their production to sell it on international markets.

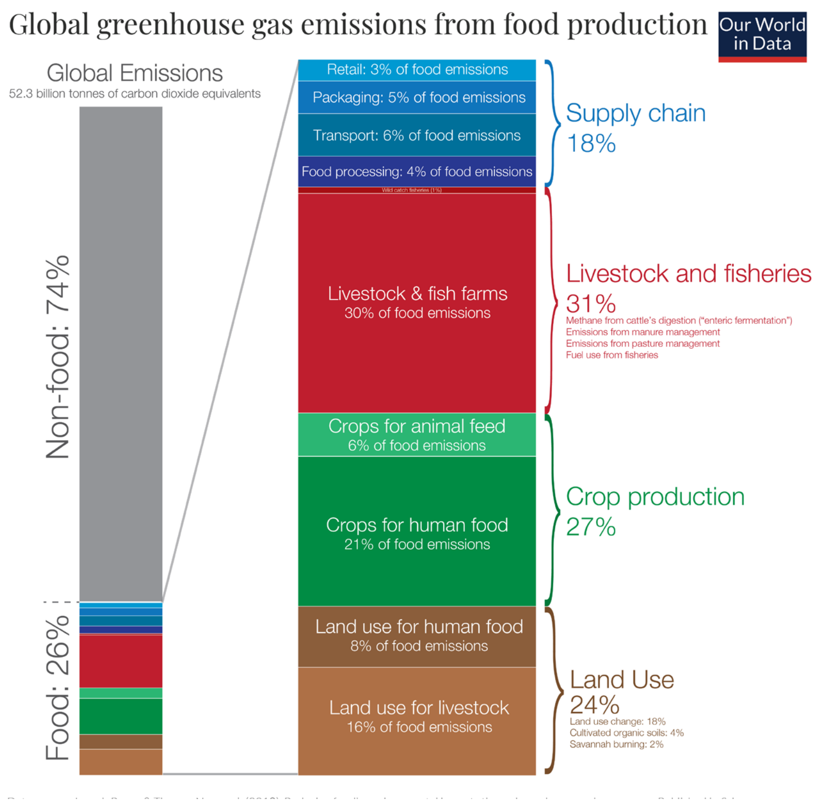
This evolution of agriculture generates considerable problems today: depletion and artificialization of soils, loss of natural biodiversity and introduction of genetically modified organisms with risky impacts, destruction of natural cycles (e.g. commercialized seeds are sterile, industrial fertilizers interfere with the phosphorus and nitrogen cycles, etc.), chemical pollution and hormone disruptors (pesticides)...

We will focus here only on its consequences for global warming: why is the agricultural sector such a large emitter of GHG? How come agriculture emits GHG?

6.3 GHG emissions from agriculture

The figure[9] shows that agriculture is responsible for 26% of GHG emissions:

9 — Source: OWID https://ourworldindata.org/environmental-impacts-of-food#environmental-impacts-of-food-and-agriculture



There are of course direct CO_2 emissions, linked to industrialization: use of machinery, fertilizers and pesticides (which must be manufactured), transportation of crops to places of consumption (often thousands of kilometers away), and processing food.

But the main culprit is livestock farming. Ruminants, including cattle and sheep, emit methane. This is due to their physiology: they do not directly digest the grass they graze. Instead, it is decomposed by specialized bacteria, and the process emits methane. Agriculture is responsible for 40% of methane emissions in the world,[10] and this is only increasing as the demand for meat increases. We have seen that methane is 25 times more powerful than CO_2, although less persistent.

To this we must add indirect emissions. In order to feed 8 billion people, soon to become 9 billion, we are deforesting. The Amazon forest, which is a gigantic carbon sink, is disappearing to make way for soybean plantations. Existing arable land is disappearing to make way for urbanization. Besides, the remaining arable land is gradually being depleted by mainstream agricultural practices, thus becoming less and less fertile.[11] Finally, as vegetation disappears or becomes depleted, soils stop absorbing CO_2 and release it.

Let's conclude with a balance sheet. 38% of the Earth's surface is devoted to agriculture, two thirds of which is used for livestock grazing and one third for cultivation.[12] As this expands, the surface devoted to perennial vegetation and forests decreases, releasing age-old carbon contained in the soil and in the plants. The agricultural sector accounts for more than a quarter of GHG emissions due to human activities, and livestock alone accounts for a third of it, which is equivalent to 8% of global emissions. You may also remember that the emissions due to livestock farming are in the form of methane, which disappears from the atmosphere within about ten years. If we strongly reduce livestock farming, we would stop adding methane to the air, and after ten years the GHG content of the atmosphere would actually decrease! This

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10 — https://ourworldindata.org/grapher/methane-emissions-by-sector?country=~OWID_WRL

11 — France is in the European average in terms of artificialization rate. In order to build housing, roads or commercial infrastructures, the equivalent of the surface area of an administrative department is covered with concrete every 10 years, i.e. a soccer pitch every 5 minutes. Source: France Stratégie report "Zero net artificialisation"; Planestoscope website https://www.planetoscope.com/sols/2024-l-artificialisation-des-sols-en-france.html .

12 — Source: OWID https://ourworldindata.org/global-land-for-agriculture .

would also free up food resources, on the one hand because a cow absorbs 25 times more calories during its life than it gives out in the form of meat, and on the other hand because crops used for animal feed could be used directly for human food.

Summary

- The world population has grown exponentially: we were 200 million in the year 400, 1.5 billion in 1900, 7.7 billion in 2020. We will probably be 9.5 billion in 2050.
- The industrialization of agricultural production has largely supported this growth.
- Today, the main source of emissions in the agricultural sector is livestock, both through methane emissions from ruminants and the land taken up for livestock feed.
- Other sources are deforestation, and soil artificialisation and treatment.

7 The green economy, or how to act on consumption?

7.1 Acting on demand

Cattle are raised to meet a food demand. If the demand for meat or milk decreases, the ruminant population will decrease proportionally, as well as GHG emissions. It is a general law: polluting industries produce to meet a demand, even though they devote large advertising budgets to stimulate it.

We have seen that there are important limitations to the ways we can improve yields and exploit new sources of energy in order to respect the objectives of the Paris Agreement — less than 2°C of warming in 2100. If we take these objectives seriously, without relying on carbon capture techniques that are still underdeveloped, we will have to act on industrial and agricultural production, by shifting it towards non-polluting products, which means ultimately acting on demand and changing our consumption.

This can mean directly and quantitatively reducing our consumption of goods. We can imagine renewing our wardrobe less frequently for example. Modifying our consumption can also involve a change in usage (sharing a car by using carpooling services, for example, without necessarily traveling less) and a change in lifestyle (repairing your objects, which implies taking time to learn how to do it yourself or finding a repair shop close to you home, with objects that were designed to be repairable in the first place). As lifestyles are collectively and culturally determined, this will not happen without changes in role models, cultural imaginaries and social norms.

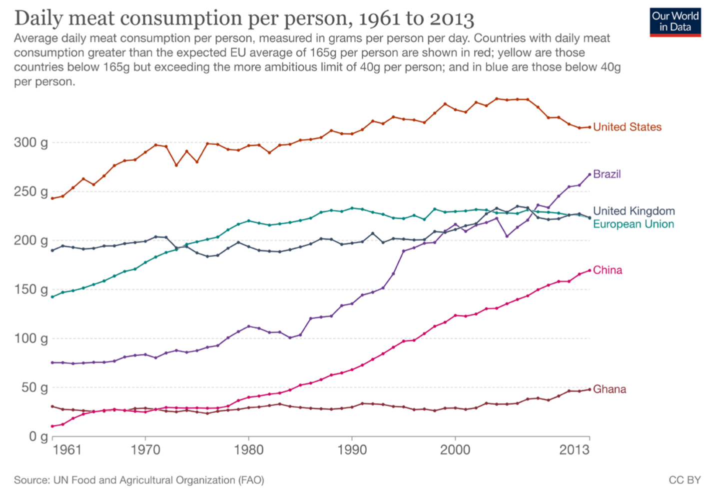
7.2 The case of livestock and vegetarian diets

Let's take the case of livestock farming, which is an illuminating example. As we have seen, eating less meat and dairy products, and thus shifting consumption to a vegetarian diet, would allow for a considerable reduction in GHG emissions. But is it that simple? What exactly does it require?

To get an idea, think of examples: yourself, friends or acquaintances who have reduced their meat consumption. How was this change in behavior perceived by those around them? Did they have to reinvent a new diet all by themselves, or had they already observed imitable vegetarian menus elsewhere? Did money play a role in their decision? Were there restaurants or food stores near their home that had a suitable offer? Did this facilitate their choice? How do they now justify their decision to others? Does it have a moral dimension for them? How did they become aware that they could be vegetarian? Did other people around them or in their social group adopt a similar behavior?

Such an analysis should reveal that it is never a purely individual decision, based on innate individual moral criteria. Many of the parameters affecting our choices are determined by collective decisions, within different types of organizations and at different scales. It is not for you to decide that there will be a food store near your home which carries tasty and affordable vegetarian products. Food also has a very strong social and cultural dimension. It is not easy to turn down the burger or the chicken at meals with family or friends! In many societies, eating meat is a sign of success, which one seeks to share with one's friends and family. This explains why meat consumption, which is currently decreasing slightly in rich countries, is increasing in poor countries.

This figure[13] shows the evolution of meat consumption per person in the world and in various countries. We see that at the world level it has doubled since 1961. As the population has increased from 3 billion to 8 billion, the global consumption of meat has multiplied by more than 5.



Daily meat consumption per person, from 1961 to 2013

Moreover, food companies do not take food demand as given. They invest to steer it in a direction that is good for their business. Advertising, and more generally the information we receive on what we can eat, are powerful levers to influence behavior.

Finally, everything happens within a legal and regulatory framework that can be modified through political action. For example, in 2018 in France, the "EGalim" law states that as of January 2022, food catering in public institutions should include at least 50% of "sustainable products or products with labels of origin and quality". French children

13 — Source: OWID https://ourworldindata.org/grapher/daily-meat-consumption-per-person?tab=chart eating in the school cafeteria in 2022 will not have the same eating habits as older cohorts.

To conclude, beyond the example of food and meat, we see that acting on consumption is a complex problem, which requires action at several levels: on individuals, on companies, and on the state. The means are also diverse: economic incentives, legal prohibitions, modes of governance for private companies...

Summary

- Acting on demand can be a powerful lever to reorient production.
- This requires action at different levels, mostly action at the collective level.

Conclusion

We have identified various ways to reduce GHG emissions. There is the agricultural transition, with the double advantage of a rapid impact, since it would act largely on methane, whose lifetime in the atmosphere is much shorter than that of carbon dioxide, and of beneficial effects that we have not discussed here on biodiversity and health. Another possibility consists of improving energy efficiency and transitioning to other sources of energy, although historical experience warns us that this can actually lead to an increase in overall consumption. Avoiding this effect will require some additional action, such as changing our consumption habits.

To sum up, in order to fight global warming, we must act on our consumption patterns as much as on our production patterns, and this requires the mobilization of all actors: individuals, companies, the State, NGOs, etc. This also requires coordinated action: there is not just one lever to act on, as we have seen, there are many, and all this requires a coherent overall plan, a credible and feasible transition scenario. Proposing one goes far beyond the ambition of this course, but there are several solid plans: you may refer, for example, to the Afterres scenario[14] regarding the agri-food transition, or to the scenarios from the Shift Project[15], RTE[16] or NegaWatt[17] for the economy as a whole.

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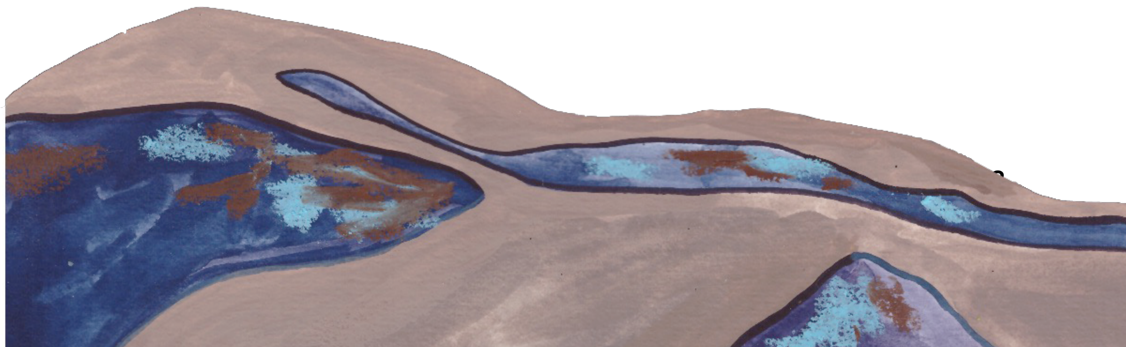
14 — https://afterres2050.solagro.org/

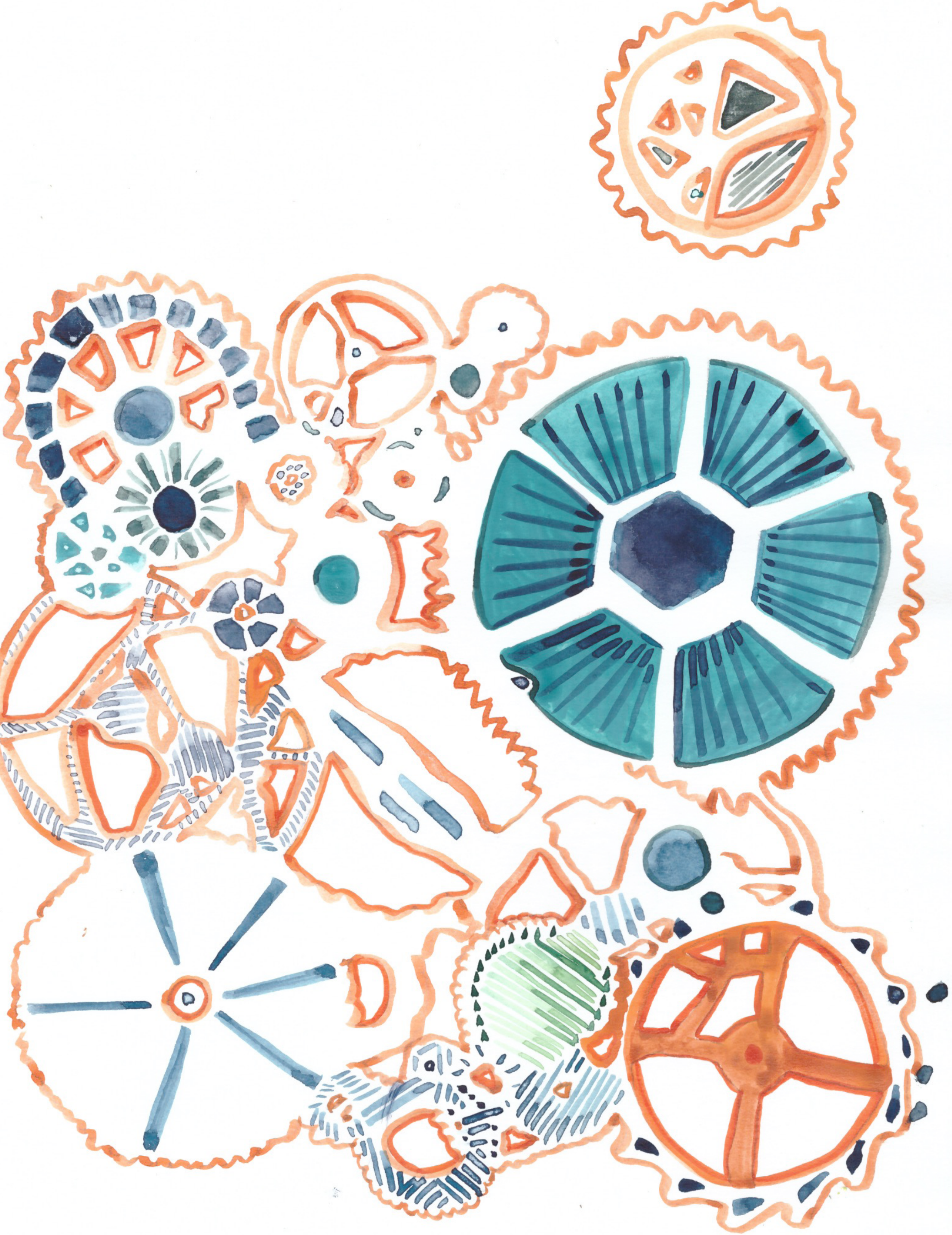
15 — https://theshiftproject.org/crises-climat%e2%80%89-plan-de-transformation-de-leconomie-francaise/

16 — https://www.rte-france.com/analyses-tendances-et-prospectives/bilan-previsionnel-2050-futurs-energetiques

17 — https://www.negawatt.org/Scenario-negaWatt-2022

Finally, we need to know where we are going. Several types of social organization are compatible with the objectives of the Paris Agreement. Some of them lead to great inequalities within nations and between them, others less so. Which one should we move towards? These are difficult decisions, inherently political, reflecting questions of justice and ethics. Remember the 2020t protest movement of the "Gilets Jaunes" in France: the feeling that the costs of environmental policy are unfairly distributed can cause great social unrest. Choosing a scenario also means choosing the society we want to live in tomorrow and for which we are ready to mobilize today.





