The environmental challenges of the 21st century

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Part 1

2021 edition

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Illustrations: Margot Malpote for 2050

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? This will be the topic of the second volume.

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.

Thanks to the Madeleine Foundation and the company 2050.do for their support, notably through the work of Aicha Ben Dhia. Their support was key in sharing the course under a Creative Commons license.

Thanks to Quintin Leeds for the layout of this first volume and to Margot Malpote for the illustrations of each chapter.

Thanks to Charly Berthet, Meyha Camara, Dominique Dron, Marie Ekeland and Jacques Treiner for their proofreading, corrections and contributions.

This is only the first 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, due to 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?

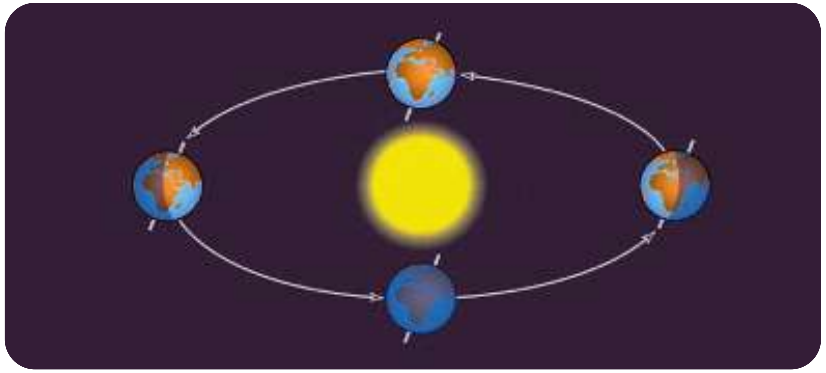
The problem is that it’s changing very quickly. Much too quickly in fact. Until now, change has been gradual, as it followed the very slow changes in Earth's orbit. These changes can take tens of thousands of years. This gave life time to adapt. However, the change that we can observe today is concentrated 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 brake, or 1 metre? In the first case it's breaking, 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.

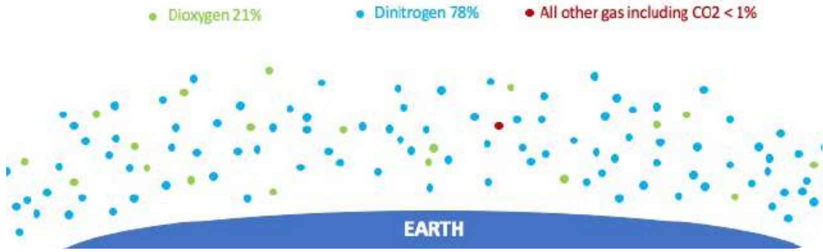


Variation of Earth's exposure to the Sun due to the inclination of its axis of rotation.

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.

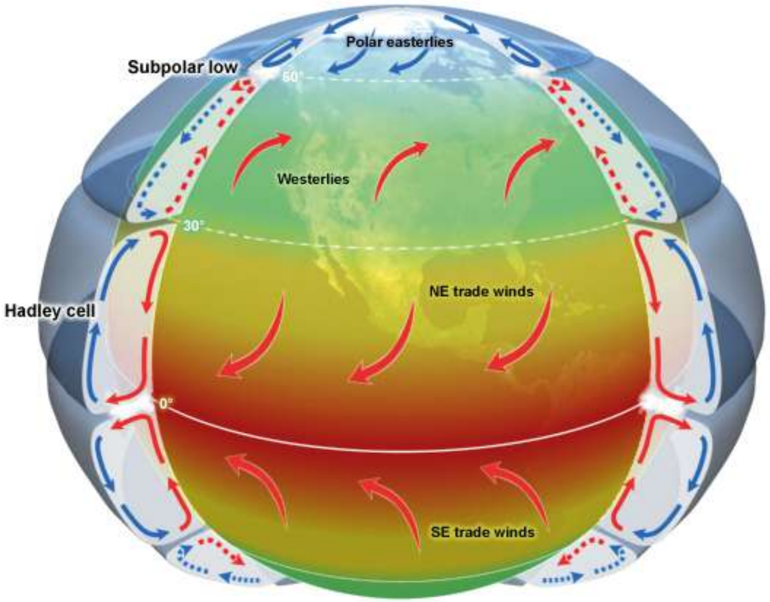
By the way, you too, certainly, know some regular and predictable air movements. In a sauna, for example, does hot air rise or fall? It rises! And what happens when you boil liquid water in a pan? The molecules break off from each other and liquid water turns into gas water, also called water vapour. 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 company emits CO_2, the gas emitted will not stagnate above it. If this were the case, it would suffer the impact itself, and it 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.

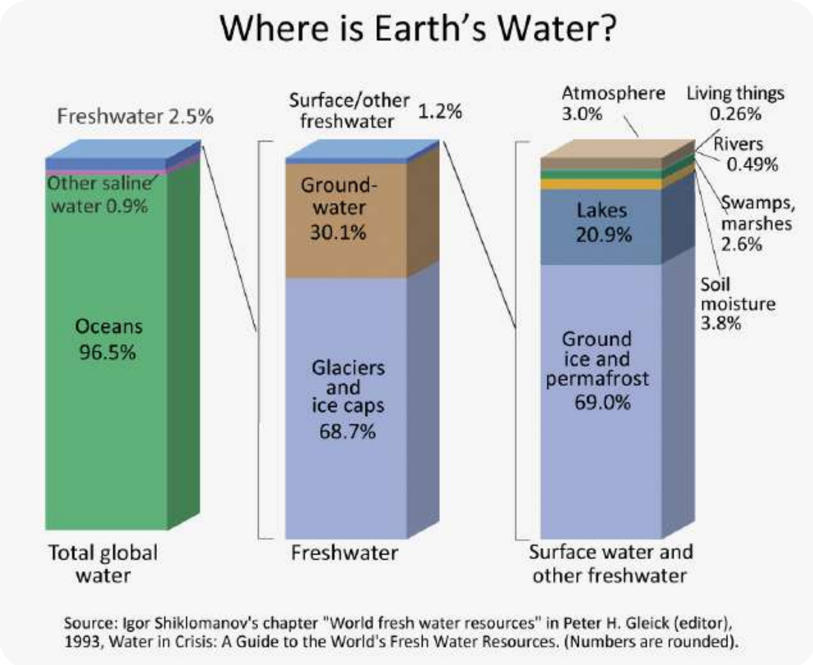
3 Water

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 a trip 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.

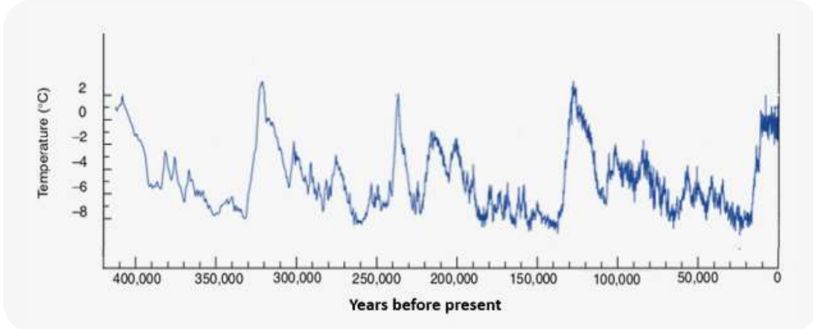
At present, Earth's orbit is almost circular: if it becomes more flat, with solstices moving closer to the Sun, then winters will be more far away from it, and, as a result, we will have hotter summers and colder winters. Likewise, if the axis deviates further from the vertical, summer days will be longer 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 is a reproduction of the temperature curve from the article in which, later on, we'll see the original graph. The curve does not directly provide an absolute temperature, 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.

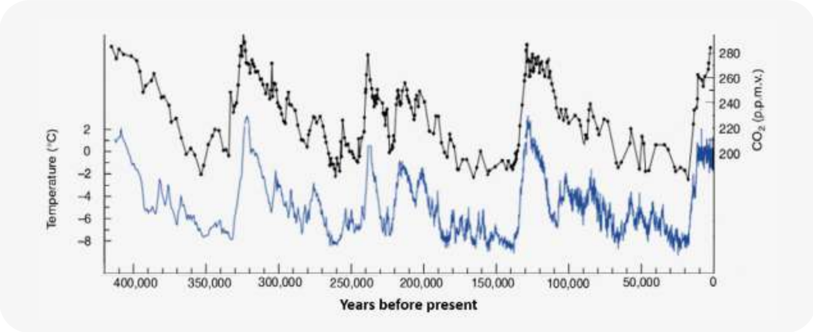


Evolution of the temperature above station Vostok.

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!

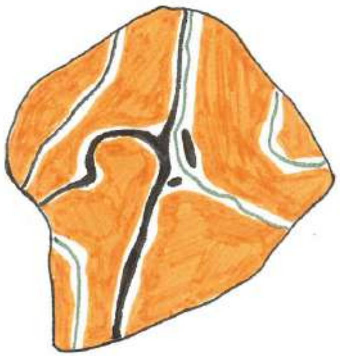
Let's overlay the CO_2 concentration curve in black. The variations are remarkably similar. As we have seen in the previous section, the air in the atmosphere contains very few molecules of CO_2, around 0.05%. In order to express the CO_2 content of air, we don't use percentages but "per-millions", that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

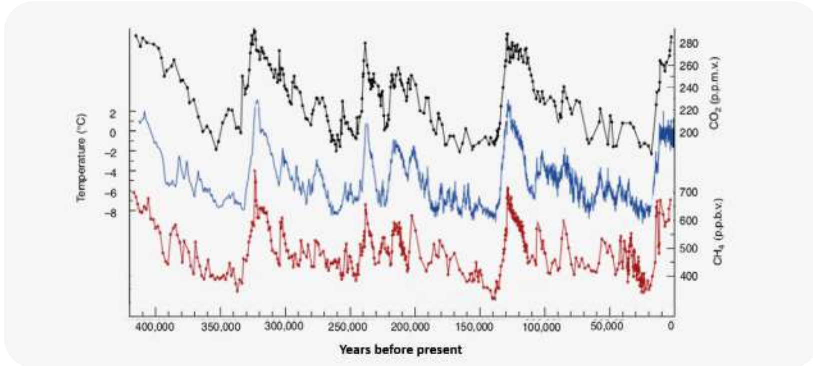


Joint evolution of temperature and CO_2 concentration above station Vostok.

