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Master of Science Thesis

CLIMATE CHANGE: THE SCIENCE BASIS
Models and Scenarios for Climate and Energy future development

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Abstract

According to the Planet "vital signs", climate is changing mainly due to anthropogenic factors. This work aims to address the main aspects of climate change with a strict approach, starting from its mechanisms and impacts on life, switching to mitigation and adaptation actions, going through the most updated scientific literature. Seven climate development scenarios are worked out using Java Climate Model (JCM).

Global Mean Temperature (GMT) started to increase in 1880, getting momentum: 2016, 2015, 2017, 2018, 2014 are the "top five" warmest years on records. 2019 is on track to be the new third. The anomaly w.r.t. 1880 ranges from 0.74 °C to 0.94 °C. Arctic Sea Ice Minimum (ASIM) lowest was 3.8-3.9 Mkm^2 in 2012, 4 Mkm^2 lower than the '80s values. ASIM "top five" smallest occurred between 2015 and 2019 and its average extent diminishing rate is 12.8% per year. Antarctica and Greenland keep losing mass since 2002. W.r.t. then Antarctica lost 1,870 (± 175) Gt, while Greenland lost 3,771 (± 98) Gt, dropping now by 127 (± 39) and 286 (± 21) Gt per year respectively. The cumulative glacier mass balance - negative 63 of the last 68 years - shows a 20 m water equivalent (w.e.) loss from 1980 and is currently falling by 847-1,036 mm w.e. per year. The 93% ($17x10^{22}$ J) of the excess heat produced since 1970 has been absorbed by oceans, increasing their top 700 m temperature by 0.09-0.13 °C per decade. Global Marine Sea Level (GMSL) increased by 235 (± 5) mm w.r.t. 1880 as a result. Never has the atmospheric CO_2 concentration exceeded 300 ppm during the last 1 Myear, but it started to climb from 311 ppm in 1950 to the today's 414.83 ppm. These Planet's alterations are producing several impacts on natural systems. Replacing fossil fuel demand with a renewable-based one, together with energy efficiency improvement and demand reduction are the most effective impact mitigation strategies. Nevertheless, a certain grade of modification in Planet's life due to climate change is likely, so crucial are adaptation actions too including smart planning of cities, preservation of ecosystems and literacy work on the perception of climate change.

Projections about future climate are made using climate models. Through econometric, demographic and energy assumptions, they provide estimates gathered in scenarios, then checked against real observations. The outputs from the main ones show strong correlation towards a further warming in the year to come.

Among the scenarios provided, three "normative" Stabilization ones (ST1.5 ST2.0 and ST3.0) aim to stabilize the GMT increase to 1.5, 2.0 and 3.0 °C by 2100. Three "predictive" scenarios focus on the energy system evolution, with the first two Current Policies accounting for a fossil-based one (CP1) and a more balanced one (CP2), and the New Policies Scenario (NPS) including climate policies announced after COP 21. The last "exploratory" Sustainable Development Scenario (SDS) models the most preferable future possible, with social equity, fast energy transition, cleaner air and water. Looking at the results, the only two scenarios not exceeding 2.0 °C are ST1.5 and SDS. The sole SDS shows a peak-and-decline GMT trend, meaning that according to the others the GMT rise will continue after 2100. Given the current socio-economic, energy and demographic conditions seems extremely unlikely not to exceed the 1.5-2.0 °C increase in GMT by 2100. Science has never been clearer than now. Climate change is no more ignorable.

Summary

CHAPTER 1 – INTRODUCTION

We are currently facing one of the greatest threats in thousands of years: climate change. For long time a changing climate was something that scientists have been considering would have happen in a distant future. The fact that humanity has been acting on climate system, altering it, is known since 1800. The new thing is that right now we are acting so profoundly on climate that we can actually experience the impacts of the changes on our skin in real time: temperature rise, poorer air quality, floods, droughts, extreme weather events, sea level rise. All of this is happening faster than lot of estimates from the scientific community projected. The Science is now clearer now than ever. Multiple reports from the most important world institutions have proven on the one hand that urgent action is needed, and on the other that the actions we take now and in the next few years will affect deeply the life on the Planet in the next hundreds.