9

A Brief Social History of GHG Emissions

Part I —
The industrial revolution

Preamble

Why include social sciences in a climate course?

So far in this course, we have studied the major physical-biological balances that regulate the climate and life on Earth and shown how they have changed within only a few centuries. Should we stop there? Do you think that ecological issues should be limited to discussions between physicists, chemists and biologists? Is it enough to talk about the greenhouse effect, biodiversity and IPCC scenarios to understand the situation fully and take action?

We think not. Human beings are undoubtedly major actors in these transformations, and we must also try to understand them. Discussing only physics and biology, forgetting social sciences, i.e. history, anthropology, economics, politics, sociology or even law, would be like describing how the human body works but mention only the heart and the blood circulation, forgetting the role of exercise, nutrition and the mind. It would explain little, and cure even less.

To understand the way human beings act, we must understand what makes them act: ideas matter! The myths and beliefs of our societies, their internal hierarchies, their systems of exchange and values shape human relationships and their connection to the rest of this planet. For instance, the belief that trees or springs shelter a spirit, like in ancient mythology, or that an entire clan stems from an animal ancestor, the totem, as contemporary hunter-gatherer tribes still believe, is not a simple whim without material consequences. Who would want to cut down a hundred-year-old oak tree if its spirit can retaliate one day? For the clan members, the killing of a totemic animal cannot be undertaken without serious reasons. Are these beliefs not a way These beliefs are they not a means for these societies to preserve collective resources, as the way laws and regulations do in ours?

Conversely, beliefs and value systems can have a destructive effect on the living conditions of a society. The greenhouse effect is due to the exploitation of fossil fuels, which allowed the development of societies of consumption and material abundance. This model has been widely spread all over the planet. But was it the exploitation of fossil fuels that caused the race to material prosperity, or was it the race to material prosperity that resulted in the exploitation of fossil fuels? Did oil create the consumer society, or did the consumer society call for the massive exploitation of oil? Did you know, for example, that the first industrial exploitation and production systems appeared in the 15th century, in the Portuguese colonies of Madeira and Sao Tomé, to meet the European demand for sugar? This was long before the discovery and exploitation of coal, and the energy that was necessary was provided by slaves. The consumer society therefore existed before oil, and oil opened up new horizons (with cars, planes, plastics). The former goes along with the latter, just like the egg and the chicken, and so they must be studied together.

The purpose of the two chapters that follow is to explain the social systems that allowed uncontrolled combustion of fossil fuels and thus global warming. But history is not linear. It stretches out in length and sometimes suddenly accelerates. Sometimes it may seem predetermined, and some other times, unpredictable. In any case, it is always made of multiple and complex forces, and we will not be able to do justice to this complexity here. We will therefore use brief highlights on the key moments and ideas that explain the current environmental upheavals. This "time capsule" narrative is strongly centered on the Western powers, in Europe and later on in the United States, because they are the ones who created, and then imposed on the whole world, the economic and political systems at the root of global warming and the loss of biodiversity.

You will see that social forces studied in humanities are just as decisive in the recent history of climate and biodiversity as the physical-biological balances. We cannot think of changing the latter without changing the former. In order to overcome the environmental challenges of the 21st century, it is not enough to find technical solutions (improving the insulation of buildings or the energy efficiency of cars, reintroducing bees into the fields), we must also change production systems, individual and social values, collective representations and the foundations of the social contract, and therefore call upon the inventiveness of engineers, economists, lawyers, philosophers, and undoubtedly appeal even more so to the creativity and motivation of citizens. Just like ethnologist David Graeber said, "the ultimate and hidden truth of the world is that it is something we do, and that we might as well do it differently".[1]

1 — Cited by David Wengrow, in Guardian of 10/31/21

Introduction

This first chapter covers the period from 1500 to 1950, with the industrial revolution and the first GHG emissions. During these four and a half centuries, the world changed more than in the previous two millennia. If a time machine had taken a French peasant woman of the 16th century fifteen centuries back, she probably would not have felt lost. She would have found a rural and communal society, with agricultural practices largely similar to hers, in a world with life expectancy barely over 40 years and with over 50% of children dying before the age of 5. But she would likely feel stunned and out of place in today's France, where life expectancy exceeds 80 years and where agriculture represents 1.5% of total employment. The ideas and institutions that are familiar to us, such as a globalized economy or a farm's financial balance sheet, would be incomprehensible to her, and she would not recognize the countryside, which has been profoundly transformed by the industrialization of agriculture.

Why go back to 1500? Because the 16th century was the century of Galileo's discoveries and also that of the colonization of the New World. These two events made Europe prosperous and shaped today's world. Galileo's discoveries marked the beginning of modern science, which led to the industrial revolution and ensured Europe's technical and military superiority. The colonization of the American continent, and of the others afterwards, created globalized markets and provided the European industry with the resources and commercial routes it needed to function, at the price of the destruction of traditional social and commercial structures. These markets encompassed the entire planet and allowed the growth of industrial production since the 1850s, and particularly since the 1950s. This led to the GHG emissions of which we bear the first consequences today.

A few questions to warm up

- In 1800, in France, what was the proportion of children that died before the age of 5?

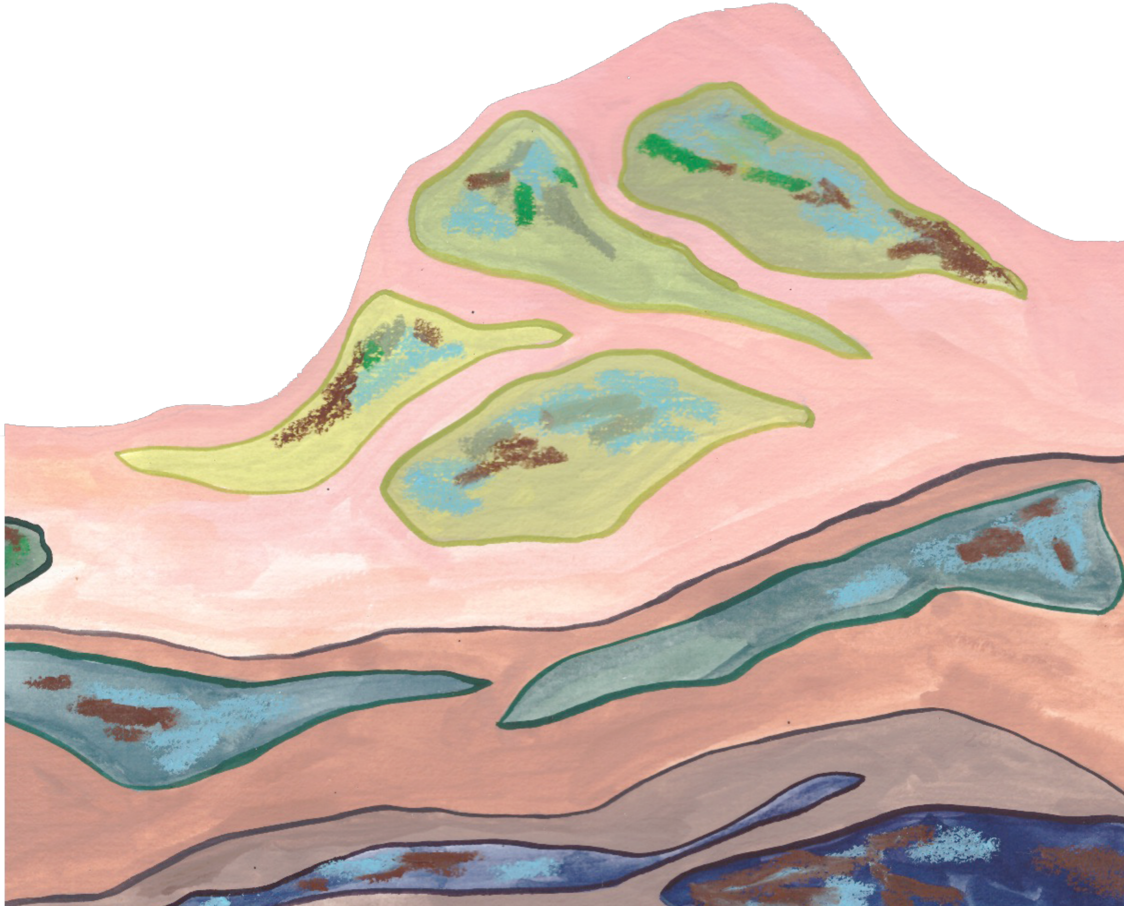
Answer: 4 out of 10

- Are sugarcane and cotton American plants?

Answer: no, sugarcane was imported from Guinea and acclimatized; cotton, yes.

- Who wrote "Natural resources are inexhaustible because otherwise we would not get them for free"?

Answer: Jean-Baptiste Say, in his Traité d'économie politique *(1803).*



1 The shift in our living conditions

So what happened from the 16th century on? You can start guessing by looking at these graphs:

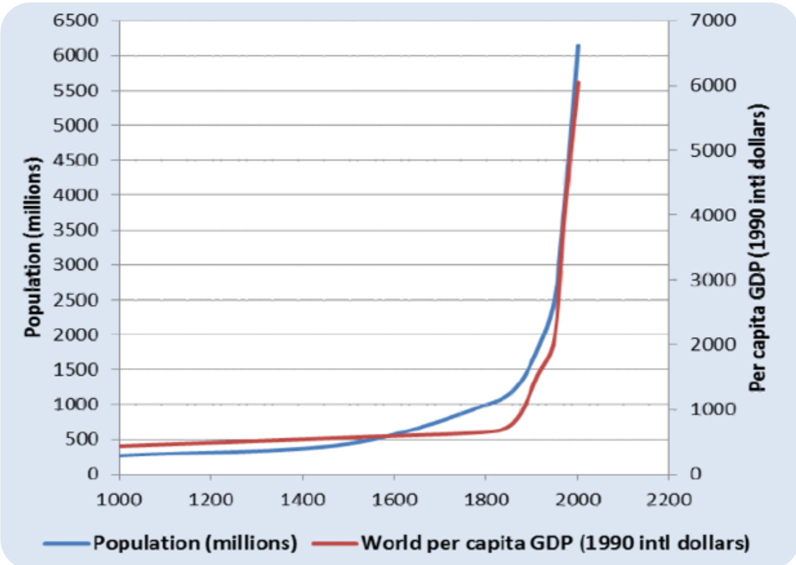


Figure 1: World population and per capita GDP since 1000

Source: Research Gate[1]

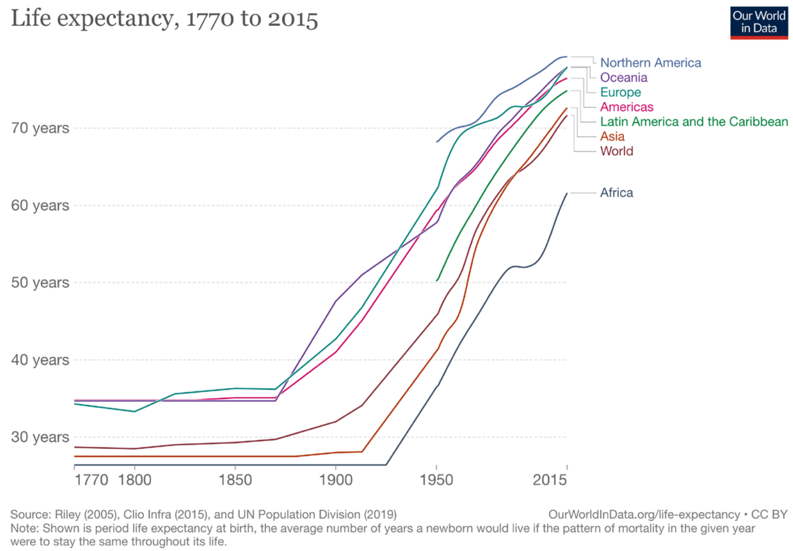


Figure 2: Evolution of life expectancy in the world since 1770

Source: OWID

1 — https://www.researchgate.net/figure/World-Population-and-Per-Capita-GDP-PPP-1000-AD-to-2001-Data-from-17_fig2_49599352

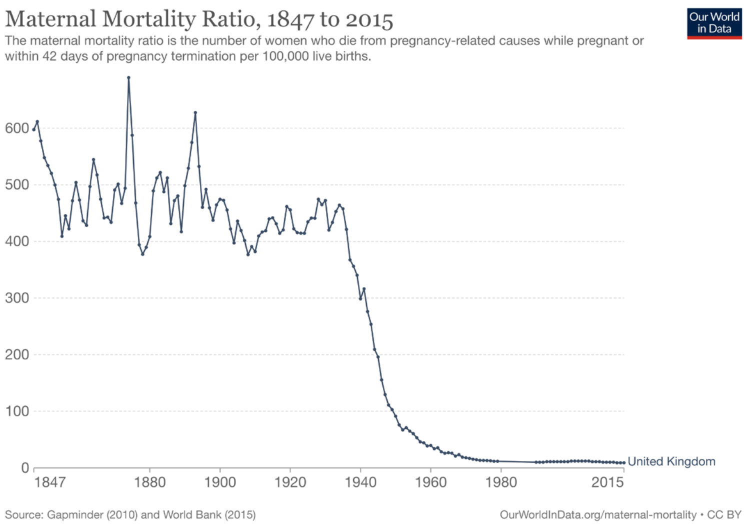


Figure 3: Mortality rate in childbirth in England per 100,000 births since 1850

Source: OWID

Interpretation: In 1850 in the United Kingdom, there were 500 maternal deaths in childbirth per 100,000 births, or one death for every 200 births.