Source: www.climatedata.info

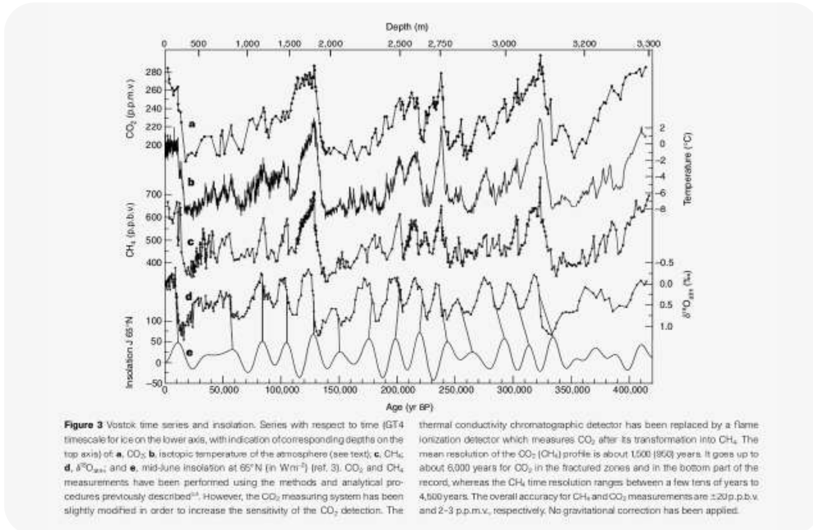
Finally, let's overlay the methane CH_4 curve in red: it follows the same pattern as the two first variables. There are even fewer particles of CH_4 than CO_2 in the atmosphere. Therefore, the content of air in CH_4 is expressed in "parts-per-billion". This is denoted by "ppb".





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

Source: www.climatedata.info



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

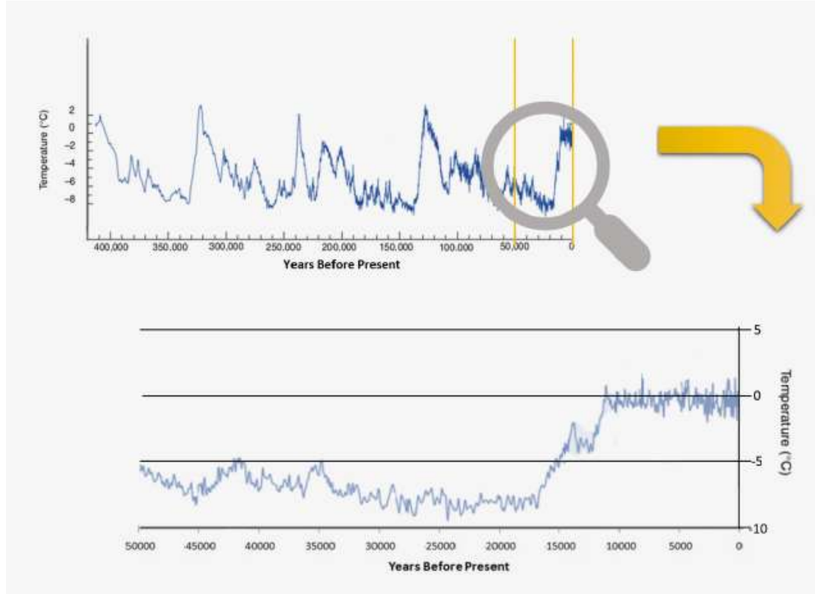
There is an obvious correlation between the content of the atmosphere in CO_2 and in CH_4 (methane) and temperature. Does this imply that the CO_2 and CH_4 content is the cause of temperature variations? Without additional data, the rigorous answer to this question is "not necessarily": in principle, it could be the opposite, or perhaps, due to some other unknown factor which may influence all these parameters. However, at this stage of the investigation, one thing is certain: the periods when the atmosphere contains most CO_2 and CH_4 are also the hottest periods.

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 others! 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 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

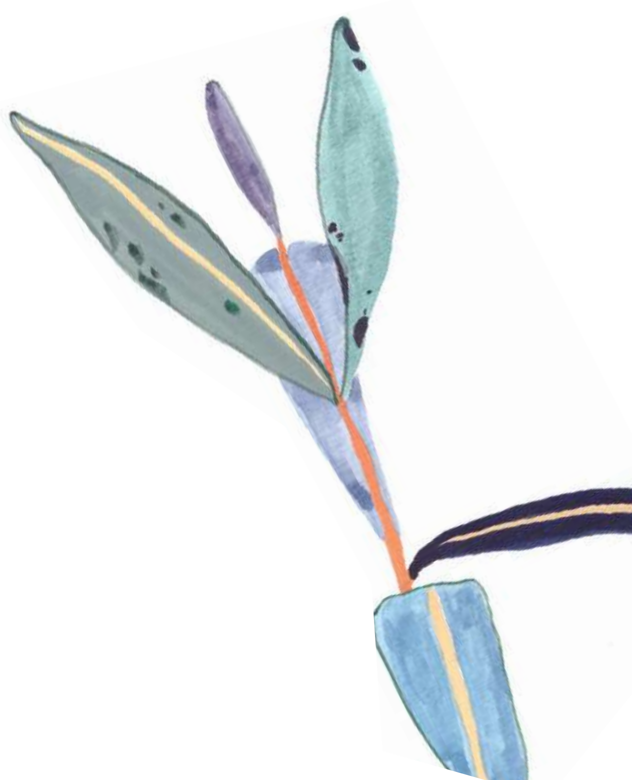
The atmosphere as a sleeping bag

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.

The more there is, the warmer the atmosphere. 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 a 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 want to put hot water to brew your tea.

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 described in the twentieth century.

3. Let's get back to the kettle: why, in this case, does it not become a mirror ball in 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, similarly to sea waves, can take several forms: some waves are very spread out (the peaks of each wave are very spaced), others are very 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, by heating it, for example. 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 reason. 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

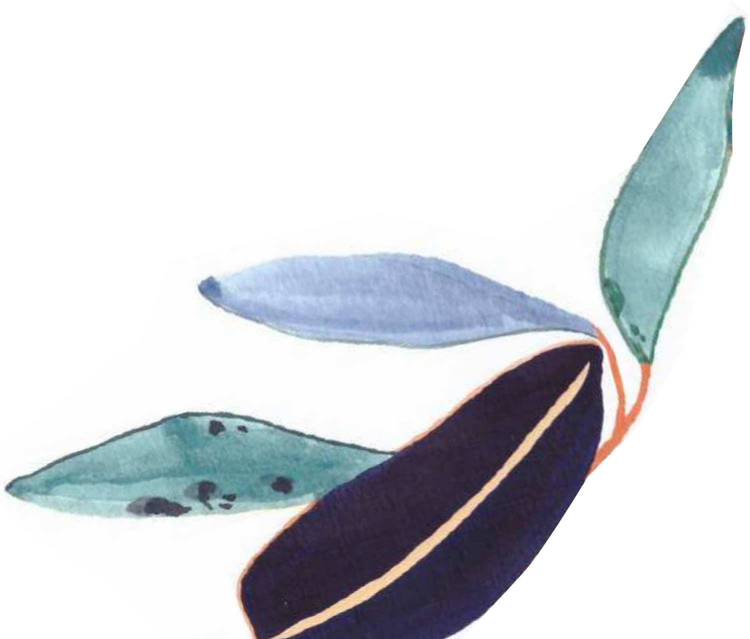
Physicists have studied extensively the radiation emitted by a hot body and found an equation which allows us to perfectly predict the shape of light waves emitted by a hot body as a function of its temperature. We saw that in the case of the Sun, at 5,700°C, most of the light waves emitted possess a 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.

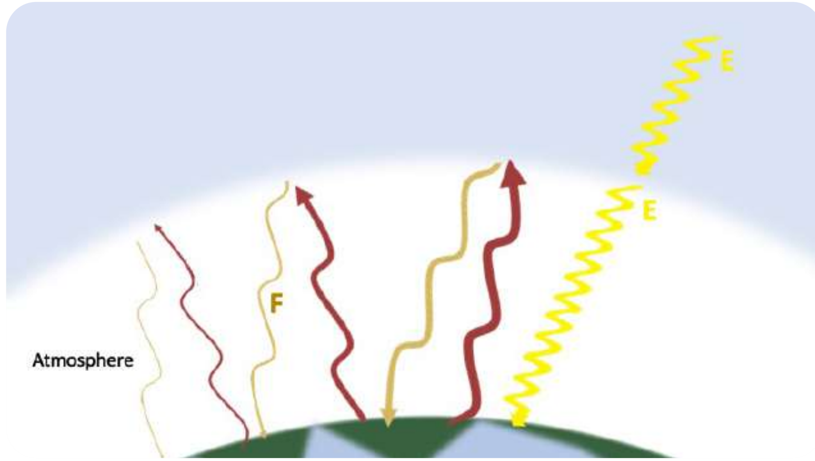
Therefore, this terrestrial radiation escapes our vision... but not the atmosphere! Or rather: not all the molecules in the atmosphere. Some large molecules in the air (CO_2, H_2O, etc.) are particularly sensitive to the long-wavelength waves emitted by the Earth. Instead of letting them pass (like a 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.





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 415ppm, but constantly increasing, responsible for 65% of the remaining greenhouse effect (that is, excluding water vapour)

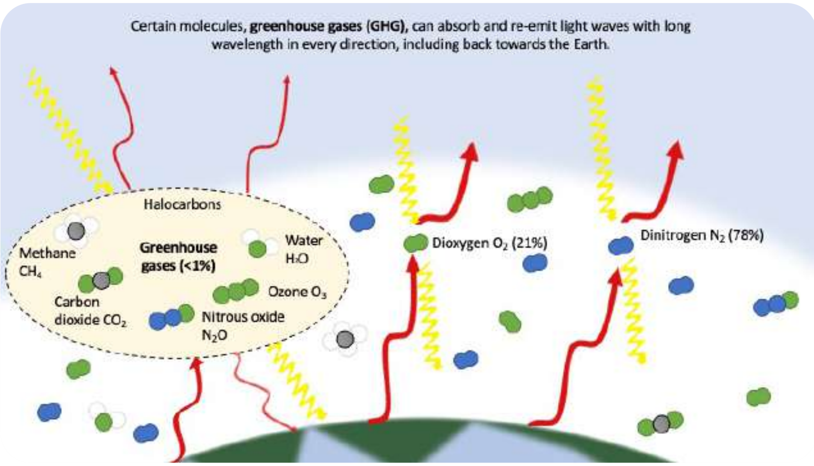
2 — https://planet-terre.ens-lyon.fr/article/effet-de-serre.xml

- 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%

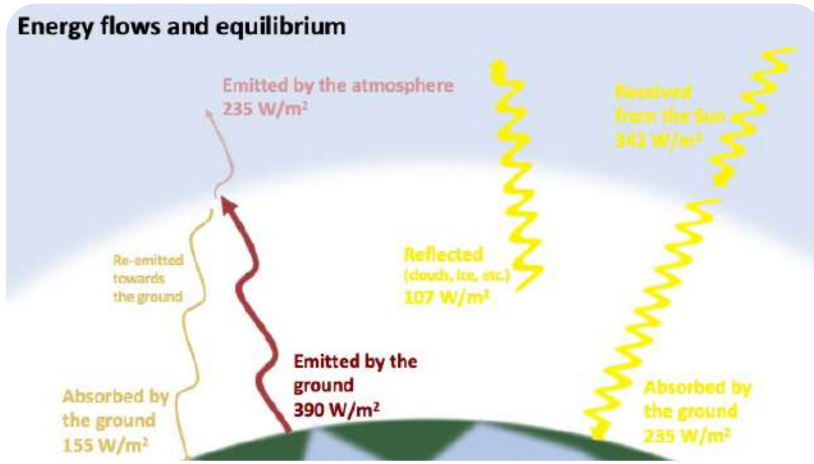


3 Radiative forcing

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 returns directly through snow, ice or clouds.