- 1.1 - What is going on

The climate system is changing for one simple fact: the Planet is getting hotter. Data from the most important meteorological and climate centers[1] show that 20 of the hottest years on records are placed in the last 22 years. A clear, sharp rise in temperature has been recorded since 1850, when the first recordings have started. After decades of researches and studies on water, land and atmosphere, the facts are now unequivocal: this warming trend cannot be explained by natural drivers for reasons that will be discussed in *Section 2.7* but is caused by human activities. The main responsible for this, is fossil fuels burning. The big issue with that is that at the moment, our existence is vitally relying on fossil sources. From the moment we get up in the morning, we take the phone and do some social networking, till the moment we go to bed at night, we are consuming energy all time. Basically, that energy is almost entirely powered by fossil fuels.

As any other combustion reaction when we burn fossil fuels (coal, gas, oil), we get carbon dioxide (CO_2) as a waste product. The increasing quantity of CO_2 released in atmosphere acts like an enormous blanket above the Earth surface, absorbing the heat radiation it emits. This ends up warming the Earth surface. Right now, we are progressively and systematically adding up CO_2 and other Greenhouse Gases (GHGs) into the atmosphere, making this effect even stronger. Before the starting of the coal to be burned by the human energy supply system (conventionally we refer to 1850 as the baseline year, calling that period "pre-industrial times"), the carbon dioxide concentration in atmosphere was around 280 ppm. Right now, is 414-415 ppm.

One or two degree Celsius of temperature rise may not seem so dramatic, but actually that means that there are going to be more frequent heat waves, droughts and extreme events broadly speaking. It is not about climate change is causing or not an event to happen. It is rather about climate change will make (and is making right now) some events more or less likely to happen and eventually more or less intense. It is about 30 times more likely now to have a heat waves than it would have been without climate change according to the Met Office. This of course have a remarkable effect on the Planet life. In summer 2018 - when temperature in some parts of Australia reached 42 °C - even creatures adapted to heat, did not manage to survive [1].

Animals of all species are now adapting to a changing climate, struggling to be able to survive. Especially the areas near the Equator are the ones interested by this huge threat, being the one exposed to the strongest temperature rises. If climate change will follow a too fast developing, this will certainly push a lot of species off the Planet. We are already causing major extinctions. Roughly the 8% of the species is now on the edge of extinction exclusively due to climate change. Eve with the loss of the smallest bacteria existing in nature, the biosphere ecosystem is irreversibly destabilized and risks major collapses on a large scale.

- 1.2 - The effects of a changing climate

As temperatures rise up, the consequences that originate are multiple. One of them is the increase of wildfires. 2018 has been a record-breaking year as regards the frequency of wildfires across the globe. Greece, Australia, Western US, and even the Arctic or other countries between the coolest places on Earth, have been tormented with that. The fires in the sole California, in 2018 have caused nearly $24

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[1] The UK's Met Office Hadley Centre, the US Climate Center National Oceanic and Atmospheric Administration (NOAA), the Japanese Meteorological Agency and the National Aeronautics and Space Administration (NASA) are heading all together in the same direction.

billion worth of damage. The chances that the very hot and dry conditions in which wildfires originate rise with a warming climate.