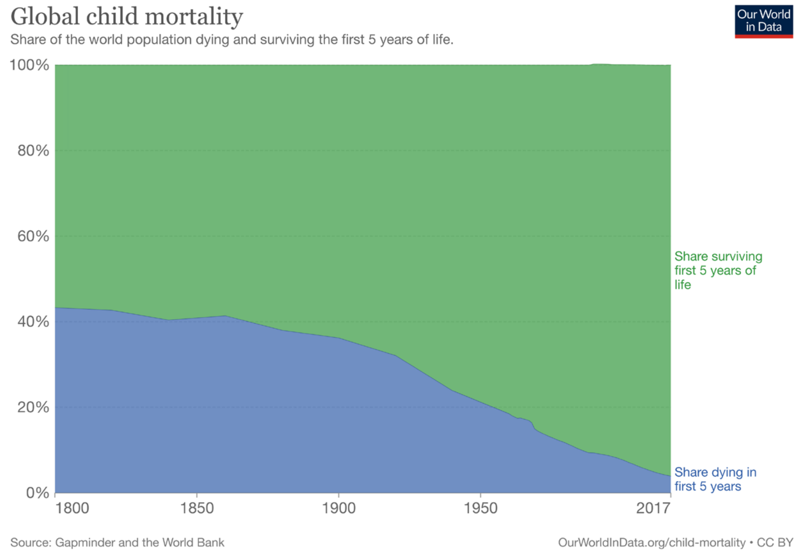


Figure 4: Global infant mortality rate (under 5 years) since 1800

Source: OWID

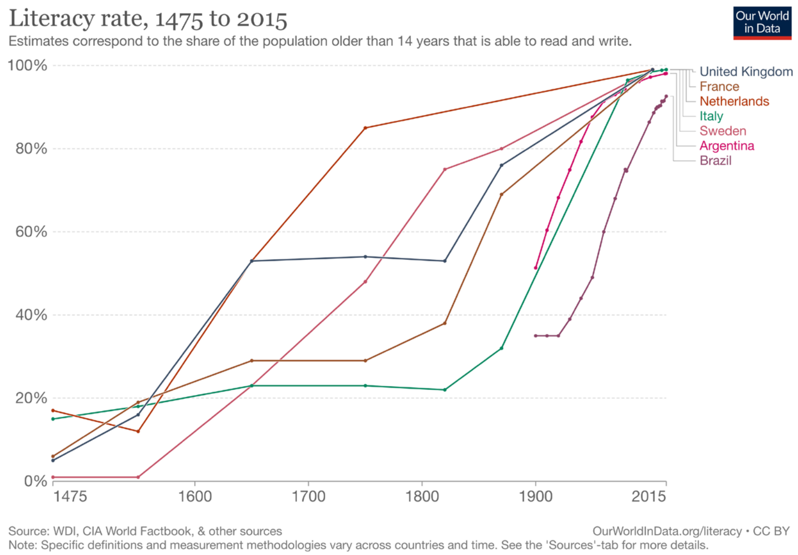


Figure 5: Literacy rates in 7 countries of the world since 1500

Source: OWID

Interpretation: In 1750 in the Netherlands, almost 85% of the population could read and write.

For centuries, the world's population as well as our living standards have stagnated, until all of a sudden, everything exploded! This is what you can see on Figure 1. Note that the red curve shows the GDP per capita! To obtain the global GDP, you have to multiply the two curves, and the take-off would be even more remarkable.

No less impressive is the considerable improvement in life expectancy (Figure 2), partly due to the decline in maternal and infant mortality (Figures 3 and 4). These improvements are also reflected in the literacy rate (Figure 5), which took off in European countries from the second half of the 16th century.

In 1800, out of ten babies born in France, four died before the age of five. One can imagine the consequences of these figures on women's lives: more births were sought in order to compensate for infant mortality, and each birth would threaten the mother's life. This is what Figure 3 shows: until 1940 in England, more than 4 out of 1000 births ended in the death of the mother.

European societies thus visibly and profoundly changed, followed gradually by other countries. Meanwhile...

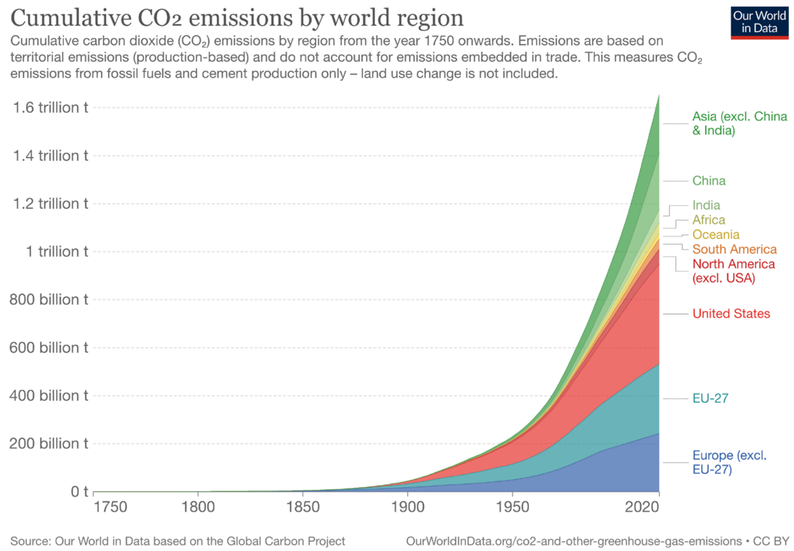


Figure 6: Cumulative CO_2 emissions in the world since 1800

Source: OWID

Interpretation: In 2017, the cumulative stock of CO_2 emitted on the territory of the European Union countries (EU-28) reached about 350 billion tons.

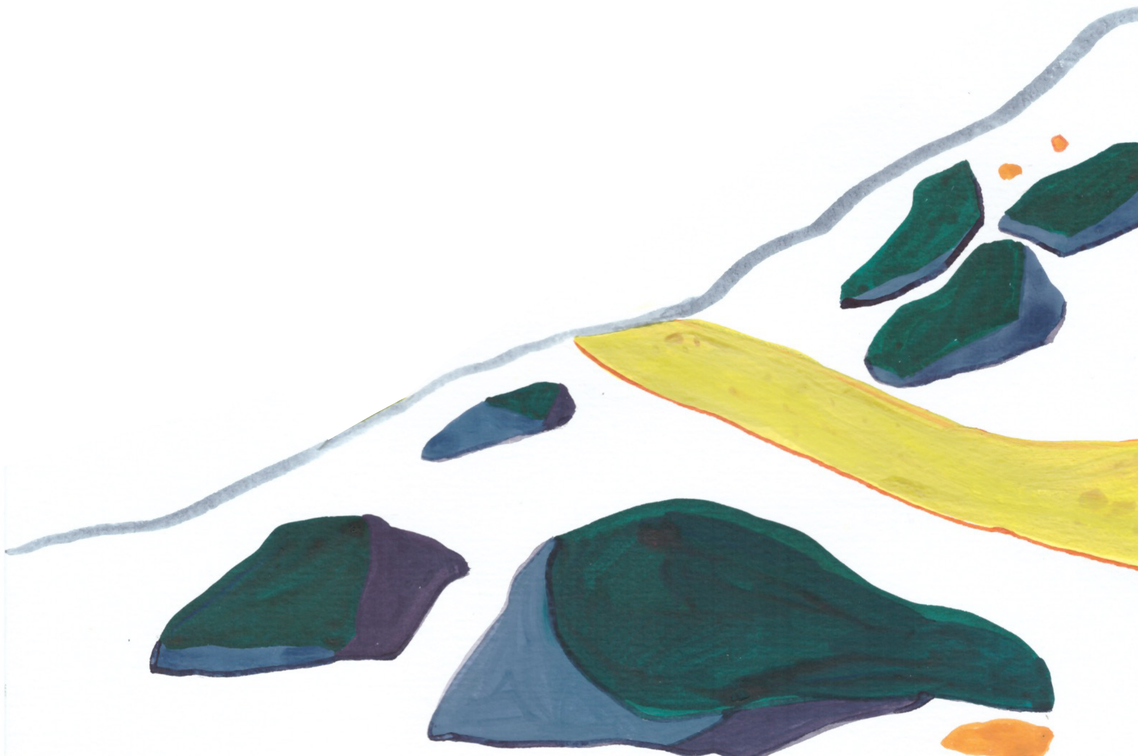
Meanwhile, CO_2 emissions took off. The distribution of emissions by country is illuminating. The first emitter, and even the only one for a long time, was the United Kingdom. At the end of the 19th century, the United States caught up with the UK and became dominant throughout the 20th century. After 1950, the emissions of the United States and European countries increased exponentially, and were met by others, such as Russia, India and China.

In the end, cumulative global emissions rose from almost nothing in 1800 to more than 200 billion in 1950, and then exploded to 1,580 billion cumulative tons in 2017. In the 70 years since 1950, in the space of a human lifetime, we have emitted 7 times more CO_2 than in the 150 years before. This is what we can call an acceleration phase, and it is visible through other indicators, such as the world population, which goes from 2.58 billion in 1950 to 7.71 in 2019. It justifies that we split our study in two parts: before and after 1950.

The rest of the course will outline the economic, political and ideological history behind these curves. The objective is not to discuss everything, of course, but to highlight the key factors in the development of our societies that explain the environmental upheavals we are experiencing today.

Summary

- Living conditions have changed profoundly ever since the 16th century, first in European countries and progressively in other countries of the world.
- These changes are notably characterized by a considerable increase in life expectancy and an explosion of the world population.
- CO_2 emissions followed the same evolution, both globally and by country.



2 1500 - 1800: the rise of Europe and the first industrial systems

Why start in 1500? Because the first major change in the global organization of production and power that interests us took place in 1500: the creation of globalized markets by European countries, thanks to which they commercialized certain commodities such as sugar and cotton, produced in the new American colonies, processed in Europe and distributed throughout the world. But in order to produce goods and distribute them, one needs energy. Hence the creation of more complex commercial routes: energy is fetched at its source, transported to the places of production, then the raw material is transported to Europe for processing, and in the end the final product is distributed throughout the world, thanks to a globalized market.

What source of energy was available before the industrial revolution? Slavery, used to extract gold and silver from American mines and to produce sugar and cotton. It was slavery that structured Atlantic trade for three and a half centuries between the discovery of America and the Industrial Revolution.

2.1. European expansion to the Americas and mass slavery

In 1492, Christopher Columbus landed in the West Indies. He took possession of this territory on behalf of Queen Isabella of Castile. The Europeans, first the Spanish and the Portuguese, then the French and the British, conquered and exploited what they called the "New World".

The pattern of exploitation was unprecedented in more than one respect. Firstly, because the arrival of the colonists led to the disappearance of most Amerindian societies and the depopulation of the continent, through imported diseases and military action.[2] Secondly, because those colonists set up a complex organization on the lands they appropriated. This organization included multiple stages of production, financial investments and commercial exchanges at the scale of several continents. Lastly, because these exchanges were intended to meet new needs, starting with sugar.

2 — See Pierre Clastres *La société contre l'état* (1974), or https://en.wikipedia.org/wiki/Population_history_of_indigenous_peoples_of_the_Americas. It is estimated that the population of America, which was between 50 and 100 million inhabitants in 1500, would have fallen to less than 5 million in a century. Some historians see in the Little Ice Age that affected Europe in the 16th century the consequence of the depopulation of America: the disappearance of the Amerindians would have led to the disappearance of cultivated fields in favor of the forest, whose growth would have absorbed atmospheric CO_2 and led to a significant drop in temperature. See https://fr.wikipedia.org/wiki/Petit_%C3%A2ge_glaciaire

Sugar[3]

In the Middle Ages, sugar was still a luxury product in Europe, imported from the East. In 1226, King Henry III of England asked the mayor of Winchester if it would be possible to provide him with 3 pounds of sugar during the annual fair. But things changed when the Portuguese settled in Madeira and established a whole sugarcane industry. Once a luxury product, sugar became a product of everyday consumption. During the 16th century, it became commonplace, and per capita consumption in Great Britain rose from 5 to 25 pounds per person during the 17th century. This led to the exhaustion of Madeira's resources, especially in wood, and production moved to the New World.

Sugarcane was not an American plant: it had to be imported and cultivated, even though it meant replacing local plant species, food crops and natural balances. Sugar production required a lot of manpower and water for irrigation and wood to distill the syrup. The first industrial processes were then set up: a series of different production stages requiring the investment of a substantial initial capital and the division of labor. The rationalization of this process led to the invention of plantations, large properties dedicated to monoculture and organized like the later factories.

Just like plants, the labor force was imported in the form of slaves. In 1800 there were 500,000 slaves in Santo Domingo and 80,000 tons of sugar were produced annually. This was the famous triangular trade, in which the great ports of Liverpool and Nantes played an important role. Their ships fetched slaves from Africa, crossed the Atlantic to sell them to planters in America, and returned to Europe loaded with sugar. The sugar industry thus appears as the cradle of modern capitalism. For the very first time, we can see its founding principles at work: an initial investment in capital and the division of labor within a framework of globalized exchanges.

Comme les plantes, la main d'œuvre est importée : ce sont les esclaves. En 1800 il y a 500 000 esclaves à Saint-Domingue, et on y produit 80 000 tonnes de sucre par an. C'est le fameux commerce triangulaire, auquel participent les grands ports de Liverpool ou de Nantes dont les navires vont chercher les esclaves en Afrique, traversent l'Atlantique pour les vendre aux planteurs d'Amérique, et reviennent en Europe chargés de sucre. L'industrie du sucre apparaît ainsi comme le berceau du capitalisme moderne, car on y voit pour la première fois ses principes fondateurs à l'œuvre : importance du capital investi et division du travail dans un cadre d'échanges mondialisés.

3 — See Patel & Moore *A History of the World in Seven Cheap Things*, (2018), ch. 3 for more information.

Summary

- 1500 marks the beginning of Europe's domination of the world order in the military, political and economic fields.
- The raw materials of interest to the Europeans, sugar and then cotton, replaced the old food crops and were produced on plantations before being transported to Europe where they were processed and marketed.
- Sugar is the emblematic product of the emerging model: a system of industrial production of new consumer goods for Europe, organized and rationalized on the scale of several continents.
- This model is based on the exploitation of slaves transported from African and Amerindian lands, at the expense of local cultures and ecosystems, whether natural or social.

2.2. An exponential path

At the end of this first sequence, you may very well wonder: some characteristics of this economic and political system are already starting to look like the modern world we live in. But on the other hand, we are not quite there yet, and the consumption of sugar alone would not have been enough to double life expectancy in Europe. So what happened?

This question was raised and formalized at the end of the 17th century by an English conservative clergyman and economist, Thomas Malthus, who opposed the Poor Laws, a system of public assistance for the poorest. His *Essay on the Principle of Population* (1798) is a classic reference in the history of Economics because it is the first to ask the fundamental question: what determines and limits the growth of a population? His answer also has the merit of clarity: the food resources available. For Malthus, population growth can only come from an increase in food yields from existing land or from the exploitation of new land.

This answer makes sense in the light of previous centuries. Exponential population growth was inconceivable. With finite land, food production could not keep up. Any overshoot of the equilibrium population level would be stopped: either directly by episodes of famine or malnutrition, or indirectly because society would limit its own growth by delaying the age of marriage or by using contraception. In both cases, this would lead to a return to a smaller population. According to this reasoning, there is no possible social equilibrium when the population receives a material surplus that allows it to grow and when workers are paid above the subsistence minimum. Hence Malthus's opposition to the Poor Laws: granting aid to the poor only delays an inevitable deadline, at best, and at worst, worsens the situation, since the poor are thus encouraged to start a family, and their children will only swell the number of paupers who must be supported!

The subsequent evolution of the world economy contradicts Malthus's ideas: the world population grew exponentially without encountering any limits, and workers in European countries saw their standards of living increase way beyond the vital minimum. Instead of relying solely on traditional agriculture driven by a flow of energy —solar energy— development since 1850 has been based on the exploitation of energy reserves, extraordinarily concentrated and accumulated on Earth over hundreds of millions of years: coal and then oil and gas. These sources of energy have, among other things, allowed the transformation of agriculture into a real industry based on the systematic use of machines, fertilizers and pesticides. At the same time, economic, legal and ideological systems changed, accelerating the development of techniques based on these new energy sources and their contribution to the improvement of living conditions. This will be discussed in greater detail in the following sections.

Summary

- According to Malthus, it is not possible for a population to grow sustainably because it is constrained by available land and agricultural productivity, which are limited.
- The food problem was solved in a way that Malthus could not foresee: through the discovery and exploitation of new energy reserves, and concomitant transformations of economic, legal and ideological systems.