It is therefore necessary to slightly modify Earth's energy budget, which finally, appears as follows (unit is W/m^2, Watts per square metre):

- received from the Sun: 342 W/m^2
- reflected: 107 W/m^2
- reaches the ground: 235 W/m^2
- emitted by the ground: 390 W/m^2
- crosses the atmosphere: 235 W/m^2



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, from 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. It's like when you light the fire under a saucepan: the temperature of the water increases, but that's not all: the liquid begins to agitate. In relation to Earth, it is to be expected that the atmosphere will warm up, and be crossed by more violent currents.

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 could be 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 temperature rises 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. Thus, 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 happens? Unless some meteorite displaced it, she would find it perfectly intact. What if she was to replace the pebble with a fish? Or, let's get to the point, with a whole tray of vegetables, 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.

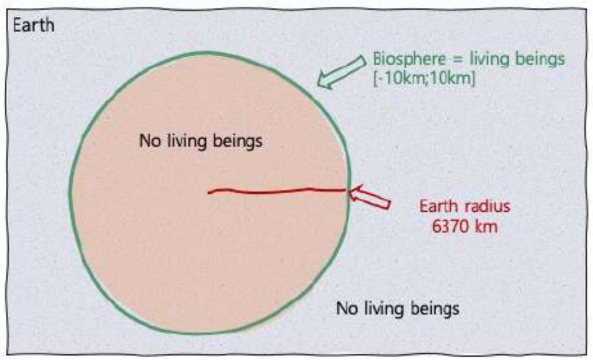
As we will also see in this chapter, and more in-depth in the next one, not only life on Earth is impacted by the climate, but the opposite is also true! Life has influenced, and continues to influence, the Earth's climate. The dioxygen we breathe in the air, for example, you may think that it has been part of the atmosphere since the origin of the world, a bit like the setting of a theatre stage where human beings have appeared, 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 similarly to when 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

1.1What do we call a living being?

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. Everywhere else: there's no life!

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, crossing each other and following different logic.

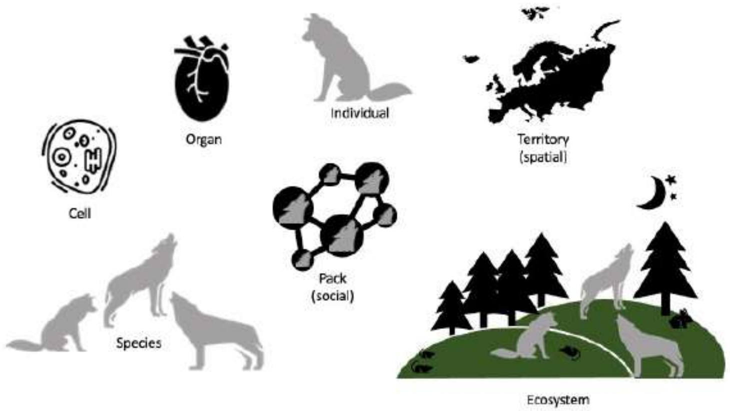
For example, let's consider the wolf to illustrate this point:

- 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: individuals 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 newborn, becomes juvenile, then adult, and finally reaches old age. His position in the social hierarchy changes over time, depending on his abilities surely, but also on his actions: he has a strategy.

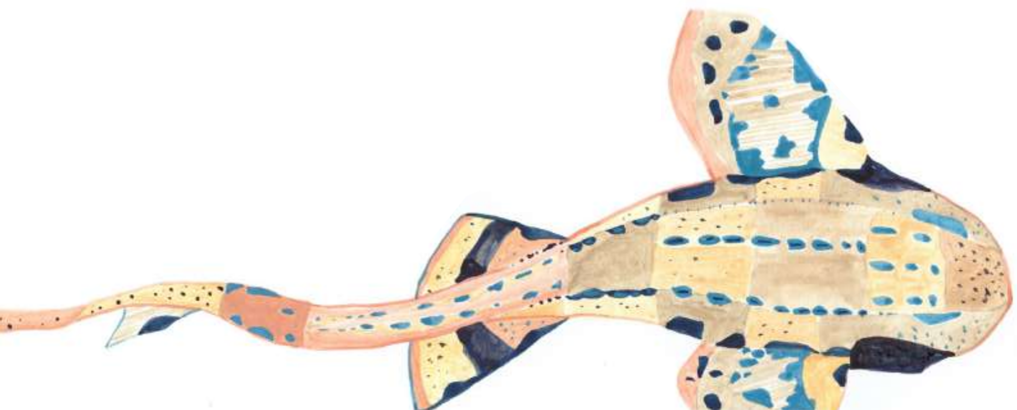
4 — To learn more and discover how the delimitation of the territory, the definition of borders, are the subject of negotiations between packs, read "The diplomats" by B. Morizot.

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 limestone stone. Its 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 there 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 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, they may be there tomorrow, but it's unlikely that they will still be there in twenty years; if it's the case, they will have changed a lot. If I were to put them 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.

This way, 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 indeed a daily 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, in a hammam, where the humidity is 100% and where it's only 40 degrees, the body cannot sweat and is in danger of death.

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. Thanks to the example of sweating in a steam room saturated with water, it's easy to understand how living beings quickly reach their limits in maintaining themselves in a healthy state.

And this, not only in relation to 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.

Species can even disappear 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: based on their means, they seek to establish and maintain it.
- 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 do the oxygen that living beings need come from?

4.1. Photosynthesis

All through their life, living beings breathe, feed and reproduce. To survive, human beings inhale dioxygen (O_2) and expel carbon dioxide (CO_2) when they breath out. 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 jar. 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 was made by Joseph Priestley in the 17th century; that's how he found 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

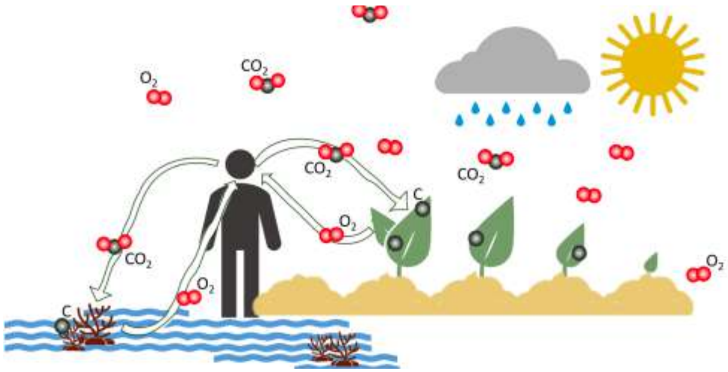
- Photosynthesis is the mechanism which is 'complementary' to animal respiration, through which plants absorb carbon dioxide (CO_2) to release oxygen (O_2).
- Animals, us included, are therefore absolutely dependent on plants and other living beings such as plankton, as they produce the oxygen we need.
- 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, in good life, 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 organisms 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.

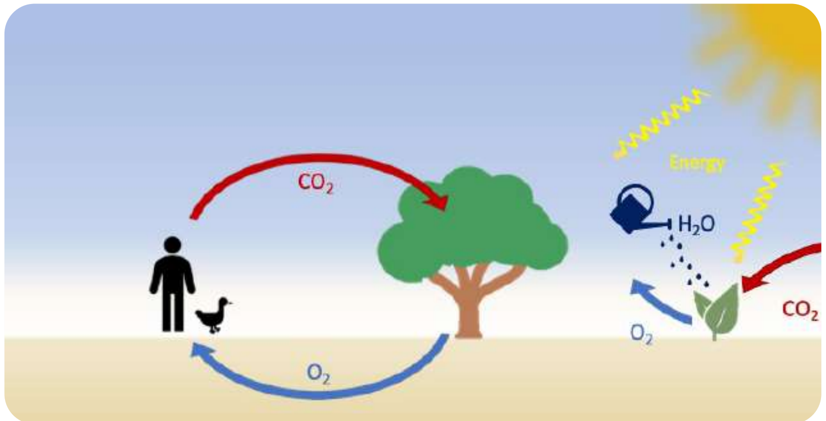
This cycle pattern is not unique to oxygen. Almost all gases in the atmosphere have their own cycle: they are produced by some processes and absorbed by others. The atmosphere is a temporary storage place, before being sent back elsewhere on Earth, similarly to a bathtub connected to a phreatic zone 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 due to them 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]

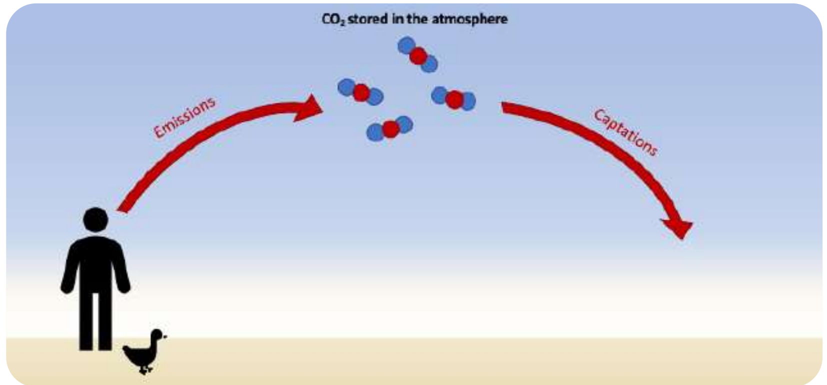
6 — NASA's SeaWiFS instrument examines oceans and land to observe flora and phytoplankton. To discover the SeaWiFS instrument, you can visit: https://svs.gsfc.nasa.gov/vis/a000000/a002000/a002077/index.htm

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 such carbon they 'breathe in'.
- 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 compared to ordinary plants, because when it breaks down, the carbon it contains remains trapped at the bottom of the ocean.