Climate change is not only exerting its impacts when talking about heat waves but is already changing the weather system in multiple other ways. With a degree of planet warming, it goes consequently an increase in moisture coming from water evaporating off rivers, glaciers and oceans. Obviously for this reason more rainfalls are expected. This last decade saw a dramatic increase in super storms and flooding events in China, Japan, Indonesia, Kerala, Sri Lanka, etc. A brief explanation of the main climate change impacts is provided in Section 4.2. Along with that, another issue rises. Earth's ice is melting all across the world, after being frozen for millennia. Multiple assessment on the global state of glaciers and ice tell us that Greenland ice has lost 4 trillion tonnes of ice with a progressively increasing trend, as it is doing it at a pace five times higher than 25 years ago. Even going to the South pole, the majority of models in the 80' and the 90' predicted that Antarctica's ice was to grow. That is not the case, as it is losing mass three times as much as it was 25 years ago. If the icesheets lose mass, sea level goes up accordingly.

Although sea level has been steady for millennia, it has already risen by nearly 20 cm during the last 100 years. Sea level rise is a crucial issue for the hundreds of thousands of people living in the most vulnerable areas of the world, including the South Pacific, Indonesia, Bangladesh, Southern China, etc. As the 72% of the planet is covered with the oceans' water, more than 600 million people (nearly the 10% of total world population) are currently living in coastal areas less than 10 meters above the sea level, while approximately 2.4 billion people (the 40% of total world population) live in areas less than 100 km off the coasts. For this reason, the sea level rise issue is gaining so much importance. Sea level rise trigger phenomena of coastal erosion, floods, high tides rising in the estuaries and river systems, causing in turn fresh water contamination, marshlands loss and damages to the nearby agriculture. Nearly two-thirds of the over-five-million people cities are placed in potentially threatened zones. For instance in the US, Louisiana is losing land at an impressive rate (one football field in 45 minutes)[2]. The majority of projections indicate that if no political actions will be taken to fight climate change, future generations are going to face from 80 cm to 1 m of sea level rise by 2100.

Another big issue we are going to face in a hotter Planet involves the greenhouse gases that have been locked down for centuries in the Arctic's permafrost. In particular, large amounts of methane (CH_4) - which is 21 times more powerful as a greenhouse gas than CO_2 - as the temperature goes up and the permafrost starts to unfreeze, is going to be released increasing even more the GHG effect and triggering an even stronger increase of the Earth's temperature. Historically, more than 90% of the heat that has warmed our atmosphere ends up being trapped in the oceans. Besides the expansion, another consequence of this getting-hotter behavior is coral bleaching. Nearly one third of the world's corals has been bleaching and dying only during the last three years.

The ways in which climate change is affecting our Biosphere are multiple and wildfires are certainly one of them, but they are not the only phenomenon threatening in particular the world's vegetation: also forests clearing plays a fundamental role. The world's green exerts a crucial role in the planet's carbon cycle as it has taken up approximately one-third of our global total greenhouse gas emissions. Plants and threes absorb carbon dioxide and use it to build tissues and leaves within the two processes of respiration and photosynthesis that will be discussed deeply in *Section 2.5*. Vegetation basically acts as a huge lung for the Earth. Forests are one of the biggest and most important climate regulators as they moderate actively the variations through which the climate system undergoes with the so-called climate feedbacks. Focus on climate systems is provided in *Section 2.3.* Since 1972 the satellite images have

[2] Emblematic is the case of Isle de Jean Charles in Louisiana which has seen its 400 people relocated due to rising seas caused by subsidence, because of oil and gas extraction.

been tracking the trends of global forests extension. What comes out is that forest disturbance has been going on for decades all over the world, with strong deforestation and clearing happening particularly in Paraguay, Peru, Bolivia, Colombia, China, Indonesia, Norway, Russia and middle Africa. Forest removal occurs mainly due to agriculture, farming and infrastructure building. Plants are cleared, burned or sold as fuels and then replaced with rubber, soybeans or other more profitable cultures. However, one of the biggest driving forces for that is the palm oil cultivation; this product is basically everywhere in product consumed in western countries[3] and right now is causing inadvertently but systematically the lion's share of deforestation. As these centuries-old plants and trees are first cleared and then burned, huge quantities of CO_2 are no longer stocked but rather released in atmosphere, added to the amount that is emitted because of anthropogenic activities. As this process goes on, the Planet's natural ability to mitigate climate change shrinks dramatically. At the moment, nearly a third of the total carbon emissions are caused by deforestation.