2.3. Making the best use of Nature

An intellectual discipline played an important role in the ideological evolutions of this first reorganization of the world: economics, the "dismal science"[4] that must shed light on the optimal allocation of scarce resources, as Malthus had begun to envision it. A key characteristic of this emerging economic science is it describes nature as a sum of resources available for human use. In his 1828 lecture, the French economist Jean-Baptiste Say wrote: "Natural wealth is inexhaustible, for without it we would not obtain it for free. Since they cannot be multiplied or exhausted, [natural resources] are not the subject of economic science."

Before 1500, the main problem of states was to feed the people: the vast majority of these populations were rural, and these peasant civilizations knew they were dependent on an often miserly and sometimes hostile nature. On the contrary, from its beginnings, the economic science advocates the autonomy of human activity. Humans are considered free from the old subjection to nature. The latter is no longer an inconvenient and difficult partner: it is a wasteland to be developed, a mine of inexhaustible resources to exploit.

4 — "The dismal science", as Scottish historian Thomas Carlyle named it in the 19th century.

At this point, Western civilization introduces the new idea that it is necessary to "develop" nature. This means that nature does not have an intrinsic value to be preserved, as in traditional Chinese or Japanese civilisations. It is there to serve the material needs of mankind, and it may be acted upon to better satisfy those needs. Descartes, in the *Discourse on Method* (1637), invited us to use scientific discoveries to "make ourselves masters and possessors of nature", especially for the "preservation of health".

In his *Treatise on Civil Government* (1690), the philosopher John Locke wrote in turn that "a piece of land in virgin America, while it might be just as fertile as a comparable piece in England, would be worth a thousand times less, if we calculated all the profit an Indian would receive if it were valued and sold on the spot." The conclusion, in his mind, is clear: America must be developed until two similar lands can yield the same thing and therefore be worth the same price. Property systems, especially land, must help optimize this exploitation. Most of the natural conditions (water, air, biodiversity...) essential to human life are not taken into account in these approaches: they are free factors of production!

Summary

- Western culture, influenced by the emerging economic science, transformed its relationship with nature at the turn of the 16th century.
- Nature is seen as a deposit of free resources without intrinsic value. One can and must act to maximize its economic value.

2.4. A moral narrative

To "enhance" nature means using it for our needs. For a Christian, it is also to comply with the biblical injunction to Adam: "Be fruitful and multiply, fill the Earth and subdue it. Rule over the fish in the sea and the birds in the sky and over every living creature that moves on the ground." (Genesis 1:28).

For Locke, and for the heirs of Christianity, subduing nature is thus a true moral duty. Not to do so, that is, not to leverage entirely the possibilities offered to human ingenuity by the exploitation of natural resources, is to be lazy, and ultimately to sin against God who placed them at our disposal. It will come as no surprise that Adam Smith, the father of modern economic theory and famous for his book on *The Wealth of Nations* (1776), first wrote a *Theory of Moral Sentiments* (1759).

It is then in *The Wealth of Nations* that we can find the first description of the famous "invisible hand" of the market, which is supposed to make individual egoisms motivated by profit converge towards the collective well-being. In a famous sentence, Smith wrote that "It is not from the benevolence of the butcher, the brewer, or the baker that we expect our dinner, but from their regard to their own self-interest. We address ourselves not to their humanity but to their self-love, and never talk to them of our own necessities, but of their advantages." Here Smith makes a radical distinction between market activities, where greed is the only game in town, and the rest of human activities, where benevolence and other moral sentiments are allowed. One can afford to be generous and compassionate in private life, but this has no place in business!

What is left, then, once moral sentiments have been removed from the economic sphere? What remains is "the propensity to barter, trade and exchange", which, according to Smith, "is common to all men and is not found in any other animal species". According to him, this is enough to ground universal harmony, thanks to a new institution, the market. The market's "invisible hand" will miraculously reconcile the interests of all, provided that it is given free rein. It is important to note here that no anthropologist or psychologist has ever found any trace of this "natural" propensity to barter. The common principle of exchanges in primitive societies rather seems to be based on gifts and countergifts: I give you something today, I don't expect anything in exchange immediately, but we remain in a relationship, and for this relationship to continue in the long term, you will have to return the favor one day, not too far away from now.

However, Smith's argument is simple and catchy. From then on, the economy will be understood to operate on the principle of "private vices, public virtues": individual greed, the search for profit, should be given free rein, and the invisible hand of the market will make all profit-oriented endeavours concur to the general good. Throughout the 19th century, Great Britain will thus try to create from scratch a regulatory framework and a market functioning according to Adam Smith's principles.

Summary

- Economics as a science was developed within a moral framework, rooted in 18th century European bourgeois culture.
- Adam Smith, an influential figure in the emerging science, introduced a separation between business life, where the only acceptable motivation is profit, and private life, where one can afford to be generous and compassionate.
- According to Smith, it is by seeking their maximum individual profit that individuals best contribute to the welfare of all.

3 1800 - 1950: the coal revolution

3.1. An energy source for machines

Around 1800, a new source of energy emerged: coal. Coal had been exploited for a long time, especially for heating and metallurgy, in competition with wood. But the depletion of forests created new needs, and encouraged the systematic exploitation of coal mines. The first steam engines were invented to extract the water that seeped into the mine galleries. It is only as their efficiency improved that these machines could be used for other purposes, and launched on railroads, then on ships.

A 140 C locomotive and its tender

Source: Wikipedia[5]

Interpretation: This type of locomotive was used by the SNCF, the French railway company, between 1920 and 1950. Behind the locomotive is the tender, a special wagon that carries the coal and water needed to operate the machine. In the passenger compartment, two characters, the mechanic and the driver, the latter shoveling coal into the boiler.

The 19th century was Great Britain's century. Coal mines were easy to exploit and close to ports, making coal available for maritime transport. The world merchant fleet grew from 9 million tons in 1850 to 35 million tons in 1900, 60% of which were under the British flag.

5 — https://commons.wikimedia.org/w/index.php?curid=47094072

Maritime lines structured the world: immense colonial empires, English and French, drained the world's resources to Europe and redistributed them in the form of manufactured goods. Railroads structured the nations: in 1869 the transcontinental line connected the East Coast of the United States to the West Coast, and in 1916 the Trans-Siberian Railway connected Moscow to Vladivostok. The world's rail network grew from 100,000 km in 1860 to 1,000,000 in 1920. To illustrate the new transport capacities, note that in fifteen days, between August 2 and 17, 1914, Germany transported more than three million men on its borders, with their equipment, their cavalry and their artillery.

Great Britain, India and cotton

From the 17th century, cotton began to compete with wool in Europe. India and its sunny climate alternating dry and wet seasons is the main producer and transformer. So much so that in 1724 Great Britain introduced customs duties against Indian fabrics to slow down the import of cotton and develop its own textile industry. Watt's steam engine (1769) made it possible to operate mechanical spinning machines, and the cotton mill became the prototype of the modern factory, around which workers were housed in miserable conditions. In the early 19th century, cotton fabrics represented 42% of British exports.

The conquest of India in 1757 provided the British industry with a captive market: the local textile industry disappeared, and India's only role was to produce raw cotton. British industrialists even imposed that local cotton varieties be replaced by American cotton, which was stronger, but more water-intensive and depleted the soil much faster. Cotton clothes also heralded a new relationship to material consumption: they were disposable objects that could be changed several times in the course of one's life. This would have been inconceivable for an English peasant two hundred years earlier.

The economic reorganization between India and Great Britain around cotton is typical of the new world order. Placed under political tutelage, India would produce only raw material, while Great Britain would derive most of the added value by transforming it and adapting the legal framework for trade. Despite India's initial comparative advantages, two hundred years later, Great Britain had taken a considerable industrial, economic and political lead, and India could no longer catch up.

In industrialized countries, technical progress transformed lifestyles profoundly. Two examples are the widespread use of public lighting and clocks. For centuries, humans had gotten up and set with the sun: one could hardly work in the dark, and neither candles nor oil lamps provided sufficient lighting. All this changed with the industrial revolution. In 1817, Brussels became the first city in the world to have its streets lit at night, thanks to "city gas", produced from coal. Lamplighters would come every evening to light streetlamps and every morning to turn them off. From 1850 onwards, street lamps were used with petrol, and from 1870 onwards with electricity (no more need for lighters). Inside the house, lighting also became generalized, thanks to oil lamps. Whale oil, made from whale blubber, was the best, the one that smoked the least. Whales were thus hunted all over the world's seas to light homes. Fortunately for the whales, petroleum was found, if suitably distilled ("kerosene"), to be even better for lighting! We can say that petroleum saved the whales, even before other uses were found for it.

The lamplighter
Source: https://i.pinimg.com/originals/e5/de/38/e5de38a2aaa7f1b1d53ca830864c-35ce.jpg

Thanks to the progress of lighting, men were able to work at night. In factories that appeared with the industrial revolution, work started and ended at fixed hours, independently of the sunrise or sunset. Working hours became part of the employment contract, which was new. From then on, workers were no longer paid by the task, but by the hour. This is wage labor, which is the most widespread form of work in our industrial societies. But this is in fact a novelty from the industrial revolution, which would not have been possible without another invention: the clock. With working hours, reading the time in the sun is no longer good enough: one must "know the time" to go to work and leave! At the same time as public lighting, public clocks became widespread, usually on town halls and train stations, and church bells or factory sirens announced the time.

The use of coal and improved engines provided the material surplus that Malthus had not expected. This was supplemented by the establishment of public health and sanitation systems, as well as advances in medicine and labor law. New factories required workers and the 19th century saw a massive rural exodus in European countries. Public health and hygiene systems were created in unhealthy cities whose populations had exploded. London installed a sewage system: a sanitary revolution as well as an olfactory one! As late as 1858, the summer heat had caused the nauseating odors of human excrement and industrial waste to rise from the Thames, to the point that Parliament was unable to sit, and that water pollution was held responsible for the latest cholera outbreak! Building such an important infrastructure as a sewer system implied digging deep, demolishing constructions if necessary, installing iron pipes,... all engineering feats that were made possible by the power of the new steam engines.

Illustration from the Punch magazine, on July 1858

Source: Wikipedia « The Great Sink » (https://en.wikipedia.org/wiki/Great_Stink)

Interpretation: A worker uses lime to mask the smell of the Thames. Indeed, the curtains of the English Parliament were soaked with chloride of lime to try to mask the smell.

Summary

- A new industrial revolution, in which the United Kingdom was a pioneer, was based on coal.
- The emblematic product is cotton: produced in India but processed in the United Kingdom, under commercial conditions that greatly benefit the latter, especially since India became a British colony.
- New social systems, regulations and public infrastructures were created, gradually improving the poor living conditions of the urban and working class populations.

3.2. Transforming institutions

In the 19th century international trade exploded, particularly for food. Grain was imported into England from North America, and even from Australia. In 1815, the English Parliament raised taxes on imported grain to protect its agriculture (Corn Laws), but forty years later it took the opposite decision and lifted customs barriers. Following the principles of Adam Smith and his successor, economist David Ricardo, Great Britain bet on industrial exports and "comparative advantages": importing cheaper food resources from abroad, even if it meant losing food self-sufficiency and impoverishing, at least in the short term, agricultural workers. In return, since food prices were low, workers' wages could be kept low, and therefore competitive, and industrialized products with higher added value could be exported.

The new world order is depicted in the following painting, hung in 1778 on the walls of the premises of the East India Company, which held a monopoly on British trade with India. The picture depicts Britannia (the United Kingdom personified) in an elevated position, receiving tribute from India (a crown surrounded by rubies and pearls) and China (porcelain and tea), while a troop of coolies carrying bales of merchandise are walking up to her under the leadership of Mercury, the god of trade. And as for the bearded old man in the foreground, you've already seen him: it's Old Father Thames, the Thames! This painting illustrates the relationships of domination underlying the new economic system.

The East offering her riches to Britannia
Source: https://greatgameindia.com/the-east-offering-her-riches-to-britannia/

New laws are enacted to support this new economic and geopolitical system. On a global scale, Britain seeks to remove tariffs and institutional barriers to accessing natural resources in order to create a globalized market. On a national scale, the Enclosure Laws privatize English common land, previously managed in common by local residents, as described by economist Karl Polanyi in *The Great Transformation* (1944).

Private property

Changes in ideas and lifestyles always come with changes in laws and institutions. For the first time in the history of mankind, private property appears as a fundamental right, and humans are defined, not by who they are, but by what they own. Here is article 2 of the *Declaration of the Rights of Man and of the Citizen* of 1789, a founding text from the French Revolution, marked by the bourgeois origins of the movement: "The purpose of all political association is the conservation of the natural and imprescriptible rights of Man. These rights are liberty, property, security, and resistance to oppression." Note that property comes after liberty, but before security!

This is extraordinarily new compared to previous societies. In the Middle Ages for instance, the land could only belong to the community, represented or embodied by the sovereign. The serf did not own the land he cultivated, any more than the lord owned his fiefdom (in 1523 in France, King François I confiscated for treason all the lands of the Constable of Bourbon!). Instead of land ownership as we understand it today, a network of differentiated rights around land prevailed. Thus, in England, the *Charter of the Forests* of 1215 granted to all free men of the kingdom who did not have personal property free access to the forests and the use of what they produced: wood, game, water, fruit. The same charter forbade the enclosure of cultivated land, so that multiple rights could be exercised for the benefit of others, such as the right to graze cattle on the land once the harvest was removed.

The rural history of England from the 15th century onwards is that of a long regression of these collective rights in favor of an exclusive conception of private property. The cloth industry was prosperous, and merchants sought land to graze their sheep. They obtained enclosure acts from Parliament,[6] edicts imposing the enclosure of land and the erasure of collective rights. The movement continued until the total disappearance of these rights, around 1830. The legislative system was completed by very repressive laws against vagrancy,[7] which evicted from the villages anyone without visible means of subsistence. The rural poor were thus driven to the cities, where they faced a new reality: wage labor.

The wage labor[8]

Wage labor started with the industrial revolution. In all earlier societies, the craftsman was paid by the task and the peasant lived off his harvest. Their time was their own. Their work, moreover, was hardly distinguishable from family life: the craftsman worked at home, often with his family, and the farm was never far from the animals and the fields. There were people who were not masters of their time, and who were controlled so that they would not waste it: these were slaves. They were employed in the mines or on the plantations, separated from their families.

In the factories that were being created in England after the Industrial Revolution, men, women and children were paid by the hour and worked at set times. They clocked in at the factory or mine in the morning, and returned to their slums at night. The condition of workers has improved with time, but the new definition of work has not changed. It is no longer something that is a private part of life, involving the whole family. It is done outside the home and the family setting, and only to support oneself. Real life begins when one returns home or, in the next century, when one goes on vacation. The dissociation between nature and man, a characteristic of European modernity, finally translates into a dissociation within the individual himself, between the work he does and his personal life. The professional must not let the individual show through, with his qualities and faults, his feelings and opinions: in short, everything that is important to him and makes him different from the others.

The industrial revolution and the creation of a global market to exploit natural resources and sell manufactured goods required massive amounts of capital. Money was needed to build railroads, commercial and military fleets, factories and machinery. This capital could be raised and spent on investment because of a legal innovation that fundamentally changed the business world: the invention of the "joint stock company". Until the 19th century, commercial firms were under a legal regime close to private property: the owner of the business was responsible for the damage caused by it, and the various forms of shareholding that already existed consisted in sharing rights and responsibilities between shareholders.