2 | CO_2 Cycle

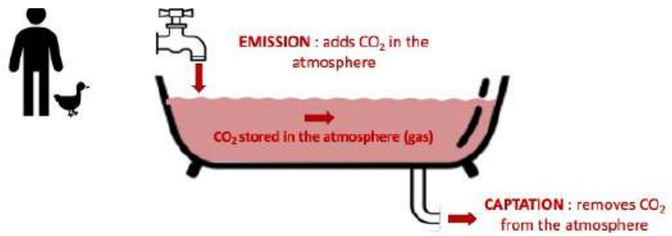
Let’s get back to the central theme of this course: climate. As we saw in the first two chapters, the accumulation of CO_2 in the atmosphere was the main factor in the greenhouse effect, which heats up the Earth.



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.

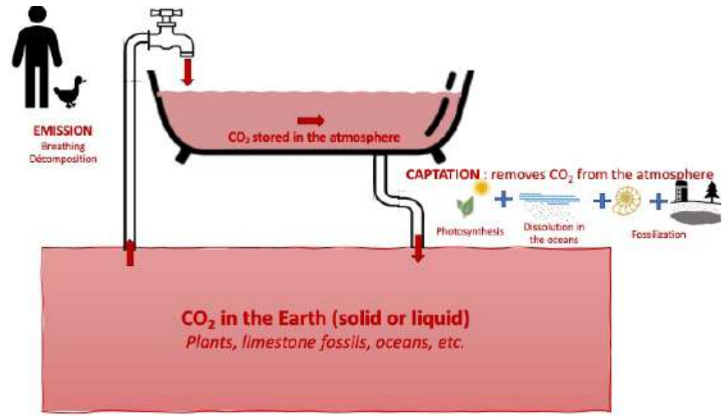
We can compare this problem to a bathtub. There are two things determining the quantity stored in the atmospheric bathtub: the quantity emitted by the tap on the one hand, and the quantity discharged by the drain, on the other hand. Where does the carbon discharged through the plug go? It's simply stored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

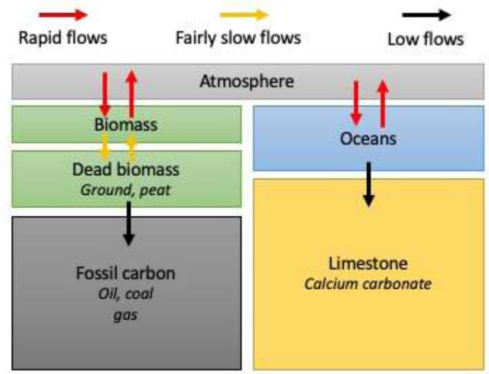


On the other hand, terrestrial carbon outside the oceans is fixed by plants and animals, to be slowly returned to the atmosphere when these decompose. However, some may escape decomposition, because of special circumstances, for example, due to the fact that they are buried in swamps, far from the oxygen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

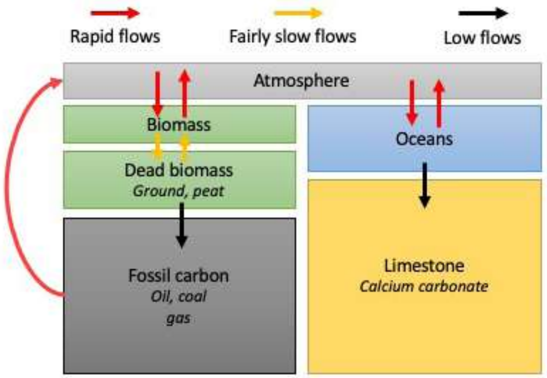
3.1 The unbalanced carbon cycle

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.

Therefore, it's been two centuries, that 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's the radiative forcing, which we have defined in the previous chapters.

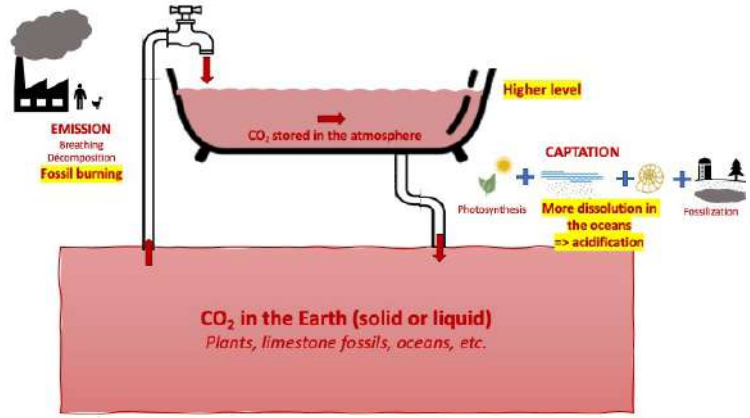
3.2 A double issue

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

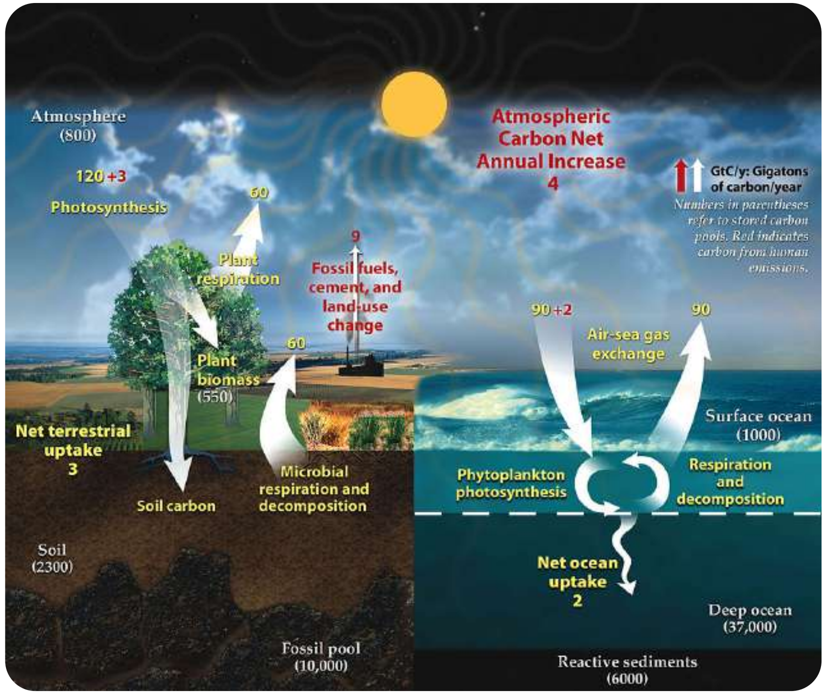
If we get back to our bathtub, then we understand how the level is increasing:



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/CO_2%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 plug 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 416 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 plug 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 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 the oldest garbage first), so that the last 5.2L bag will of course no longer contain any of the beer cans of your evening.

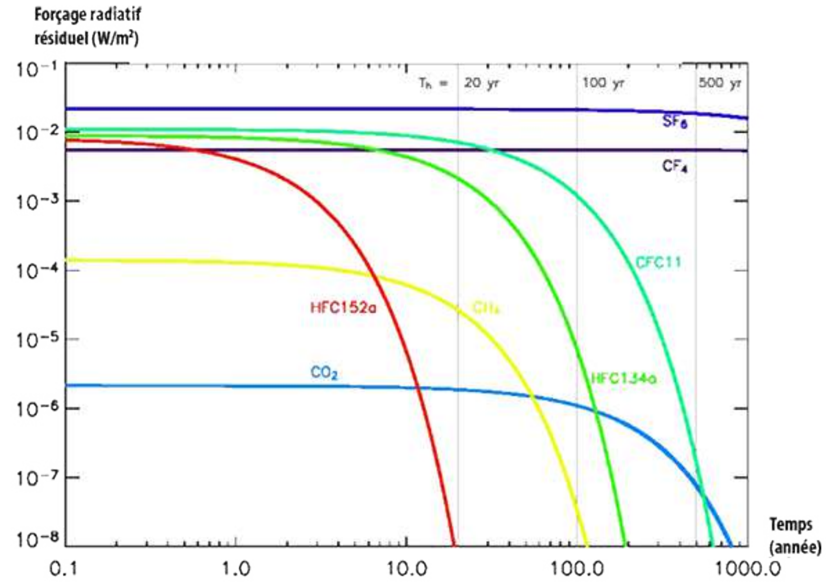
The main thing here is not your birthday junk in itself, but the lasting change in the level of junk that the one-time excess of your birthday has caused. The level of waste in your kitchen, for 20 weeks, would bear the signs of that one-time surplus.