- 1.3 - Science versus...

It has to be remarked that much of the phenomena we are actually seeing were abundantly predicted decades ago. The first concerns about an unlimited economic development, strongly fossil fuels relying and not environmentally sustainable were raised even in 1968. With the report commissioned by the Club of Rome in 1972 and released by the Massachusetts Institute of Technology (MIT) whose name "The Limits to Growth" was yet emblematic, the most influential scientists of that period put pen to paper an impressive amount of figures about future estimates, the majority of which have proven to be exact. The Italian economist Aurelio Peccei has been one of the most prominent personalities (and founders) of the Club of Rome and has represented a pioneer figure in the context of the environmentally sustainable development. As said, the findings in "The Limits of Growth" report are impressively adherent to what is going on right now both under a thermodynamic and socio-economic point of view.

More detailed figures were released by the astrophysicist James Hansen and his team from the NASA Goddard Institute for Space Studies (GISS) in front of the US Congress in 1988. He basically stated on the one hand that the rising of the planet temperature was 99% a physical effect triggered by the increasing carbon dioxide in atmosphere[4], and on the other that the rate at which the Earth was warming, was too high to be a systematic fluctuation[5]. As a matter of facts, the very first scientific publication that link the climate change to anthropogenic factors is from the Nobel prize Svante Arrhenius and dates back to 1896. This should convey us the idea that Science has been showing the way for years - or rather decades - but the feedbacks from the politics and the world's public opinions have been sinfully weak. Right now, things do not seem to be remarkably different from what has been going on during this time.

Policies needed to meet the Science concerns were never adopted for many reasons. On the one hand the complexity of the Science underpinning the concerned estimates has played a crucial role in confusing ideas around the concept of climate change and its causes. The second key factor has been the centrality of an economic-based cultural hegemony. grounded on goods and especially on their capacity to produce revenues, rather than a physical or thermodynamic one approaching the reality taking into account the physicals constraints of nature. In other words, whether we like it or not, we all live not only under a roof, but even primarily inside the global market. This means that we are all subject to the market's laws: climate issues together with the needed energy system transition make no

[3] Palm oil is in a huge amount of goods such as shampoo, bread, chocolate, crisps and many other refined products.

[4] In fact, the linkage between the two phenomena was not sure at that time. This is now well known and is called GHG effect. See *Section 2.5.*

[5] See *Section 2.4.*

exception. When we talk about climate change, energy supply and all the facts linked, we are definitely talking about business.

- 1.4 - The counteractions

Taking in mind these facts, the future can be quite alarming. However, it is not without hope. According to Science, it is still possible to tackle the climate change issue given that actions are put in place with urgency and determination. In order to do this, a proper level of consciousness by the public opinion together with political willingness by the institutions are required. But what are the actions we must put in place and what can be done in order to avert the poisonous effects of a changing climate? Nations, Governments, Institutions, Companies and most important, we as individuals have a great responsibility. It is up to us. The climate Science differentiates the strategies to act on climate change between two different broad categories: mitigation and adaptation. The main points of both will be discussed in *Chapter 3.*

At the 2015 United Nations (UN) climate summit in Paris, the Conference Of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCC), 196 countries signed a treaty that set the objective to limit temperature warming to well below 2.0 °C and to try to hold it to 1.5 °C by the end of the century. The International Panel on Climate Change (IPCC) has stated that this goal can be reached if and only if the anthropogenic emissions fall by half by 2030 and then approach the net zero globally by 2050. This means necessarily huge turnarounds at various levels, starting from the way we produce energy and we run agriculture and breeding, coming to both our transport system and the way infrastructure are designed. According to the International Energy Agency (IEA) and the International Panel on Climate Change (IPCC), the global emissions by economic sector see primarily the energy supply system (meaning electricity and heat production) and secondly agriculture, forestry and Land Use Change (LUC) taking the lion's share, accounting respectively for 25 and 24%. Industry represents the 21%, while Transport and Buildings account for the 14 and the 6.4%. These percentages depict quite well the situation: the U-turn that our Planet requires in order to mitigate the effects of climate change involve basically all the sectors of our everyday life.