This changed in the 19th century: the shareholder then is not more than the owner of his shares, and his responsibility ends at the price of these shares. The worst that can happen to him is that these shares become worthless. This limitation of liability has greatly contributed to attracting private capital to the riskiest companies. In today's major industrial disasters, such as the Bophal disaster in 1984 or the

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6 — See Polanyi (op. cit.) or Wikipedia : https://commons.wikimedia.org/w/index.php?curid=47094072

7 — See https://en.wikipedia.org/wiki/Vagrancy

8 — For more information, see David Graeber, *Bullshit Jobs* (2018), p. 84-92, or Patel&Moore *A History of the World in Seven Cheap Things*, (2018), ch. 3.

Fukushima nuclear accident in 2011,[9] shareholders only suffer to the extent that their shares lose value. If instead they owned the company, they would be liable out of their own pockets and would risk going to jail for such accidents. This encourages risky investments: who would invest in nuclear power if they had to compensate the victims of an accident? But in return, the risk is borne by the community: at most, the company goes bankrupt and closes down, which means that the compensation is limited to the company's value. What is TEPCO worth today compared to the damage caused by the Fukushima accident?[10]

The 19th century was marked by another change that is worth mentioning: the abolition of slavery on both sides of the Atlantic. Along with protests by slave communities (the most successful episode of which was the Haitian Revolution (1791-1804) in the French colony of Saint-Domingue), abolitionist societies, often with religious inspirations, led active campaigns based on the ideas of the Enlightenment movement. As early as 1807 Great Britain banned the slave trade and during the following century the Royal Navy hunted down slave ships of all nations off the coast of Africa! While these actions may have served the economic interests of England in rivalry with the French colonial empire, this is an important historical case where nations mutually coerced, influenced and aligned themselves to put an end to an activity that was economically profitable for some, based among other things on ethical grounds.

9 — In December 1984, a gas leak from a pesticide manufacturing plant in Bophal, central India, killed nearly 4,000 people directly and over 500,000 indirectly. See https://en.wikipedia.org/wiki/Bhopal_disaster. On the more recent accident at the Fukushima nuclear power plant, see https://en.wikipedia.org/wiki/Accident_nucl%C3%A9aire_de_Fukushima

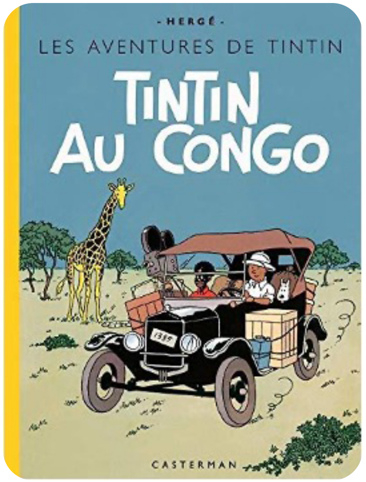
10 — Adam Smith himself, in *The Wealth of Nations*, predicted both the advantages that the new system would give to investors, and the disadvantages that it would bring to business. On the one hand, "this complete exemption from worry and risk, above a certain sum, encourages many to venture into joint-stock companies, when they would never have risked their fortunes as partners in a business. But on the other hand, the managers of joint-stock companies, as they manage the funds of others, will not take the same care of them as if it were their own money, so that one can expect from them "negligence and profusion": negligence as regards the interest of the company, profusion as regards their own advantages."

Summary

- Changes in English law happened with the coal industrial revolution.
- The lifting of customs barriers facilitated international trade, even if this meant losing some of national food self-sufficiency by exporting manufactured goods.
- Individual property rights took precedence over rights of the "commons", notably with the Enclosure Laws.
- The invention of the limited liability company allowed the development of financial capitalism and encouraged risk-taking by private companies.
- The abolition of slavery during the 19th century is a historical example where ethical motivations contributed to the international suppression of an economic activity that was still profitable for some.

3.3. The capitalist ethos and the ideal of progress

In the 16th century, Europeans justified the colonization of the New World and the exploitation of its human and material resources with evangelization: the material benefits they derived from it were merely the deserved reward for the eternal salvation they brought to populations that, otherwise, would never have known Christianity. In the 19th century, it was the enhancement of nature and the civilization process that served as a moral justification, with some variations according to the country. In America, the United States moved in half a century from the East to the West coast (California joined the Union in 1850), annexing a large part of the Spanish colonies in Mexico and justifying this conquest with the doctrine of "manifest destiny" according to which it was their obvious and quasi-divine mission to develop the whole American continent. In France, Jules Ferry, a defender of public education and a fervent apostle of colonial expansion, declared in the parliament in 1885: "there is a right for the superior races, because there is a duty for them. They have the duty to civilize the inferior races". The mission of education that the Republic is in charge of in France is naturally continued by a mission of civilization in the colonies. To immerse oneself in the atmosphere of this period, it is illuminative to read *Tintin in the Congo* (1931), preferably the original edition.[11]



Over four centuries, the Christian paradise promised to the natives became a material paradise, where the invisible hand of the market replaced divine providence. The conquistador accompanied by missionaries turned into a businessman in search of profits. This evolution was analyzed by the German sociologist Max Weber in *The Protestant Ethic and the Spirit of Capitalism* (1904). He explains how Calvinism, by seeing in the believer's material success a sign of divine grace, favored the appearance of a type of man, austere in his private life, but a shrewd and enterprising businessman, seeking profit not for himself but to reinvest it in the business. These are the first capitalists, and their future successors will seek profit for its own sake and not as a divine mission.

The moneylender and his wife, Quentin Massys (1514)

Summary

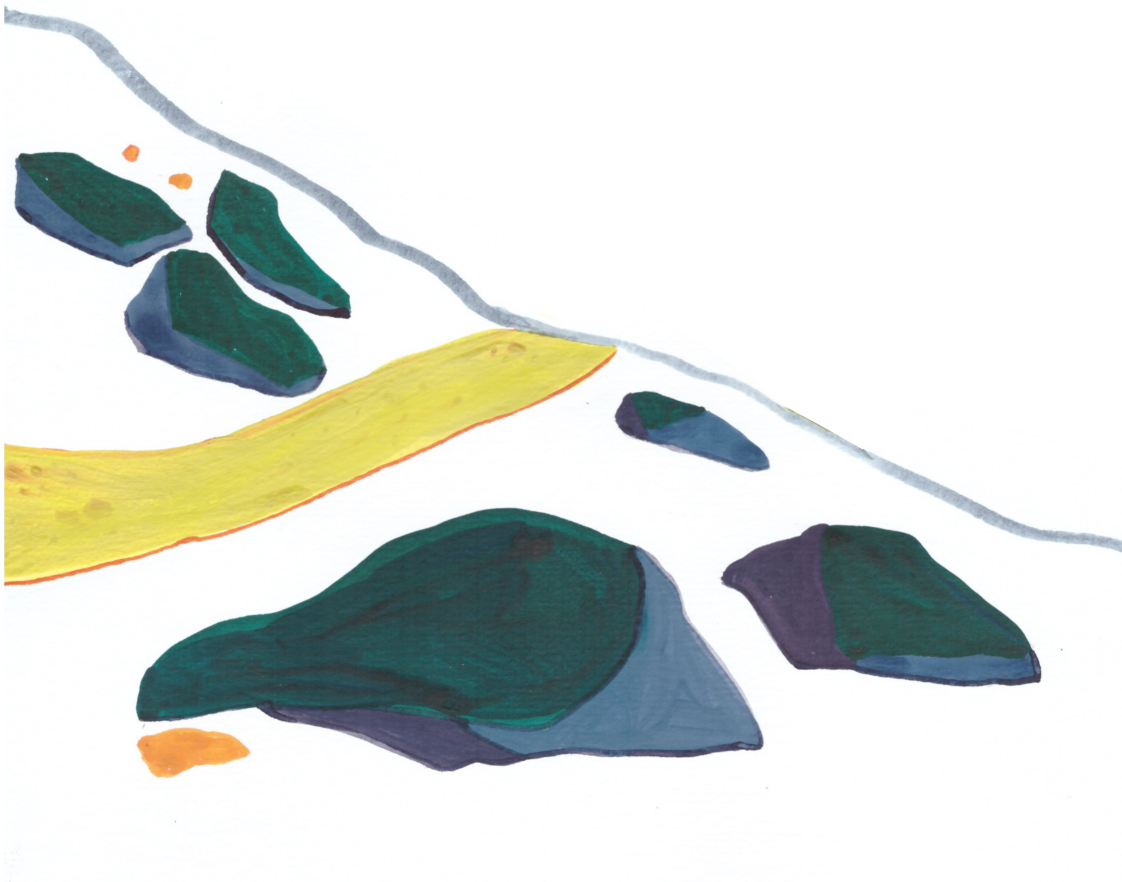
- The ideological and moral framework supporting colonization and the new systems of production is no longer based on evangelization and the prospect of eternal salvation, but on the belief in progress.
- Through Calvinism, a new ethos appeared, described by Max Weber. It values material prosperity and professional success: the ethos of the capitalist who reinvests his profits not in personal consumption but in his business.

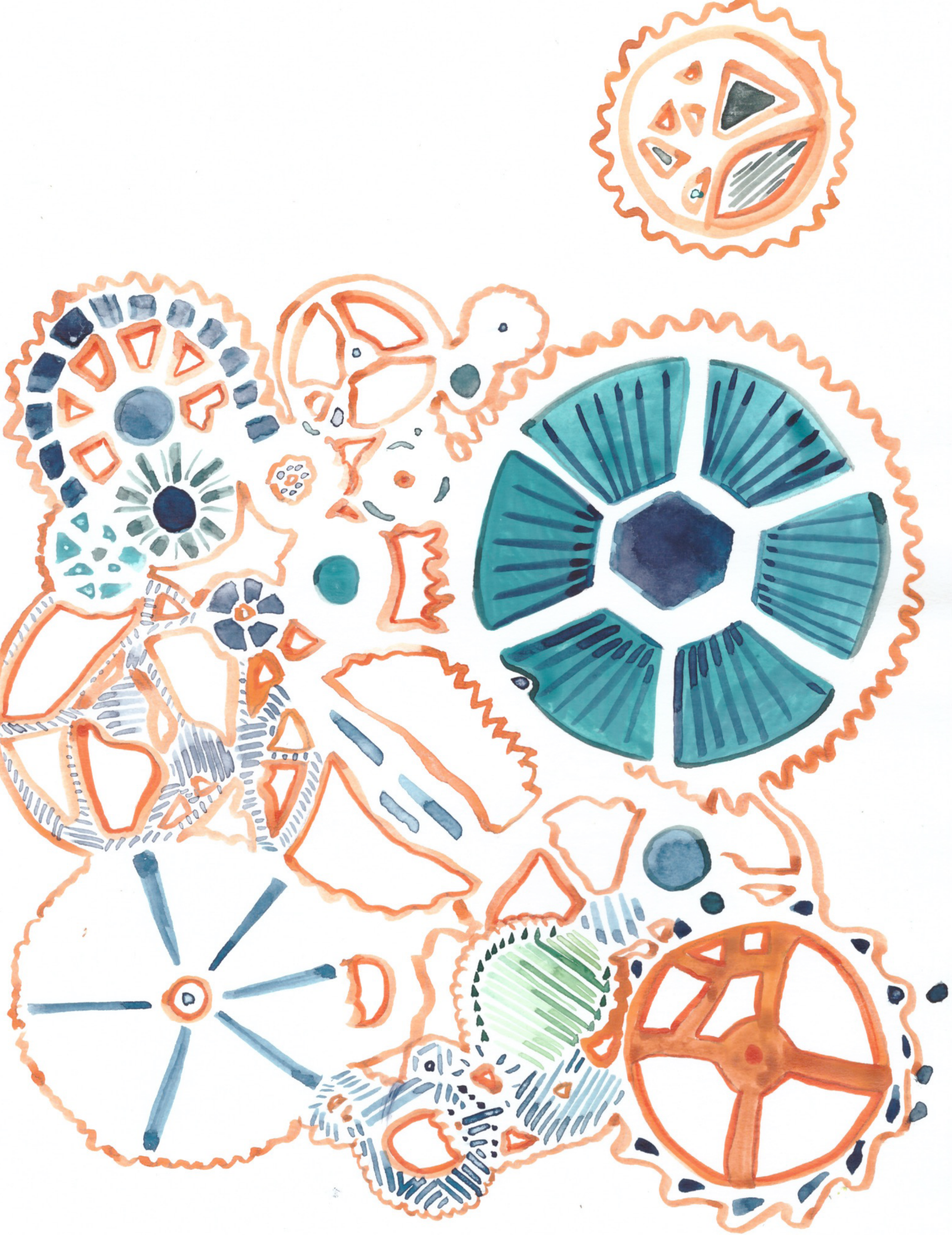
11 — To do justice to Hergé, let us note that a few years later he published *The Blue Lotus*, (1935), which shows the underbelly of the European and Japanese presence in China.

Conclusion

Europe and the United States entered the 20th century in the euphoria of progress. Material progress, which brought the whole world within reach of London or Paris by regular lines of ships or railroads. Human progress, manifested in medical advances and a longer life expectancy. Scientific progress, with the domestication of electricity, and the birth of modern economic theory. Mankind no longer seeks salvation in the afterlife, but seeks happiness through material prosperity, and the invisible hand introduced by Adam Smith must harmoniously orchestrate human relationships in the economic space.

And in the meantime: the CO_2 emissions from human activity reached 6 billion tons in 1950, and the CO_2 content of the atmosphere, which oscillated around 280 ppm in historical times until 1800, rose to 311 ppm in 1950. By this time, the exploration of the planet was complete: there were no more blank spaces on the maps, and human influence was to be seen in all the ecosystems of the planet, even in the depths of the oceans.





10

A Brief Social History of GHG Emissions

Part II — The great acceleration

Introduction

The CO_2 content of the atmosphere rose from 284 ppm in 1500 to 310 ppm in 1950. It has reached 420 ppm today. In 70 years, the concentration of CO_2 increased 4.2 times more than in the previous 450 years! This is the period known as the "Great Acceleration", where everything accelerated: the world GDP multiplied by 22 between 1950 and today, the world population tripled and the annual CO_2 emissions multiplied by 6 (they went from 6 billion tons per year to 36.5).[1]

Why and where is this frantic race heading? It is all the more important to provide answers to this question as the acceleration movement is still going on today. With the exception of the Covid-19 pandemic, neither the financial crises nor the Paris agreements have so far slowed this acceleration. Identifying its drivers is essential if we want to change the trajectory.

1 — See https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions. Note that the total GHG emissions reached 50 million tons of CO_2 equivalent: CO_2 therefore represents 72% of emissions.

A few questions to warm up

- In 1913, the first ammonium nitrate manufacturing plant opened in Germany at the historic BASF headquarters. The process was designed to boost plant growth by supplying nitrogen. Over the next 4 years, the entire production was bought up for a completely different purpose: what was it?

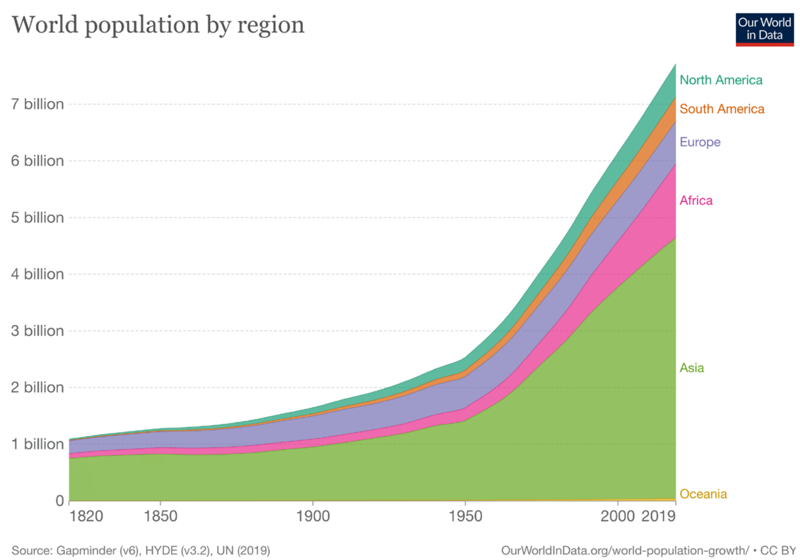
Answer: The production was bought by the German army to produce war explosives.