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

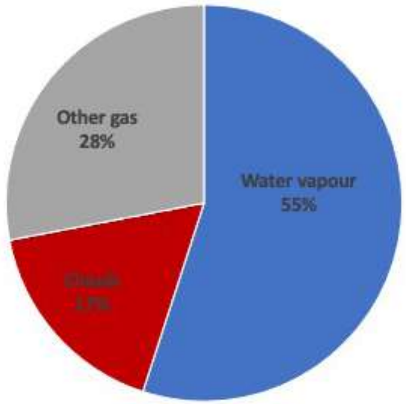
- When a gas is emitted by human activity as an "excess" into the atmosphere, the natural system will take some time to return to equilibrium.
- The time during which we continue to observe the traces of an excess is called the "lifetime" of a gas.
- For a GHG, the important thing is not its trace in 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, we are not talking about water vapour? However, 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 mainly, 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 the stock 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

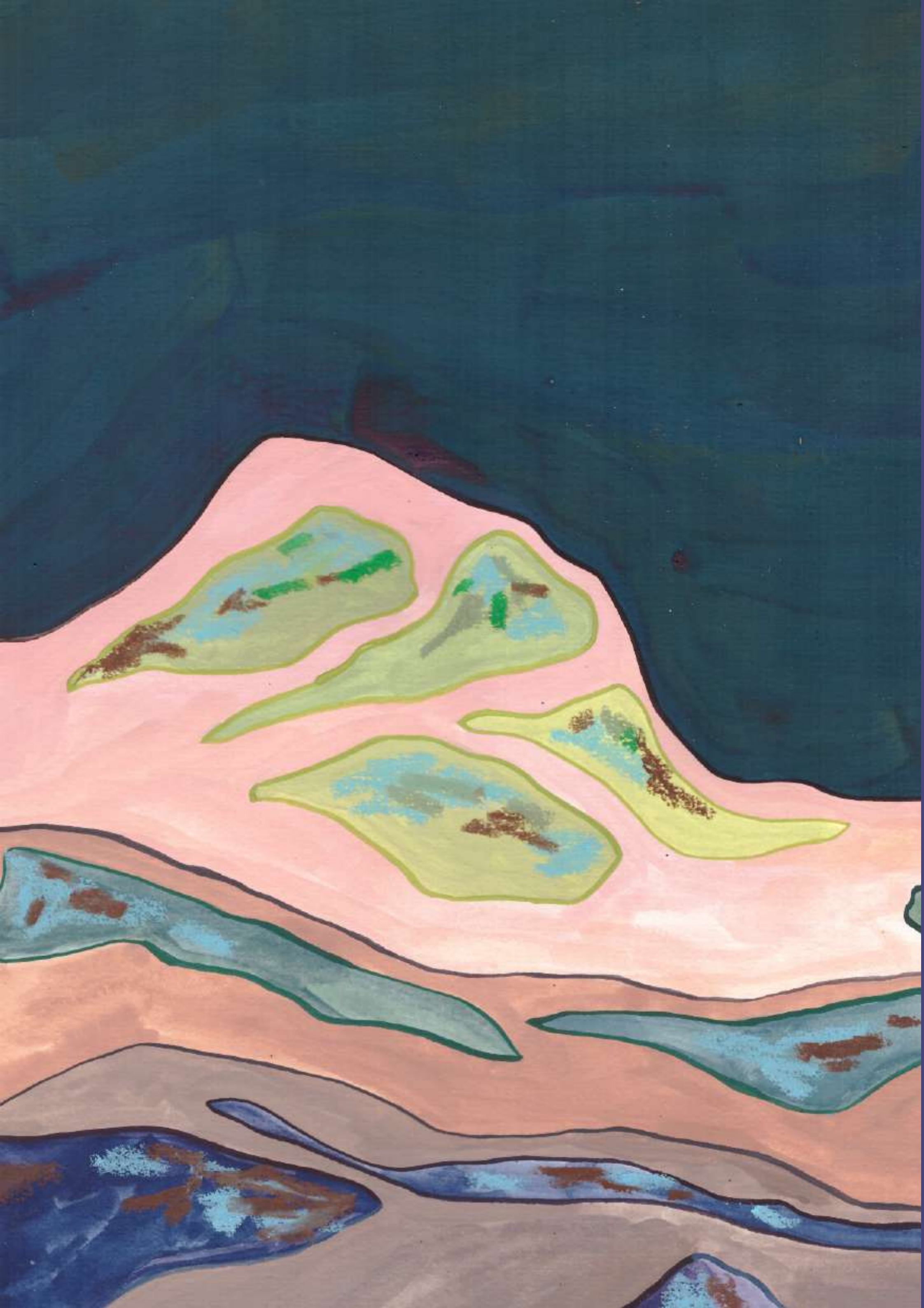
Summary

- 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.

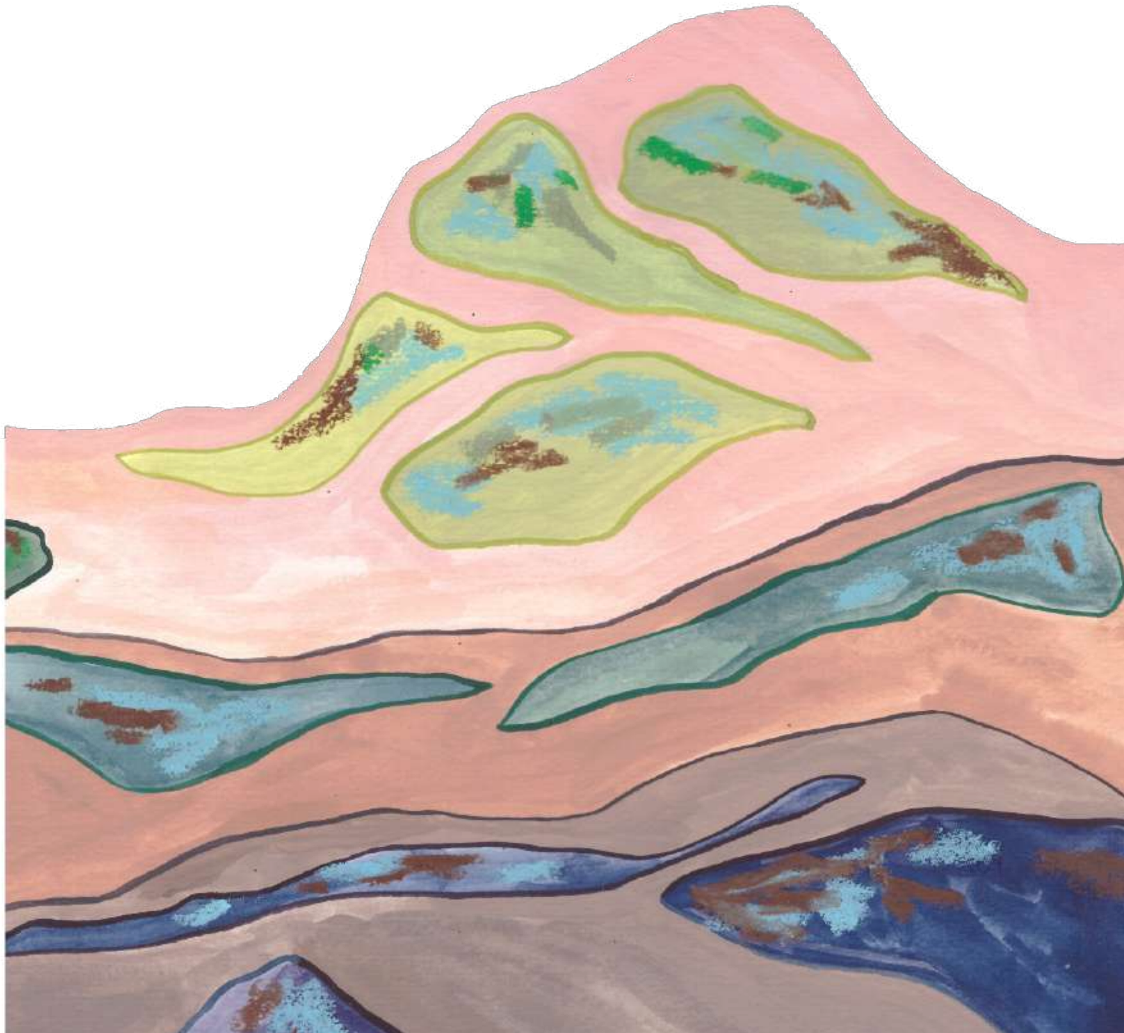
We are going to talk about climate change scepticism. It comes in many forms: some will say that nothing is happening, others that it's warmer, but not due to CO_2, and finally, there are some who say that this is not due to human activity.

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 becoming agitated, and in any case, nothing can be done about it, we just need to let it go." 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:


Donald J. Trump
@realDonaldTrump
Following

The concept of global warming was created by and for the Chinese in order to make U.S. manufacturing non-competitive.

RETWEETS 24,831 LIKES 14,654

2:15 PM - 6 Nov 2012

Source: Twitter

And still...

1.1 Heat records

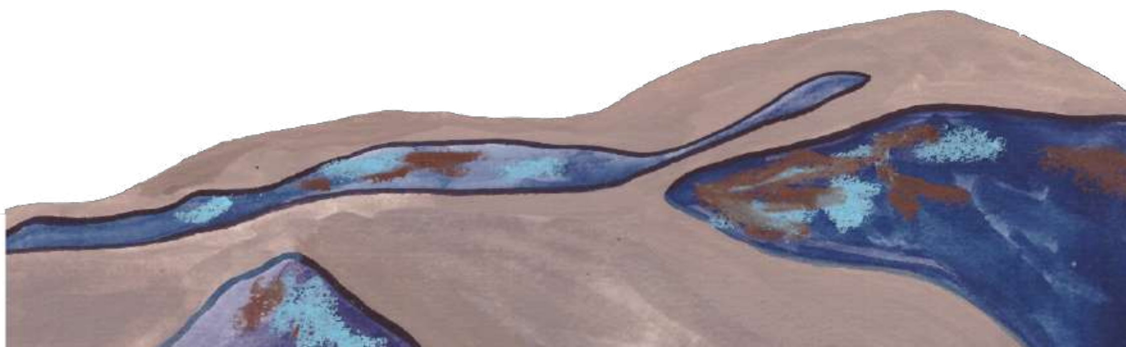
This section of the chapter needs to be rewritten every year, because every year new records are broken. As of the time of writing, April 2020, the latest numbers are:

- 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

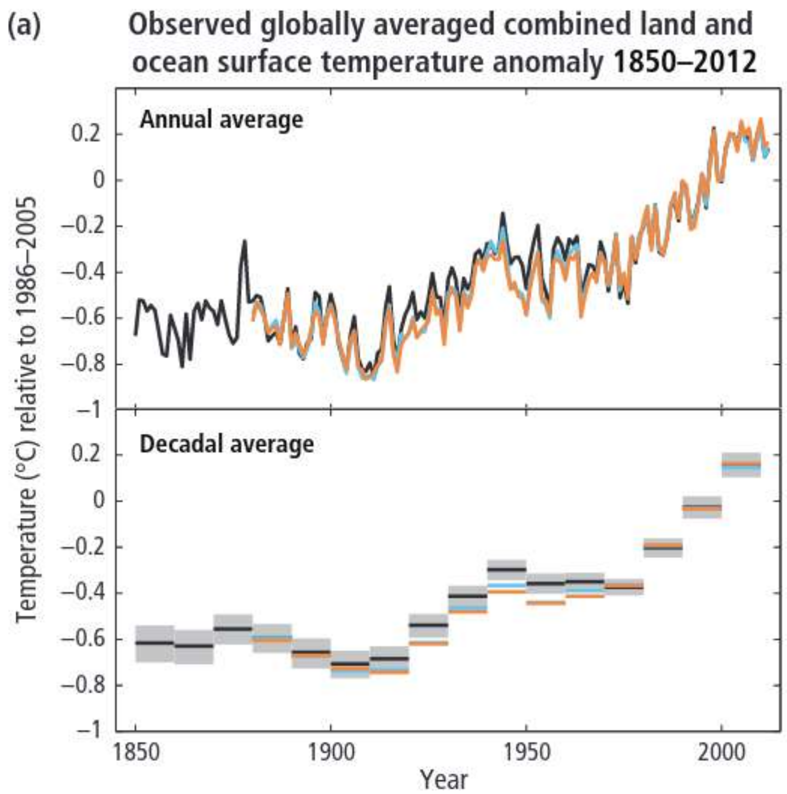
1.2 Evolution of averages

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.

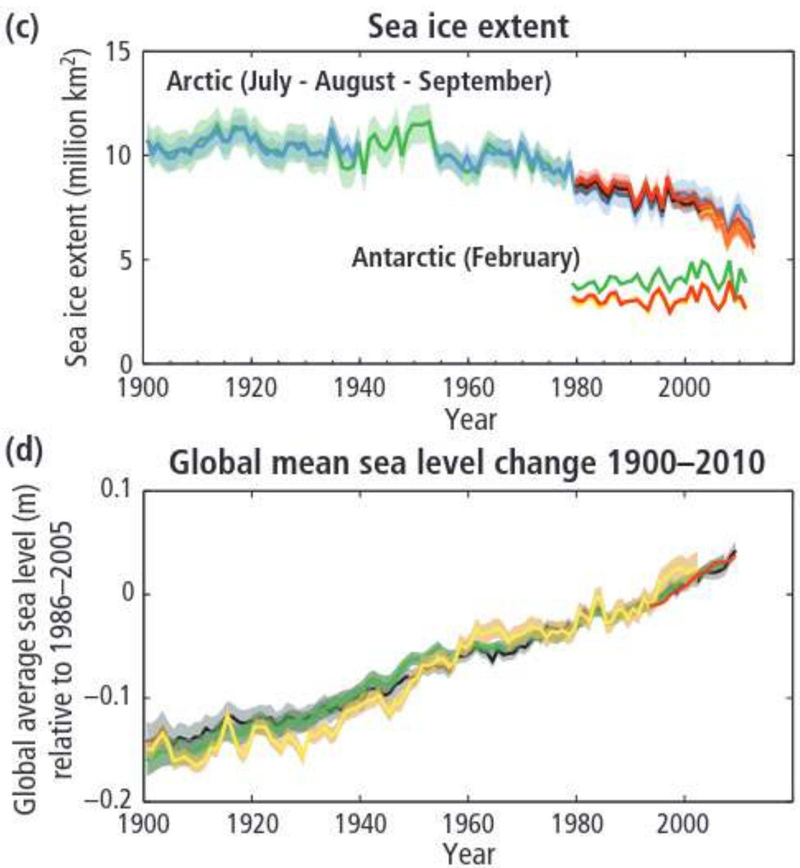
The horizontal axis corresponds to the time axis, from 1850 to 2000. The vertical axis represents the deviations from a reference temperature. The title of the vertical axis tells us what this reference temperature is: it's the average temperature over the 20 years 1986-2005. Let's take an example: in 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).



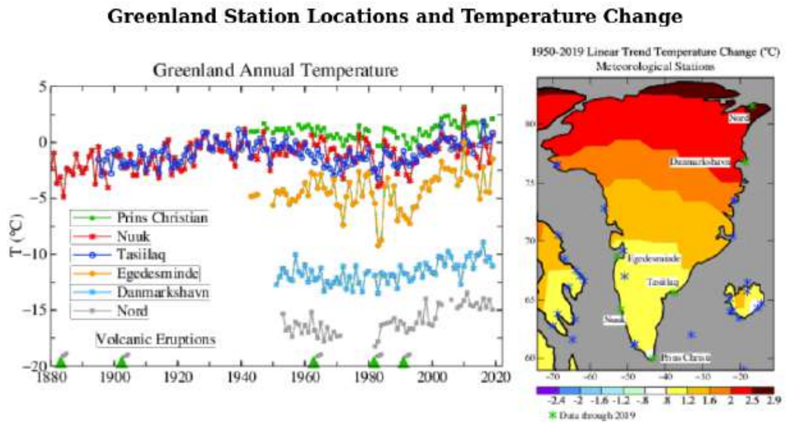
Title: Evolution of the surface covered by sea ice and of the sea level

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 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 a fool 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 specific circumstances.

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.

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 agitated, 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 on a series of boards - 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, is not for the next one, which will look at what's around them, finding it difficult to imagine 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.

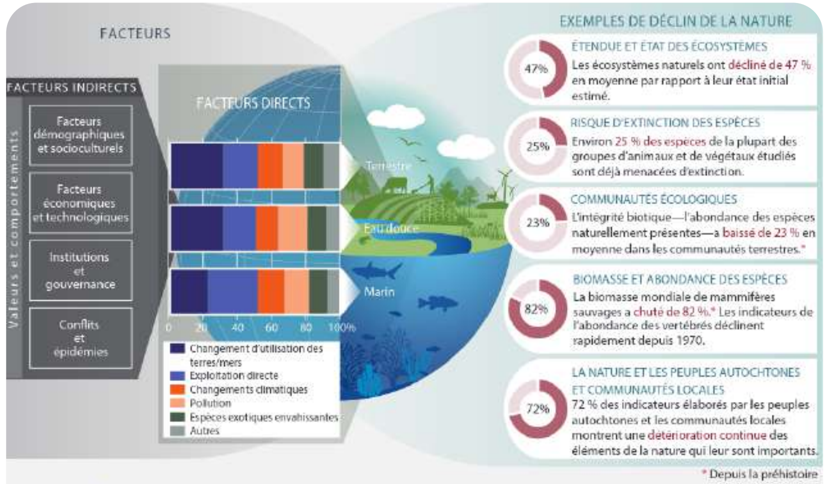


Figure SPM 2 **Exemples de déclins observés dans la nature au niveau mondial, soulignant le recul de la biodiversité provoqué par des facteurs de changement directs et indirects.**

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 occupy more than a third of the surface of the continents and use three quarters of freshwater resources.[14]

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

14 — 2019 IPBES Report

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.

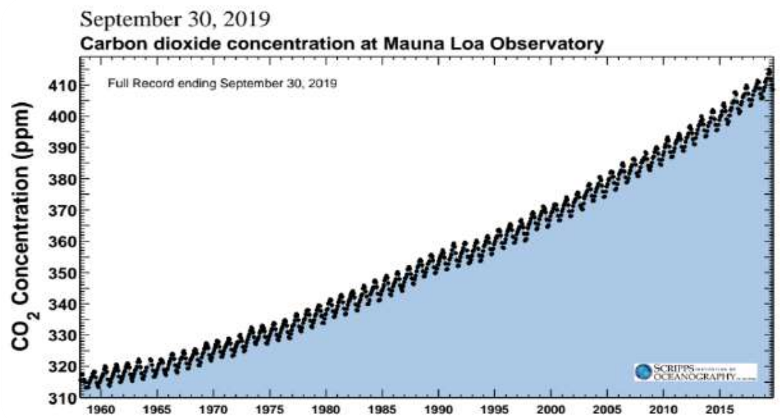
Summary

- 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.

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.

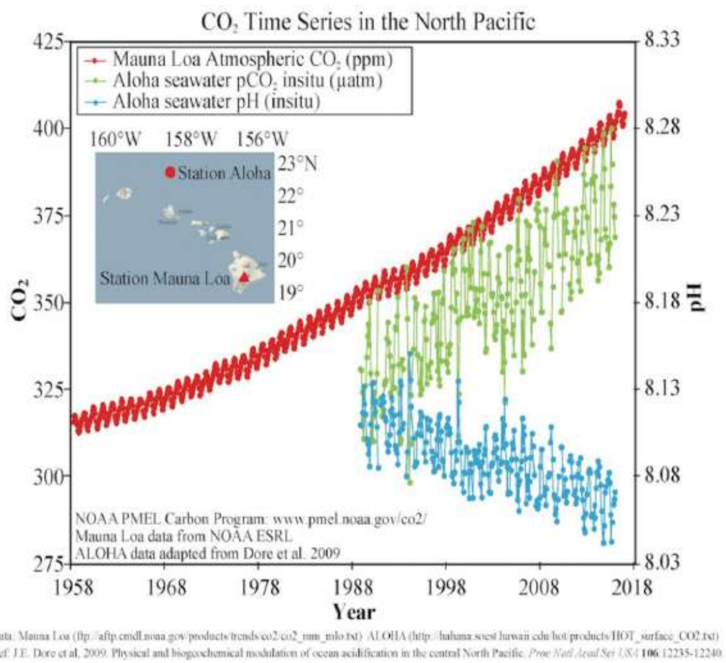


Keeling curve

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 414 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 think 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

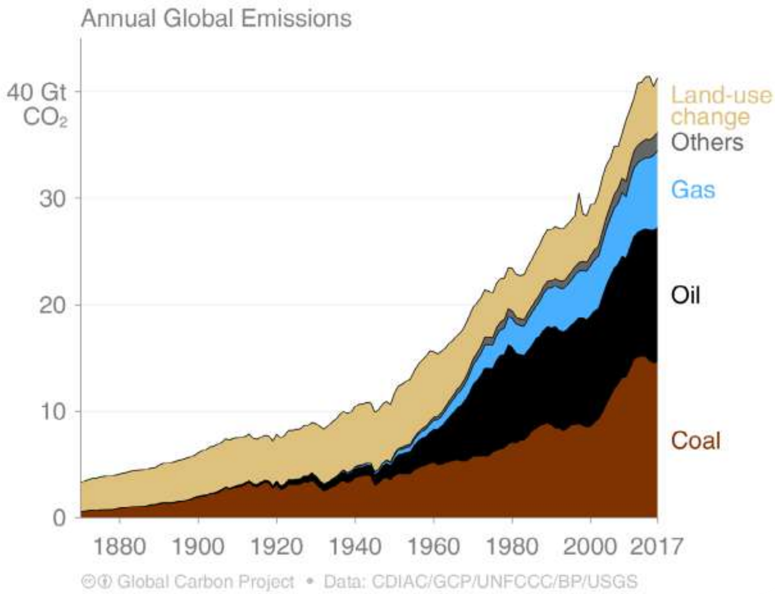
- The available measurements, including the famous Keeling curve, provide evidence of the correlation between temperature, CO_2 and ocean acidity.
- Beyond a simple correlation, the model describing the greenhouse effect through the accumulation of CO_2 in the atmosphere makes lab simulation experiments 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).