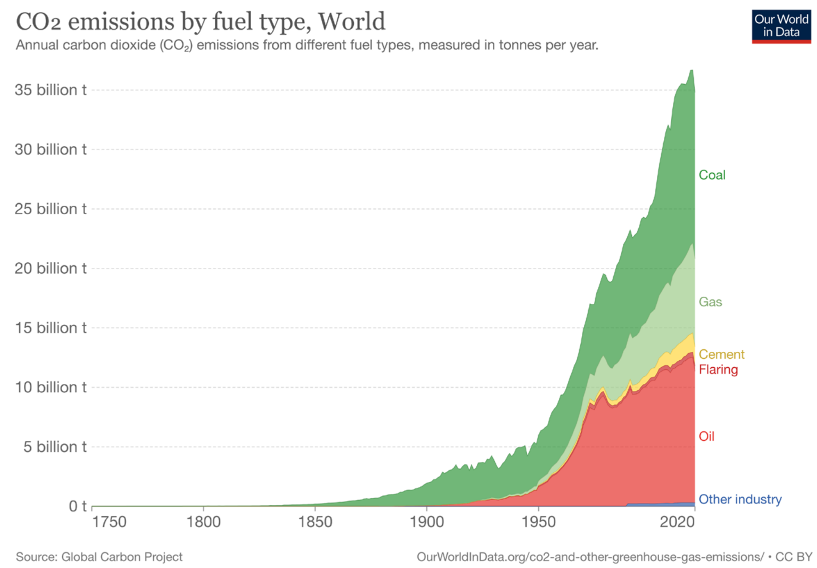
- What color are lobsters?

Answer: Blue! The reason we think of them as red, and why they are portrayed that way in children's books and cartoons, is that we are used to seeing them on the plate once boiled, like many other foods and objects that come to us already processed.

1 The "Belle Époque" of fossil fuels

Let's first go back to the introductory graphs from the previous chapter.





World population and CO_2 emissions growth

Source : OWID

From the year 1945 onwards, the world embarked on an unprecedented path of growth in every direction. The world's population increased from 2.37 billion to 7.8 between 1945 and 2020, the world's GDP was less than 10,000 billion dollars in 1950 and exceeded 100,000 in 2013. These are not abstract and immaterial figures. Quite the opposite! GDP counts objects (and services) and population... living bodies to feed.

This unprecedented material growth is based on a profusion of energy and raw materials. While in the first half of the 20th century, fossil energy consumption increased by 1.7% per year, it increased by 4.5% per year in the second half. Between 1950 and 1970, the consumption of minerals tripled, as did that of construction materials.[2] Annual GHG

2 — See Bonneuil et Fressoz, L'événement anthropocène, chap 10.

emissions were growing at the same rate: annual CO_2 emissions, for example, increased from 6 billion tons in 1950 to 36.5 in 2019.

1.1. Energy from oil

The hero of this Great Acceleration is oil. Oil had been known and exploited since the middle of the 19th century, when kerosene made from petroleum replaced whale oil in lamps. But its development really began in 1905, when Henry Ford launched the mass production of a gasoline-powered automobile.

Oil has enormous advantages over coal: it is more concentrated in energy, easier to use (it is liquid, it flows from tanks, no need for drivers to shovel coal into the boilers of ships or locomotives), easier to transport (pipe-lines instead of endless trains), and above all it is easier to extract. Liquid fuels derived from oil, such as gasoline, diesel and kerosene, thus rapidly became the preferred sources of energy for transportation and an essential lever of power, especially for the military.

This is not without social consequences. The exploitation of a coal mine requires miners, who are quick to realize that they have a means of pressure at their disposal. Historically, miners have always been at the forefront of the labor movement. An oil well, once opened, requires only a few engineers to open or close the valves, so that the closure of coal mines in Europe can be seen as one of the reasons for the decline of the labor movement.

1.2. Adding up fossil fuels

Between 1950 and 2018, world oil consumption increased from 0.47 million tons of oil equivalent (toe) to 4.7, a tenfold increase! But this is not a one-man show. As we have seen in previous chapters on the history of energy, coal consumption has also increased from 1.08 to 3.8 million toe between 1950 and 2018, a 3-fold increase. And a third fossil fuel appeared: gas. Gas was almost insignificant in 1950, with 0.17 million toe, but competes with oil in 2018, with 3.2.

Although oil played a central role, the Great Acceleration is therefore the "Belle Époque" of all fossil fuels. Oil did not supplant coal: it replaced it in some uses, such as transportation, so that coal would be used in other instances, notably for electricity production. Gas has not substituted for oil: it replaced it in some uses, such as electricity production or heating, and in chemistry. In today's power generation, coal, oil and gas are all used to meet different needs: diesel generators for individual needs or back-up facilities, coal-fired power plants near mines, and gas-fired power plants that are easy to start up at peak times.

Summary

- The explosion in population and CO_2 emissions after 1950 marks the beginning of the Great Acceleration.
- Both explosions are closely linked to an unprecedented consumption of Earth resources, notably of fossil fuels: oil consumption has increased tenfold in 70 years.

2 New military powers, new industrial systems

2.1. Redirecting the war industries

In 1950, Europe emerged from two devastating world wars. England, France and Germany: the old dominant countries of the 19th century were weakened and largely to be rebuilt. Instead, two new powers were then taking over: the United States and the USSR. The world geopolitics of the post-war decades is thus quite different from that of the previous century. It is structured around the US/USSR rivalry, without colonial empires as such, but with clearly identified zones of influence and interference.

But while the European countries needed reconstruction, the victorious countries, notably the United States and the USSR, found themselves with huge capital in the form of war industries. Between 1939 and 1944, the GDP of the United States increased by 60%![3] What was to be done with these immense industrial capacities? What was to be done with these hundreds of factories, these new materials and techniques originally intended for military use, all this knowledge and new expertise? The answer was to convert this industry to civilian uses, even if it meant creating new needs.

3 — Source: OWID. US GDP went from $1,470 billions in 1939 to 2,360, in constant dollar terms.

We are often under the impression that progress is inevitable and that its path is clear. As the saying goes, "You can't fight progress". On the contrary, more often than not, the path chosen for development depends on historical circumstances and political decisions that could have been different. In this case, the conversion of the war industries in the world of 1950 was a strategic and explicit political decision.

This general policy has profoundly structured key sectors, with energy, transport and agriculture in the lead. We would not have a civilian nuclear industry if there had been no military nuclear industry: in 1945, in the United States, the Manhattan Project employed more than 100,000 people. A few years later, in 1951, the first nuclear power plant went into operation in the United States. Similarly, the factories which manufactured trucks, ships and airplanes for the military turned to the needs of civilians. Since these needs did not exist at the time, and civilians had other things to worry about, they had to be encouraged and stimulated. In 1944, for example, it was decided not to tax the fuel used by airplanes, at the time of the so-called "Chicago Convention". Its original aim was to encourage people to fly by lowering the price of plane tickets. The convention is still in force today and creates a considerable distortion of competition between this mode of transportation, which emits a lot of GHGs, and the others. But the most striking example of war industry redirection happened in an unexpected sector: agriculture.

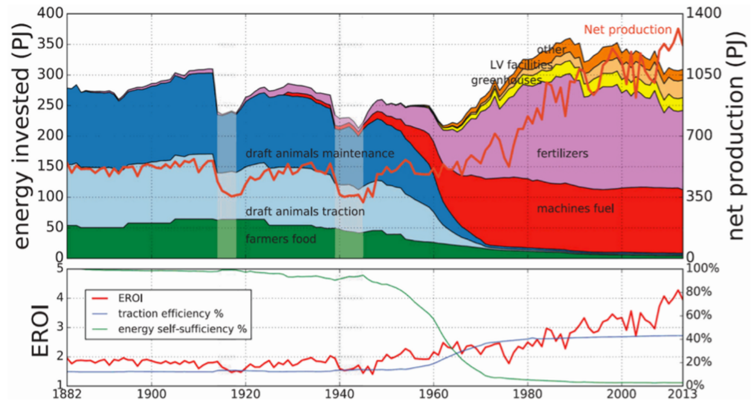
Summary

- The redirection of war industries after 1950 was an explicit political choice and ensured continuity of past techniques and economic interests.
- Three key sectors were deeply transformed: energy, transportation and agriculture.

2.2. The case of agriculture

For forty years, between 1950 and 1990, the population growth rate remained above 1.5% per year. This growing population had to be fed. Between 1961 and 2017, the world production of cereals (including rice) increased from 0.8 billion tons to 2.7 billion.[4] Over the same period, yields per hectare increased: they were multiplied by 2.4 for wheat, 1.5 for rice and 2 for corn.[5]

This feat was achieved through the industrialization of agriculture. In a few decades, tractors replaced human and animal labor: draught animals disappeared from the countryside. The nitrates and ammonia that plants need were no longer supplied by soil bacteria, but brought to them directly in the form of industrially manufactured fertilizers. [6]Finally, by using herbicides and insecticides, the farmers eliminate wild plants and insects from their fields. All these products, from fuel for farm machinery to pesticides, require a lot of fossil energy. The figure below compares the energy provided in the field in the form of labor and inputs to the energy collected in the form of food calories: the ratio of the two (EROI) doubles between 1950 and 2013, from 2 to 4, while production triples.



Energy profile of an average French farm

Source: Les Greniers d'Abondance[7]

Interpretation: Evolution of energy invested and energy recovered (net production) by French agricultural production since 1882. Energy expenditures correspond to food (farmer food and draft animals), showing the energy needed for work (traction) and the energy needed to maintain the animals, fuel for agricultural machines, the manufacture of nitrogen, phosphate and potassium fertilizers, the heating of greenhouses, the operation of livestock buildings and associated machines (LV facilities), the manufacture of phytosanitary products and irrigation (others). The evolution of the energy rate of return (EROI), the energy efficiency of mechanical work (traction efficiency) and the energy self-sufficiency of farms are shown in the lower graph. Original figure from Harchaoui and Chatzimpiros (2018).

4 — Source: OWID https://ourworldindata.org/search?q=world+cereal+production

5 — Source: OWID https://ourworldindata.org/crop-yields

6 — Ammonium nitrate was used in the form of nitric acid in war explosives and as a so-called "mineral" agricultural fertilizer, providing the nitrogen needed for plant growth. It was the same product that triggered the huge explosion in the Beirut port warehouse on August 4, 2020.

7 — https://resiliencealimentaire.org/lempreinte-energetique-du-systeme-alimentaire/#post-12761-endnote-ref-3

Plants and nitrogen

Through photosynthesis, plants store solar energy in the form of organic matter. It is made up of specific molecules, proteins, which are long chains of carbon atoms, interspersed with hydrogen, nitrogen and other atoms. Without nitrogen, there are no proteins, and therefore no organic substance. Nitrogen is abundant in the air, but in the form of N_2, which is very stable, and therefore unassimilable by plants. The splitting is performed by soil bacteria, which release the nitrogen in the form of ammonia (NH_3) or nitrate (NO_3), that plants can metabolize. This is why certain crops, such as leguminous plants, are extremely valuable as their roots contain nodules where bacteria live in symbiosis with the plant and release ammonia and nitrate into the soil.[8] For a long time, farmers have tried to bring directly to the soil the nitrogenous compounds that they needed. Manure or seaweed was spread on the fields. In the 19th century, guano was even mined in the Chincha Islands and native nitrates in the Atacama Desert. But the situation changed with the development of the Haber-Bosch industrial process. This process allows the synthesis of ammonia from nitrogen in the air and hydrogen under high pressures (200 atm) and temperatures (500°C). The process requires high quantities of fossil fuels because hydrogen is obtained by cracking methane. In spite of this, because of the low price of these fuels, it remains profitable. Today, ammonia production is estimated to require 3 to 5% of the world's natural gas production and 1 to 2% of the world's energy production.[9]

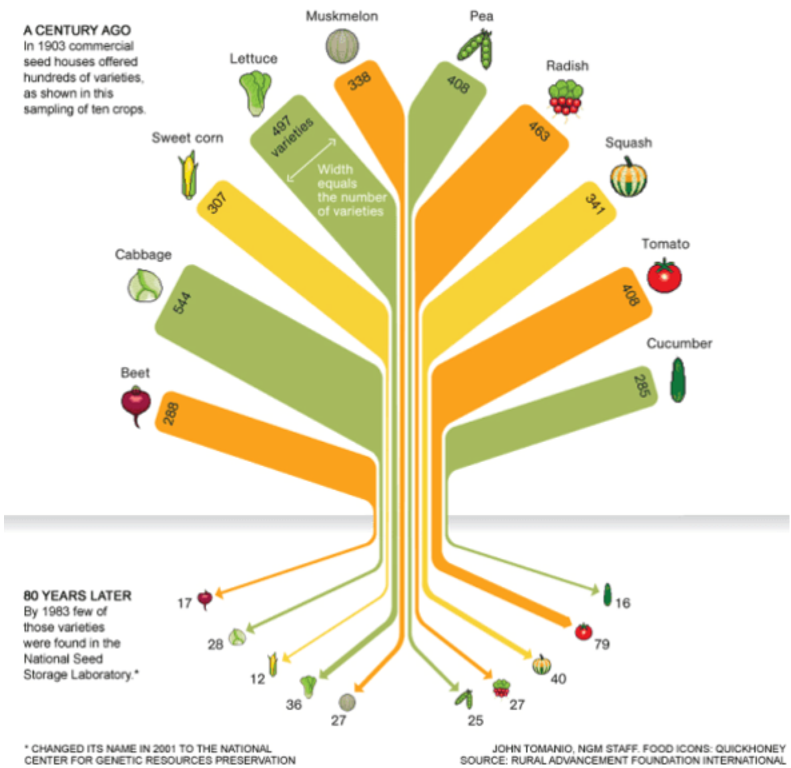
The industrialization of agriculture extends to the entire food chain, both upstream and downstream, from the supply of seeds (most often under patents), fertilizers, pesticides and machinery, to the transportation of products, their processing and distribution. Today, in France, six large retailers represent more than 70% of the food distribution market. In Germany it goes up to 85% and in Great Britain 93.5%.[10] The food industry and international trade have focused on a few standardized food products, easily traceable, recognizable by consumers and optimized to be cultivated with chemical inputs and mechanical engines. Out of 6000 species of plants cultivated for food, 200 are commercialized today, and only nine ensure 2/3 of the world's production by weight: sugarcane, corn, wheat, rice, potatoes, soybeans, palm oil, sugar beet and cassava.[11] In the remaining productions, such as fruits and vegetables, there has been a significant reduction in the varieties that are cultivated:

8 — For additional details, see Matthieu Calame « Comprendre l'agroécologie », ch. 1 http://docs.eclm.fr/pdf_livre/220ManuelAgroecologie.pdf

9 — See https://fr.wikipedia.org/wiki/Proc%C3%A9d%C3%A9_Haber

10 — See Mathieu Calame, « Enraciner l'agriculture », PUF, p.166

11 — FAO, The State of the World's Diversity for Food and Agriculture, https://www.fao.org/3/CA3129EN/CA3129EN.pdf



Comparison of vegetable varieties available for purchase in the United States in 1903 and in 1983

Source: John Tomanio, National Geographic

Interpretation: While American farmers could choose from 497 varieties of lettuce to plant in 1903, by 1983 only 36 were available at the National Center for Genetic Resources Preservation.