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

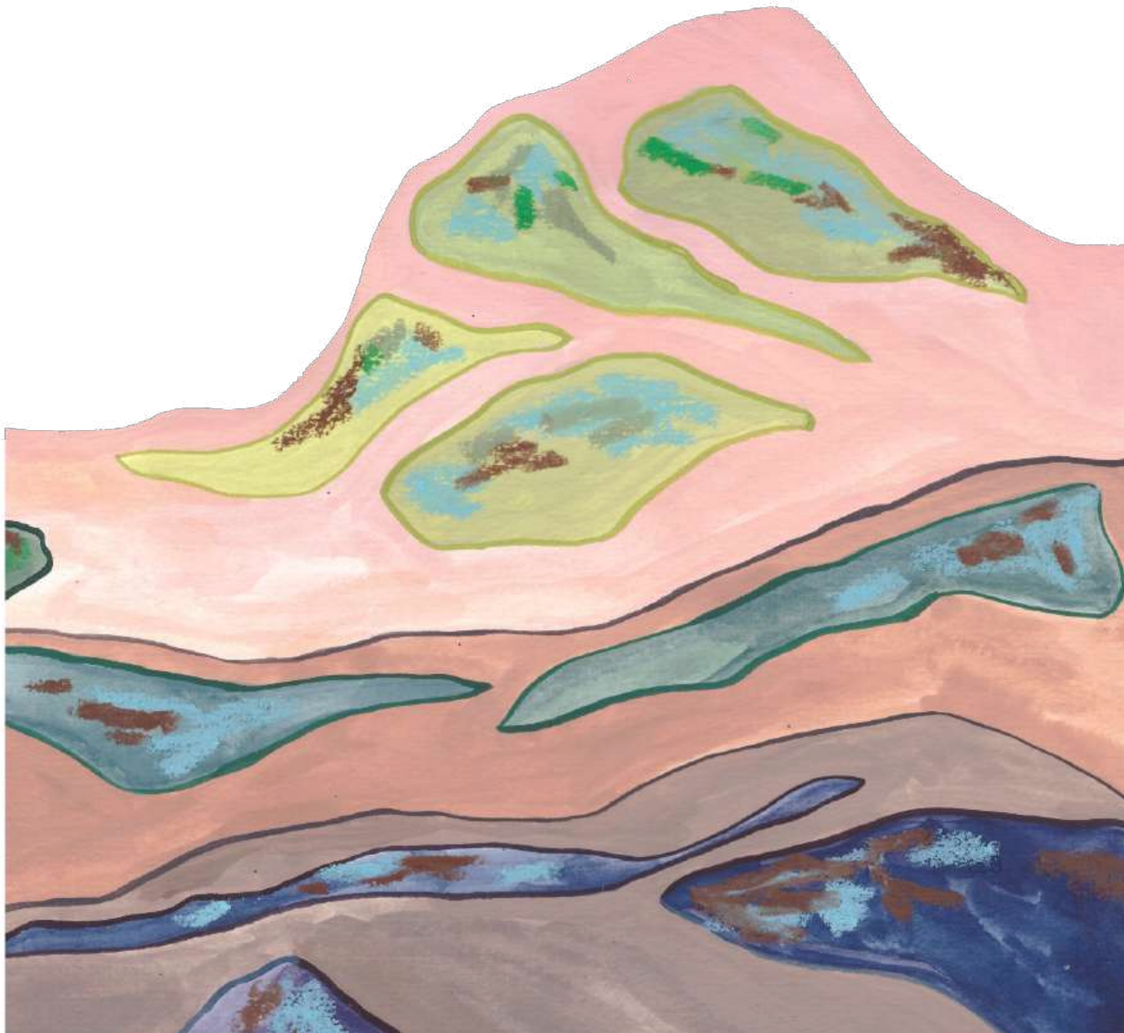
Source: Global Carbon Project

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.

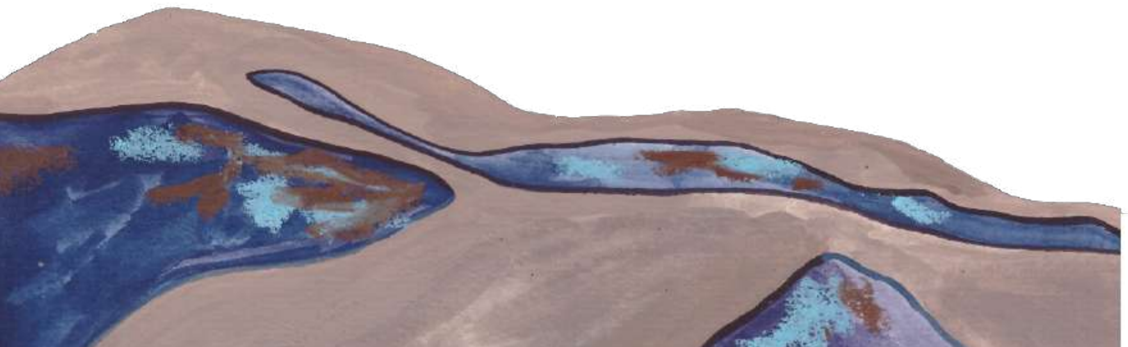


Conclusion

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 we know how climate works and how we are approaching a tipping point, we can think about where this may lead us, and if 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, what awaits us, in terms of climate - to project ourselves into our potential futures. This is what we will discuss in this last chapter.

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? Seeing as it's so difficult to predict the weather 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 you can have a look if you're interested in the future. More practically, they represent an essential working basis for communities and companies tasked with the planning of 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

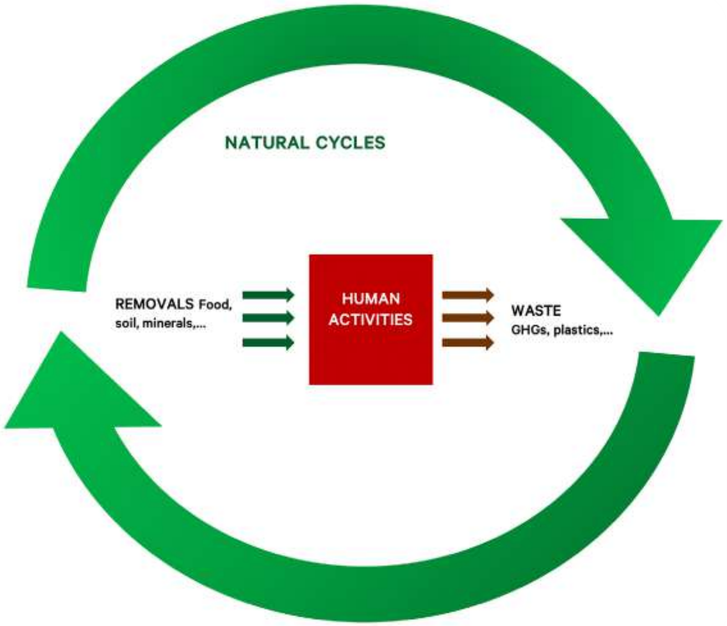
- Question: Based on the current 'business as usual' trajectory, the IPCC forecasts global warming of 4°C or more by 2100. This is the average warming of the planet. As regards just the Arctic, how much would the average warming be: 2°C, 6°C or 13°C?
Answer: 13°C

- 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 about melting sea ice and sea level rise?
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 humanity 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 as not dependent on human will, and physicists and biologists know how to characterise these 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.

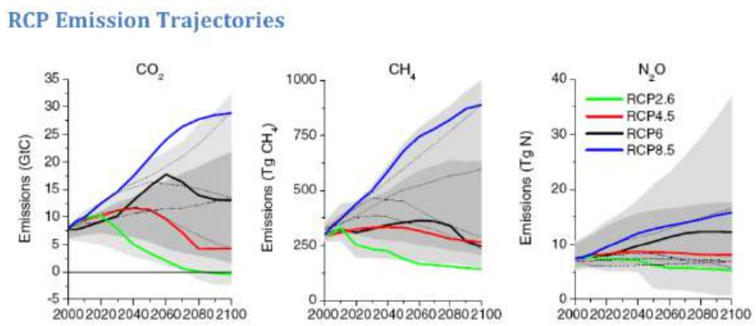
1.1. The scenarios

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 heart, 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 quantity of associated GHG emissions.

These emission scenarios are now standardised. We call them 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/m² 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 trajectory.
- 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 thrower, 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. 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 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 future date considered	The most probable average temperature and precipitation over the 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. The assessment of the results allows us to identify the most probable 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 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 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. 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 predicted according to 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 little by little: 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:

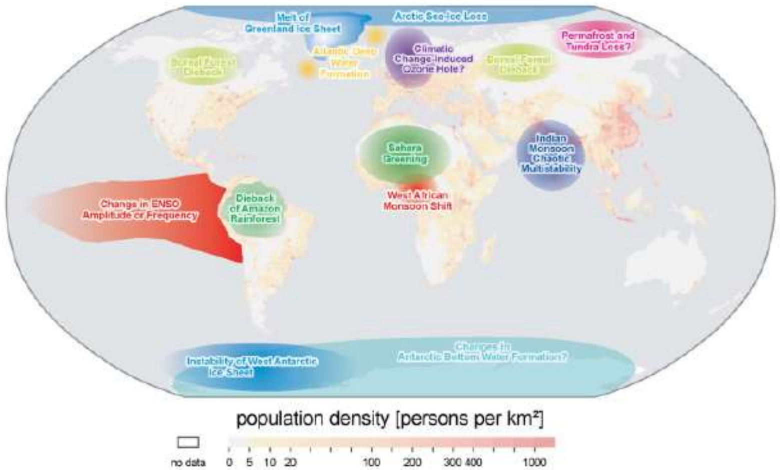


Fig. 1. Map of potential policy-relevant tipping elements in the climate system, updated from ref. 5 and overlain on global population density. Subsystems indicated could exhibit threshold-type behavior in response to anthropogenic climate forcing, where a small perturbation at a critical point qualitatively 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's the alternance between the dry season 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 would 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 acceleration phenomena, 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).

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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 rotation.[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). 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, which 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/

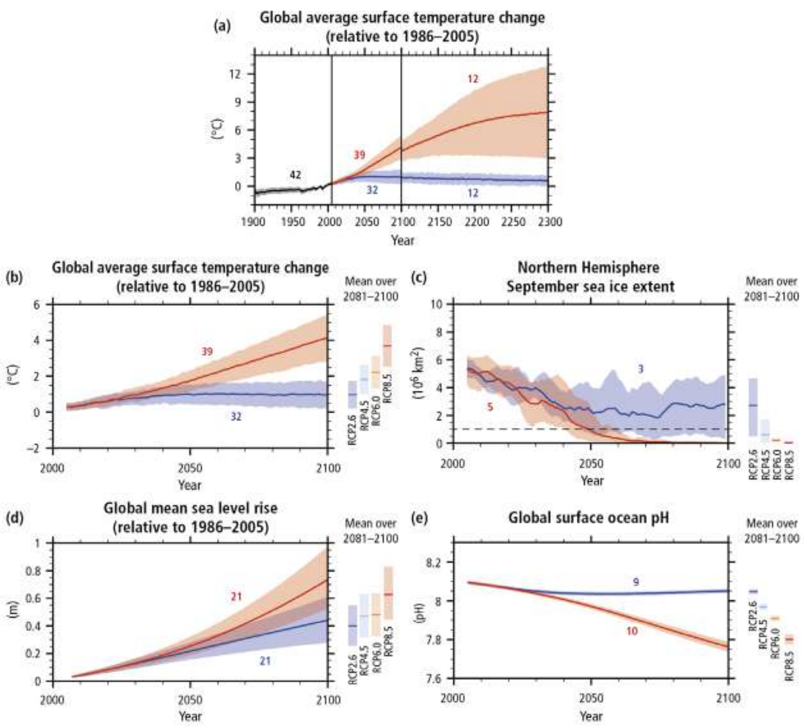
3 Reading IPCC reports

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:



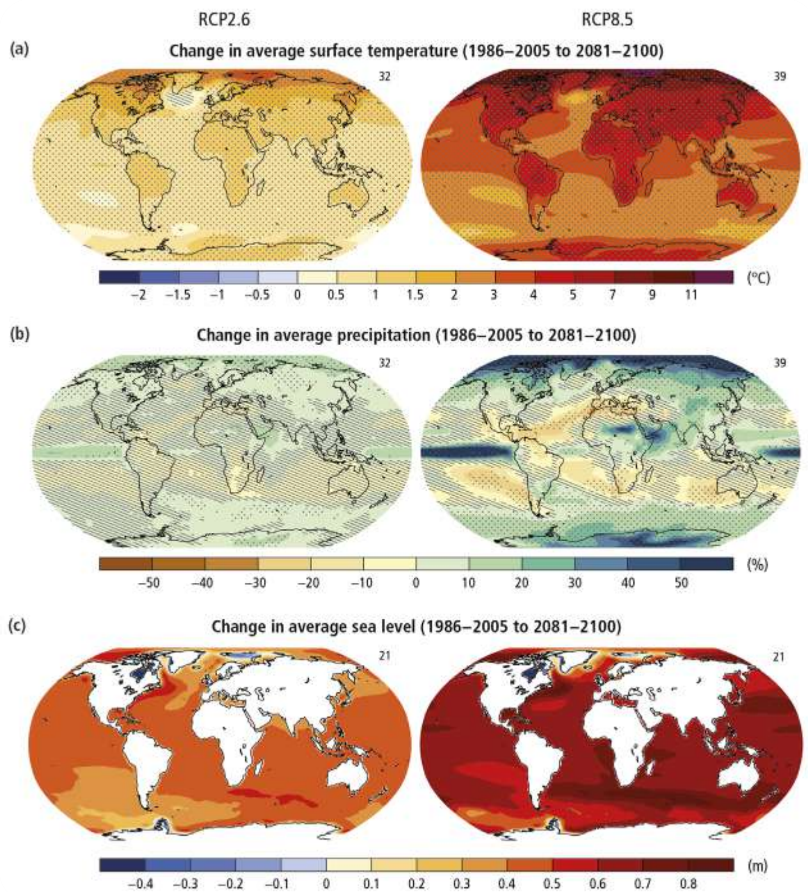
Evolution of different markers of global warming within two extreme scenarios

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:

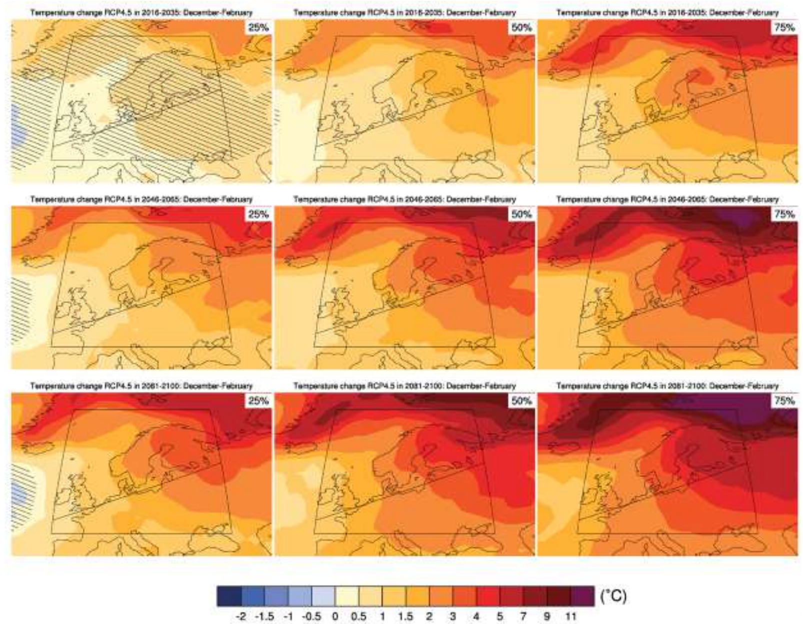


Regional climate changes according to two extreme scenarios

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 are less than 25% of chances of having lower warming than that shown on the map. Similarly, a 75% map means that the IPCC estimates that there are 75% of chances of having lower warming than that shown on the map. Thus, these three maps allow us to draw a confidence interval in 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.

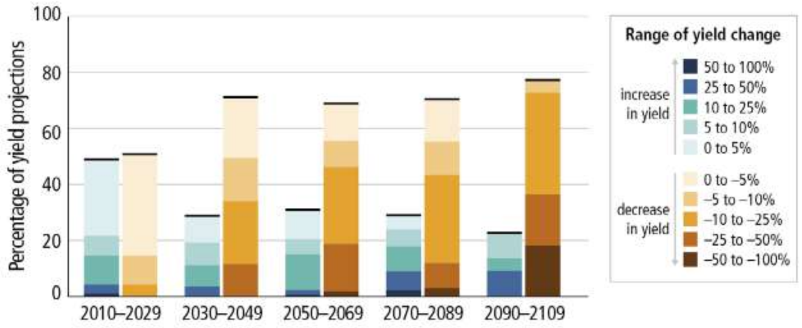
On the IPCC website you can find the evolution of summer temperatures in Northern Europe, as well as the evolution of precipitation. It's an atlas of projections, where you can find similar maps for all the regions of the world.

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).

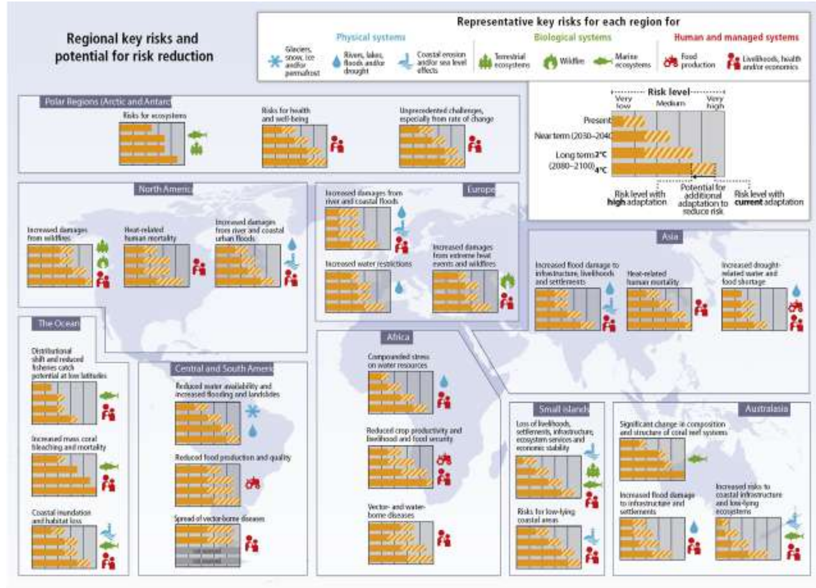


Distribution of agricultural yield projections according to different scientific studies

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:



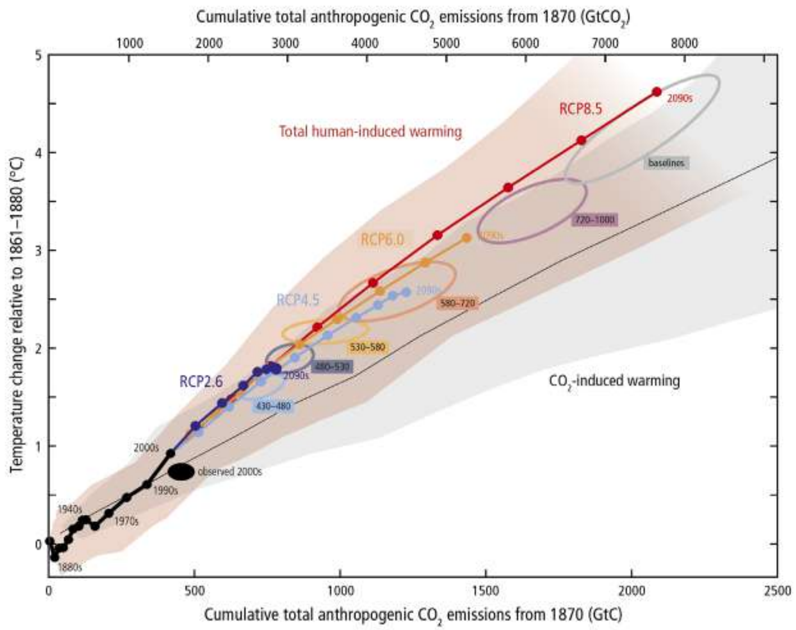
Risk projections by region

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 abscissa (at the top of the graph) we can read the total amount of CO_2 emitted by human activities since 1870, and on the ordinate, the corresponding warming figure. The dates are indicated directly in the figure. For example, we can see that according to scenario 8.5, BAU, humanity 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!