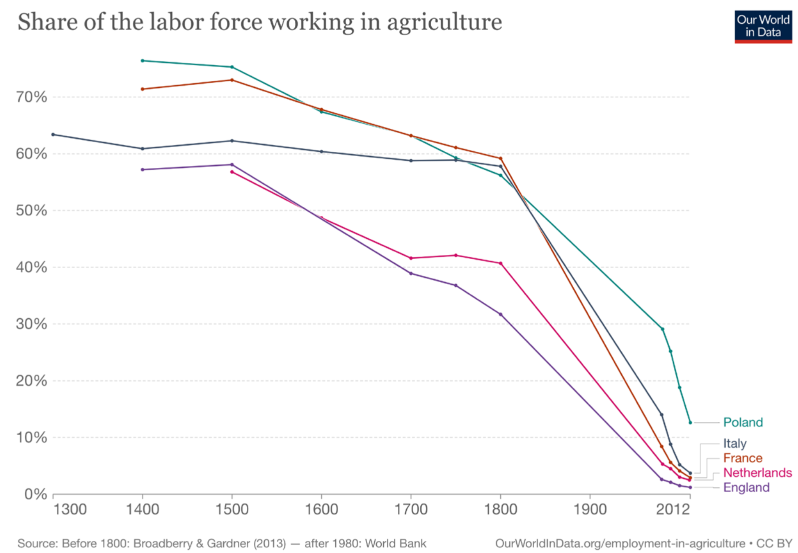
A consequence of the increase in yields per hectare is the spectacular increase in meat consumption: agricultural surpluses were so plentiful that they have been used to feed animals! In 2013, for example, out of 227 million tons of soybeans produced worldwide, only 11 were dedicated to human consumption. The rest was for animals or biofuels.[12] Similarly, it is estimated that at least 60% of corn production goes to animal feed. The result is that the production of meat in the world, all species combined, has increased fivefold between 1960 and 2018.[13] As far as cattle are concerned, we have gone from 29 to 73 million tons. Considering that one kilogram of consumed beef equals an emission of 100 kilos of CO_2 equivalent, this is a significant contribution to the greenhouse effect.[14]

The industrialization of agriculture is a factor of major social transformation. It began during the industrial coal revolution and deepened during the second half of the 20th century. Agricultural machines are all the more efficient as the surfaces to be treated are large and homogeneous, which led to the creation of large farms by the aggregation of fields, and therefore to the transformation of landscapes (hedges and ponds disappeared) and to the depopulation of the countryside. Over 200 years, the share of agricultural employment in total employment has fallen from more than a third to less than 5% in almost all European countries. Peasant populations thus displaced from the countryside became the workers of the industrial revolution factories.

12 — OWID: https://ourworldindata.org/grapher/soybean-production-and-use?country=~OWID_WRL

13 — OWID: https://ourworldindata.org/meat-production

14 — OWID: https://ourworldindata.org/meat-production#global-meat-production



Share of active population in agriculture in 5 European countries since 1300
Source: OWID

This rural exodus was also enforced in Europe by privatising ("enclosing") the rural commons and edicting vagrancy laws. It did not happen in a country like India where agriculture is still relying on half of the population, i.e. 650 million people. The average area per farm is 55 hectares in France and 1.2 ha in India. Yet the farming methods are the same: one has to pay for tractors, fertilizers and pesticides to increase production. This is possible in France, thanks mostly to the financial support of the CAP (Common Agricultural Policy of the European Union), but not in India. It is therefore not surprising that farmers' suicides are multiplying and that huge demonstrations of farmers blocked New Delhi for months in 2020.

On a global scale, the depopulation of the countryside is the dominant trend. Between 1960 and 2020, the urban proportion of the world's population rose from 34% to 56%:[15] today, more than one human being out of two lives in a city, far from the other animal and plant species that share the planet with him/her, and largely unaware of the great natural cycles that allow him/her to breathe and eat.

In this post-war industrialized scheme, agriculture has become a major contributor to the greenhouse effect. We have seen that according to the IPCC, a quarter of global GHG emissions in 2014 came from food production,[16] notably through methane emissions from livestock (ruminants burp!) or rice cultivation, the manufacture and use of synthetic fertilizers (which emit nitrous oxide) and the CO_2 emitted by agricultural machinery. We must also add the effects of deforestation, which increases arable land but destroys organic matter whose carbon is then released into the atmosphere.

But the impact of agriculture is not limited to GHG emissions. The agri-food system also impacts natural balances through its geographical reach: 1,000 years ago, less than 4% of the Earth's surface (excluding glaciers and arid zones) was used for agriculture. This figure is estimated at 50% today[17] three quarters of which is used for grazing and feeding livestock. This has naturally reduced the space available to wildlife. If we look at the biomass of mammals, for example, excluding humans, only 6% are still wild. There is therefore a major impact on biodiversity, further accentuated by the use of so-called "phytosanitary" products, designed to eliminate insects, plants or fungi harmful to crops, but which are in no way selective and therefore have a much wider destructive effect.

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15 — See https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS
16 — OWID: https://ourworldindata.org/greenhouse-gas-emissions-food

17 — OWID: https://ourworldindata.org/environmental-impacts-of-food?country=

Summary

- Taking advantage of war technologies, agriculture was industrialized and mechanized. Food is produced by tractors and nitrogen fertilizers, ultimately from oil.
- Yields per hectare increased considerably during the second half of the 20th century. This generated a surplus that allowed the consumption of animal meat to increase.
- Industrialized agriculture is now responsible for about 1/3 of GHG emissions, and has a considerable impact on biodiversity.

2.3. A new industrial revolution

Rational and quantifiable management

Modern warfare is fundamentally a logistical problem. The success of the Normandy landings during the second World War, for example, required moving 24,000 men in a few hours on a hundred kilometers of beaches, and bringing in reinforcements and supplies for a few weeks, which meant organizing the rotation of 7,000 ships and as many planes.

The progress in logistics during World War 2 is illustrated by the example of the Liberty ships. Liberty ships are multipurpose armed cargo ships of 3,500 tons. During the five years of the war, the United States built 2,710 of them, but whereas it took 230 days to build one in 1941, the average time of construction was down to 42 days in 1945, the record being set at less than 5 days. Logistics, i.e. the organization of production, became a field of research in its own right, in which mathematics played a crucial role. Rather than relying on the manager's flair or experience, one would define quantifiable performance indicators to maximize. This was the birth of the concept of optimization. These logistics principles quickly spread to all management disciplines, and proved to be central to neo-classical economic theory.

The GDP as a compass for economic policy

To apply the new management rules to economic policy, a performance indicator to be optimized was needed. The chosen one was the GNP, gross national product, which later became GDP, gross domestic product. GDP is a quantified indicator that measures the monetary value of the material goods produced in a country in the course of a year, minus the total value of the material goods used, and therefore destroyed, in the production process. For example, the contribution of a Liberty ship to GDP is the value of the ship, minus the value of the materials used.

In the second half of the 20th century, neoclassical economic theories became the backbone of public policies and promoted the use of GDP to guide economic policies towards material profusion. All nations would calculate their GDP and try to make it grow as fast as possible. From 1970 onwards, neo-classical ideas in economics triumphed. Its main champions were Friedrich von Hayek (1899-1992) and Milton Friedman (1912-2006), who were very involved in the intellectual battle against socialism. The ideas of trade liberalization and the establishment of free competition were enshrined in international treaties and founding institutions such as the single market of the European Union or the World Trade Organization.

Note that by definition, in the GNP or the GDP, what costs nothing does not count. In the end, the construction of a ship uses scarce minerals, and creates pollution, at least through GHG emissions. But GHGs do not appear in the GDP as long as it does not cost anything to emit them. As for minerals, they only appear because of their extraction cost: coal, iron or gold that lie in the ground do not cost anything in themselves and whoever finds a piece of it on his way can bend down and put it in his pocket. The only cost is due to finding and extracting them. Nature is considered as a reservoir from which is free to collect anything: first come, first served. And with the liberalization and globalization of trade, the activities of production, processing, consumption and waste disposal were spread out in different countries, making the impact of production on natural systems even less visible.

GDP therefore takes little account of the state of the planet, or of society. Individual and collective well-being does not depend exclusively on the total consumption of material resources. They also depend on the quality and the distribution of these resources, as well as on the common rules governing social life, which should guarantee the dignity and fulfillment of every individual. If the reasonable objective of an economic policy is to increase collective well-being, or at least to maintain it over the long term, this necessitates preserving natural resources and good conditions for life in society. That is why GDP is not a suitable indicator: it can perfectly grow while natural resources are depleted and our living conditions deteriorate.

Summary

- The war favors the emergence of quantifiable management techniques using mathematics.
- GDP became the new compass of economic policies.
- GDP values the increase in material production and does not take into consideration the impacts on nature or the consequences on society.
- Neoclassical economic theories are the theoretical backbone to advise public policies. They advocate creating institutions and laws which favor the free trade of goods and capital.

3 New lifestyles

What about social transformations? To introduce the previous chapter, we proposed a thought experiment of time travel with a Renaissance peasant woman. We imagined that she would not have felt too disoriented if she had been taken back fifteen centuries. But into today's world, she would be completely disoriented.

This is because we live today very differently from the generations before us: our routines, the type of work we do, our relationship to work, our cultural and ideological references have been profoundly transformed. Think about what you are used to finding on your plate and how you got that food (probably not by planting and harvesting your own carrots). Consider women's rights, the number of children in your family, and the people you share your home with (probably not your parents or grandparents, let alone the animals you raise for food). Consider your life expectancy and the difference between societies where 45 is a record age and those where more than half the population is over that age. Think about the place of religion and moral authorities in your life, the guidance you get from science, and the role you think you should play in politics. Think about the technical tools you work with and live with every day. Consider the geographical area in which you are able and used to moving.

All of this is radically different from the experience of an individual 500 years ago. There is no exaggeration in calling this a social revolution. In the rest of this section, we will present four characteristics of our modern societies that are significant in order to understand the current ecological upheavals: the massive production of waste, the relationship to manufactured objects, our estrangement from the planet, and eventually our conception of the individual.

3.1. New materials, new waste

GDP, free trade, the single market...: the explicit purpose of these new economic and political paradigms was material prosperity for as many people as possible. It is fair to say that it was a success! Between 1950 and 2018, GDP per capita was multiplied by 4.5 while the world population was multiplied by 3.25. This means that a huge mass of manufactured objects has been dumped on the population, and then ended up, more or less quickly, in nature in the form of waste.

Among these are molecules that had never existed before on planet Earth, and that natural cycles are actually unable to decompose. The cumulative production of plastic, for example, has increased from 2 million tons in 1950 to 270 in 2010,[18] boosted by the growth of disposable products. In that same year, 275 million tons of waste were produced, 25% of which was recycled, 20% incinerated, and 55% dumped into the environment where it accumulates.[19] Today, the world's wildest beaches, such as Henderson Island in the South Pacific, are littered with plastic waste, some of which is fifty years old or more. In some ocean areas the density of plastic is six times that of plankton.

3.2. Manufactured short-lived goods

Societies have to absorb all this production, and to this end, individuals have to consume. The time when individuals were limited to satisfying basic needs (food, housing, clothing) is long gone, and a whole industry, advertising, has developed to create new needs (social media, movies, traveling, fashion). Simultaneously, the relationship to objects has changed. As opposed to a time when social standing was determined by birth or by one's community, it can now be earned through material possessions.

18 — OWID : https://ourworldindata.org/grapher/global-plastics-production

19 — OWID : https://ourworldindata.org/plastic-pollution

If production does not decrease, consumption must follow: one object drives out the other. As Jean Baudrillard says at the beginning of his book *The Consumer Society* (1977): "We live in the time of objects: I mean that we live at their rhythm and according to their incessant succession. Nowadays, we watch them being born, fulfilling themselves and dying, whereas, in all earlier civilisations, the objects, instruments or perennial monuments, survived the generations of men."

The daily environment of the inhabitants of the developed countries and of a growing part of the emerging countries is mainly populated with manufactured short-lived things, and no longer with living beings, plants or animals. Even the natural objects themselves that come to us have already been transformed. Buy a carrot: it is already washed, sorted, often packed, always transported, sometimes already cooked. Nature is thus rejected far from our daily concerns and attention, especially if we live in the city. In this context, it is not easy to measure the loss of biodiversity or the permanent pollution caused by the plastic packaging of our food.

3.3. Beyond our planet's boundaries

This disappearance of nature from everyday life finds its counterpart in a new fantasy world. The second half of the 20th century was the time of the "spatial conquest": after having reached the Moon, we are out to colonize Mars. In terms of available energy, the mastery of nuclear power has opened up a range of possibilities that seem unlimited. The new agricultural methods have reinforced the idea that human beings have become "masters and possessors of nature", just like Descartes wished. They have tamed and enhanced Nature's power, they have explored the entire planet and are now able to control it. In short, humans have freed themselves from Earth's boundaries.

According to this view of unlimited progress, the responsibility of mankind then is to "manage the planet Earth", using the scientific methods of management developed since 1950. Buckminster Fuller's 1969 book, *Operating Manual for Spaceship Earth*, sums up the spirit of the times, and the distancing of human beings from their natural environment. Descartes had already considered animals as machines; now the whole planet is a spaceship, and human beings are its passengers and pilots: they are on board, but not part of it.

There were a few discordant voices. In 1972, a team of scientists from MIT published a report entitled *Limits to Growth*, known as the "Meadows Report", which predicted a collapse of the world's economies in the 21st century if current trends continued (if we were to follow "business as usual"). The originality of this report is that it is based on a mathematical model of the world economy taking into account the depletion of natural resources and the cost of pollution, and on numerical simulations, at a time when computers were large and slow machines and cumbersome to program. This report caused a stir, but was quickly rejected by influential economists, led by Friedrich Hayek, who believed that the market would solve the problem by acting on prices. The report was forgotten, the party went on, but it had raised the old Malthusian question in a modern way: how on Earth can infinite growth be possible in a finite world?

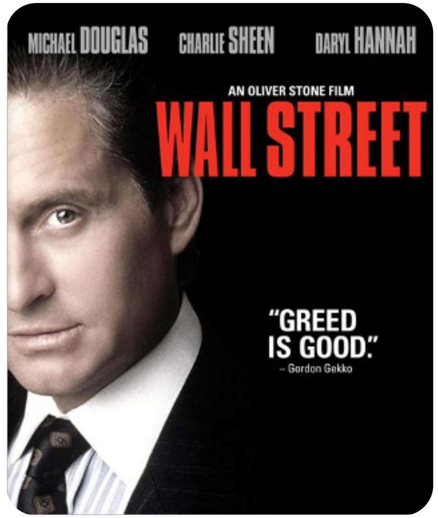
3.4. Serving the economy

The Renaissance split the individual from nature. Modernity has brought an additional splitting, within the individual himself: the separation between consumption and production. For a long time, work had been considered as a positive value, which revealed one's social status. One took up one's parents' trade (notary, baker, farmer…) and this conferred a status in the community.

In neoclassical economic theories, inherited from Jean-Baptiste Say and Adam Smith, the individual is first and foremost considered as a consumer who never gets his fill, who only works to earn the money he needs to satisfy his desires, and who only feels bound to others by the either explicit or implicit contracts he previously made with them. The role of the State is to make sure that these contracts are implemented, and companies are organizations whose sole objective is to make a profit. According to neoclassical theories, this is the best way to serve the greatest possible number of consumers with the products they want at the lowest cost and the right way to do it is through free market trades. This state of society is considered optimal ; note, however, that it depends on the initial distribution of wealth and does not purport to correct it.

In such a world paradigm, classical values of ethics, such as justice, or of citizenship, such as solidarity, are disregarded and considered as superfluous, or even dangerous. Friedrich Hayek chose to call one of his books *The Mirage of Social Justice* (1977). Gary Becker, a Nobel Prize-winning economist from the University of Chicago, models human behavior as a series of calculations and claims the universality of this approach, even in the most private domain of life, in his *Treatise on the Family* (1993).[20]

The Great Acceleration, therefore, not only led to an explosion of industrial production and its hold on nature, but to a coherent and complete social theory. This theory goes from the analysis of individual behaviors to macroeconomic recommendations, the first of which is to make GDP grow. In this theoretical framework, the engine of growth is the search for profit by companies and for material prosperity by individuals. The process identified by Max Weber is complete: no more reference to religion, material prosperity is sought for its own sake. "Greed is good" proclaims the hero of the film *Wall Street* (1987), as it is an individual and collective means of maximizing material production.



Summary

- Lifestyles have changed radically over the last 200 years, and even more rapidly in the second half of the 20th century.
- The consumption of material objects satisfying ever-growing needs has led to a material prosperity and a production of waste on an unprecedented scale.
- This relegated natural living beings far from daily concerns.
- Collective imaginaries abstract away from our planet's boundaries: any location is within reach and natural phenomena can be understood and controlled.
- The heirs of Jean-Baptiste Say and Adam Smith have constructed a theoretical economic framework, known as "neoclassical", according to which human beings behave first and foremost as consumers, bound to others only by contracts.
- According to this theory, the only objective of a firm is to maximize its financial profit.

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20 — In a book that profoundly influenced economic thought, *The Economic Approach to Human Behavior* (1978), Gary Becker illustrates his theory of calculating individual behavior with numerous examples from daily life.

Conclusion

How can things change (or not)?

We have reached the end of our journey. We have tried to grasp the main social transformations of the last 500 years that caused the ecological upheavals of the 21st century. There are many books on any of the topics we have discussed — and we probably have neglected other important questions! Not to mention that social sciences are more controversial than experimental sciences like physics or biology (at least as regards what we needed to say in this course!).

So what should we remember in the end?

First, we can be confident in saying that technical systems (energy sources, production methods, tools) and social systems (economic models, legal frameworks, ideological trends) evolve hand in hand. Without oil or natural gas, there would likely have been no explosion in world GDP. Without international trade helped by the lifting of custom barriers, probably no explosion of GDP either! And by analogy: without research on renewable energies, it is hard to achieve any mitigation of global warming. But without economic incentives to reduce CO_2 emissions (such as a carbon tax or a voluntary carbon credit market), no mitigation of global warming would be possible either!

The historical episodes of these two chapters are made of both great laws and regularities, but also of unexpected human decisions with great consequences. We can learn from both. For instance, we have seen that energy sources are cumulative and do not supplant each other: this should be kept in mind when we discuss energy transitions! Oil has not replaced coal, gas has not replaced oil. On the contrary, coal, oil and gas consumption all increased during the 20th century. Another historical fact to keep in mind is that improved yields have always led to an increase, not a decrease, in consumption.

But history is also driven by human decisions with far-reaching consequences that seem neither predetermined, nor predictable, nor entirely intentional. This is the case of GDP as an essential compass for public policies. It was never intended to be used as a measure of economic or social performance: it was designed to drive a war industry. Yet the whole period of the Great Acceleration was guided by the search for GDP growth. Since GDP is not based on measures of well-being and does not take into account the depletion of natural resources (exhaustion of mines and arable land, extinction of living species), nor the nuisances associated with the quantity of goods produced (pollution, GHG emissions), nor the distribution of wealth and its social consequences, it is not surprising that the environmental concerns of today are difficult to reconcile with economic policies.

But we can also rephrase this idea differently: choosing another compass today will lead to other major consequences! More generally, it is precisely because we can learn from historical regularities that human decisions matter and that public and economic action makes sense. We are not helpless in the face of climate change and biodiversity loss, we can influence the course of things. Things changed at the time of the abolition of slavery under the combined action of activists, ideological movements, economic incentives, political rivalries, technical innovations.[21] They changed again in the second half of the 20th century, by the creation of a globalized market and the transformation of lifestyles that came with it. They will continue to change as the ecological transition makes progress. It will be up to you to decide where and how you want to position yourself in this new wave of transformation!

21 — See https://www.lhistoire.fr/le-si%C3%A8cle-des-abolitionnistes

Conclusion

We live in an era of acceleration. In 1970, there were half as many people on Earth as there are now. There was no Internet, there were no smartphones, no GAFAMs, no traders. Even the planet has changed, and it keeps changing faster and faster. It is not the first time that climate has warmed up and species have become extinct, but it is the first time that this has happened in just over a few decades, rather than over hundreds of thousands of years.

Should we leave it there, and let things run their course? Some biologists claim that the human species has done its job as a species, that it has occupied all the ecological space that its own qualities and industry have opened up, that it is now running up against the limits of that space, and that it will suffer the fate of all proliferating species: the shortage of means of subsistence (food, drinking water, breathable air, arable land, minerals) as well as pandemics favored by the growth and crowding of the population, will lead to collapse. Some economists argue that individuals look only after their own narrow interests, and have no sufficient incentives to act on a collective problem of such a magnitude. These ideas have seeped into the general public, where many people have given up on the struggle against climate change.

But are we that helpless?

No. These scenarios are certainly plausible, but so are many others. The world is complex and the simplest scenarios are not the most likely. In the course of their short history, human beings have proved to be capable of turning things around. Campaigns led by a few activists in the name of ethics and justice triumphed over powerful vested interests and resulted in the abolition of slavery. We are at a similar moment in history, where some vested interests are clinging to "business as usual" while grassroot movements are pushing towards the weaning off fossil fuels and the restoration of natural cycles. What are the grounds for hope? What can be done to push the agenda?

1. The urge to live

The urge to live is the very condition of existence. It is the common point of living beings, who all fight for their survival. It is the cornerstone of Darwin's theory of evolution. Spinoza extends this desire to all natural things, living or inert, as he asserts that "each individual thing strives to persevere in being".[1] This urge to live is the reason why we get up every morning, and what drives us to achieve our dreams and ambitions. But who exactly are we talking about when we say "we"? A famous poem by John Donne (1572-1631) gives an answer:

No man is an island,

Entire of itself.

Each is a piece of the continent,

A part of the main.

If a clod be washed away by the sea,

Europe is the less.

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1 — See Spinoza, *Ethics*, III, Prop. 6

As well as if a promontory were.
As well as if a manor of thine own
Or of thine friend's were.
Each man's death diminishes me,
For I am involved in mankind.
Therefore, send not to know
For whom the bell tolls,
It tolls for thee.

According to the Western tradition, especially when it comes to neoclassical economics, one tends to see the individual as a self-contained island, some Robinson Crusoe fending for himself, far away from human society. This is a serious mistake: it is society that turns us into human beings. Descartes, at the beginning of the *Discourse on Method*, states: "We all were children before we were men". Four centuries later, the anthropologist David Graeber writes "It normally takes a great deal of work to turn a newborn baby into a person - someone with a name, a social relationship (mother, father...) and a home, towards whom others have responsibilities, who can someday be expected to have responsibilities to them as well".[2] In Western societies, this work is largely carried out by state institutions, which lay down rules and enforce them, but also by relatives, friends, social networks, who all convey the values of the social group. Once we reach adulthood, the process goes on: advertising teaches us what we should desire, and the media what we should think.

Social ties are therefore fundamental in the construction of the individual. There are several ways for societies to build and maintain them. In classical Chinese society, for instance, rites play an essential role. In Western societies, ever since the Roman Empire, it is the law which

2 — « The utopia of rules », Melville House, 2015, p. 51

turns the newborn into an adult with responsibilities, a person who is part of a web of reciprocal rights and duties.

Whether through rituals or through law, society impresses on us that we are one, that we have commitments towards each other, and that the feeling of empathy that we feel towards others is not only normal, but it is a duty. This duty is unconditional: pacta sunt servanda, that is, "commitments must be kept".

2. Living together

Some societies were not able to survive. Do you remember the fate of the natives of Easter Island? They arrived on a lush island, and in a few centuries they completely deforested it. Without wood, it was no longer possible to make canoes, no longer possible to leave the island or even to fish. It was a miserable population that the European navigators found, living among overturned statues from happier times. The Pascuan society literally committed suicide by destroying its environment. How can one implement at a collective level the desire to live?

More often than not, we think only of financial incentives: in order for people to do something, or not to do it, they must be paid. But there are many other means for societies to act on their members, from cultural norms to legal constraints. According to an ancient piece of legal wisdom, “Oxen are bound by their horns, and men by their words”.[3] Financial incentives are just a few of the many levers we have at our disposal to address the ecological crisis collectively.

In a celebrated 1961 paper, entitled “The tragedy of the commons”, American ecologist Garrett Hardin highlighted the inherent difficulties of collective action when it comes to sharing common resources. Let us picture two farmers grazing their cows on the same field. Har-

3 — See Antoine Loysel, 1607.

din claims that the resource will be overexploited, as it is always in the financial interest of each farmer to send in more cows, even though this makes it more and more difficult for grass to grow back. Likewise, firms or countries which, collectively, would have an interest in mitigating their GHG emissions are likely to individually let them grow out of control in order to increase their production and their profits.

Elinor Ostrom, Nobel prize winner in Economics in 2009, disputed the idea. Trained in sociology, anthropology and field observation, she pointed out that in real life, the two farmers would talk to each other! They would know each other, they could discuss the danger of overexploiting the resource, and they could devise operating rules to align their interests more sustainably. In other words, rationality, both individual and collective, is neither innate nor unalterable. It is a social construct, and human societies have used many different tools (religious, cultural, legal, ethical...) to set individual and collective rules to preserve their interests "as best as possible" over time. Using the same procedures between companies or countries is obviously a huge challenge, but it is certainly feasible, especially as the effects of climate change become more and more pressing!

Religion, culture, ethics, law, are all deeply connected to the idea of justice. The yearning for social justice and fairness has led to major social changes. Does it seem unfair to you that men are earning 28.5% more than women and 9% when they have equal positions and skills?[4] That the GDP per capita is $63,000 in the United States and $1,000 in the Democratic Republic of Congo[5] or that in 2017, the 8 richest people in the world owned as much as the 3.6 billion poorest?[6]

4 — https://www.oxfamfrance.org/inegalites-et-justice-fiscale/comprendre-et-combattre-inegalites-femmes-hommes/

5 — https://www.inegalites.fr/L-inegalite-des-revenus-dans-le-monde?id_theme=26

6 — https://policy-practice.oxfam.org/resources/an-economy-for-the-99-its-time-to-build-a-human-economy-that-benefits-everyone-620170/

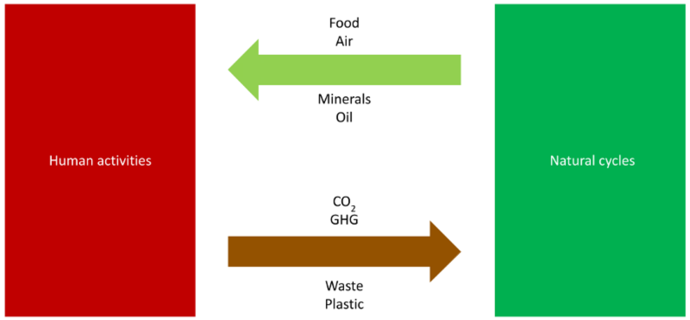
Global warming is inherently unfair. According to the IPCC, if we want to have two chances out of three to keep warming at 2°C or less in 2100, there are only 900 billion tons of carbon left to emit by then. This means that the present generations have spent the capital of future generations without asking for their opinion. And already today, the rich emit much more than the poor. The richest countries host 50% of the world's population, but are responsible for 86% of CO_2 emissions. If you find these inequalities unfair, it is because you feel connected with all human beings, including those who are not yet born, and you can leverage this feeling of injustice into action.

What is considered unfair and elicits moral outrage varies from one individual to another. Law lays a moral common ground between members of a society, which allows them to work together towards a shared idea of what is good. This common ground may vary with time and across countries. It can adapt to new situations and new needs, but as long as it is in place, it is binding on all, partly because of its moral authority, partly because it can constrain individuals to obey. Note that this constraint nowadays is almost exclusively national. International law does exist as well as its own courts of justice but they do not have the power to enforce their decisions, the effect of which therefore is limited by the goodwill of the states in charge of applying them.

In conclusion, the environmental crises, such as global warming and biodiversity loss, are urging us to reconsider our moral values and our idea of justice, and to enshrine them in law in order to raise them to the level of society and turn them into a tool of collective action.

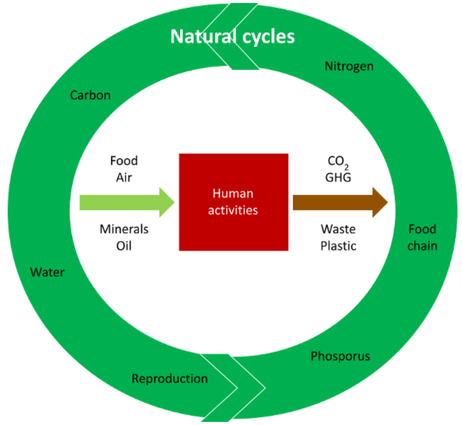
3. Living as part of nature

To live as true human beings, we must grasp one last essential idea. Individuals are not islands isolated from other humans, nor are societies islands isolated from nature. Rather, they are like clearings in a vast jungle, from which they draw and exchange resources and from which danger can pop up at any moment. We do not live from nature, we live within it! In the West, we have drawn a separation between human society and our natural environment from which we assumed we could just draw and discard resources at will.



During the Great Acceleration, Western countries were only interested in the red box on the left, trying to expand it as fast as possible, without taking into account the inflows and outflows it was taking and rejecting into the great natural cycles. Looking at this picture, you would think we were sending our waste to the Moon! You would be wrong: it's happening right here.

In reality, mankind depends on multiple natural flows which recycle back what human beings reject. We can modify them very quickly, and yet we are still very far from understanding them in all their complexity. The crises of the early 21st century show that the previous dissociated model has reached its limits. It is necessary to find other rules and ways to operate which are better suited to these great cycles and take into account the dependence between humans and non-humans. We must avoid, for example, relying on the globalized market to solve the problems it has created. We must not think that the exclusive search for profit will lead firms to rethink their production chain in order to replenish the stocks they draw from and to reduce the waste they reject.



4. Forces of change

To renew people's motivations we must therefore act on education, culture and our legal framework. The law will have to evolve to reflect the new values that are emerging as citizens become aware of the magnitude of the crisis, and as new generations increasingly assert their willingness to live. States will have to take environmental concerns seriously and translate them into law, if only to preserve their territory and the lives of their citizens. Firms will have to integrate into their performance criteria other concerns than shareholder value, and governments other indicators than GDP. The current corporate model, oriented towards short-term financial profits, will have to change to include other factors, oriented towards long-term survival. Governments will have to constrain industries to reduce GHG emissions and preserve biodiversity, for example by introducing a carbon tax as part of a general tax reform.

It should be noted that our current legal system has inherited a congenital weakness from Roman law: it only regulates relationships between human beings. Animals, plants and things are not included. Until very recently, those responsible for an oil spill, for example, could only be prosecuted insofar as it harmed the interests of a person, an oyster farmer for example, whose harvest was destroyed. The pollution of the beach or the destruction of seabirds was no concern of the law. Legislation is therefore bound to evolve in this respect. It is actually already doing so, in various ways depending on the country. In France, it is through the gradual introduction of the concept of ecological damage. In New Zealand and Canada, it is by granting rivers legal personhood. This does not solve everything (who can file a complaint? who can speak on behalf of the river?), but it is only a beginning.

Finally, behind all this, of course, are grassroot movements, carried mostly but not exclusively by the younger generations. Some of us believe that we are experiencing again the digital revolution of the last decade of the past century (yes, the Internet is less than 30 years old!). This revolution happened very fast, and very few managers and experts had seen it coming! It came from young people, researchers, pioneers, outsiders, who grasped the situation and opened up new paths for the future, taking the old generation by surprise. This may happen again. Driven by the urge to live, the younger generations will drive the future, towards a sustainable and more united economy, based on the quest for justice and respect for nature.