The main strategy to be deployed in a mitigation context is without a doubt the energy transition away from fossil fuels, towards renewable energy sources. This can be the only driving force capable of radically decreasing greenhouse gases emissions to the Paris Agreement's levels. Every country has got its own better-working resource suiting its geographical or morphological features: places like Norway or Italy have developed hydropower, Morocco, India or sub-Saharan Africa receive a lot of Sun and so are predisposed to develop Solar Photovoltaics (PV), the coast of Great Britain are particularly windswept and therefore suited for wind turbine farms. Luckily, renewable energy is yet a reality. Nearly two-third of new power generation capacity added in 2018 was from renewables. At the end of 2018, the global capacity from renewable generation reached 2.351 GW. Hydropower accounts for the 50% of that, followed by Wind (24%) and Solar (20%). The main issue with that was that the energy generated from renewables was not economically competitive with fossil fuels one. Anyways, it has happened (and it is actually happening more and more), that some types of renewable sources have become cheaper than their fossil sisters. This is yet true for wind and solar PV in some places [3]. Solar power in particular, is the cheapest newly installed electricity in more than 60 countries at the moment. With the increasing installed capacity - that is projected to grow at unprecedented rate during the next few years - wind power is to become much cheaper than fossil fuels. A survey on the various renewable energy solutions as well as a state of art of the current energy market is provided in *Section 4.3.3.1.* Other than this drastic change in the energy supply chain, efforts must be put in the improvement of energy efficiency. The International Renewable Energy Agency (IRENA) has stated that the boost of the renewables, together with improved efficiency and a smart-planned reduction in energy demand, can meet the 90% of the energy-related reduction pledges needed to meet the Paris goals.

However, challenges remain in the context of availability and reliability. As known, the main issue with an energy system strongly relying on renewable sources is that it become alarmingly liable to their historical limits, the most important of which are being intermittent and having (broadly speaking) pretty low efficiencies. The sector that can make this turnaround real is definitely the energy storage one. With a strong development of new technologies in this field, it is extremely likely that renewable energy limits can be overcame in the next following years, according to the International Energy Agency (IEA). Besides the need of decarbonizing the energy sector, it will be crucial to make efforts in trying to decarbonize also agriculture, industry and transport.

Besides the multiple mitigation actions existing with the objective of reducing the amounts of greenhouse gases released into the atmosphere now, others are aimed at reducing those gases that have been yet released. Carbon Capture Storage (CCS) and Capture Sequestration (CS) follow this idea using different principles. The rationale beyond CCS and CS is discussed in *Section 4.3.4.*

In a context of a changing climate - and actually yet changed – other than mitigating the impacts, becomes crucial to implement strategies that tries to cope with them, accepting the fact that they have already shown their negative potential on life on the Planet. This way of reasoning is often referred to as “adaptation” and with mitigation is one of the two twin pillars of the counteraction strategy against climate change. Adaptation means anticipating the adverse effects of climate change, pursuing actions intended to minimize or prevent damages they can cause. In other words, adaptation means indeed to adapt to a changing climate and this can be done at multiple levels. Examples of adaptation measures include building food defenses, developing drought-tolerant cultivations, choosing three species les vulnerable to storms, fires and other extreme events, adapting buildings to future climate conditions, consuming food and water in a more efficient way, etc. A focus on the adaptation concept and on the related actions is done in *Section 4.4*.

- 1.5 - The future: climate models, IEA and IPCC’s scenarios

With today’s knowledge, it is possible to state with no doubt that the consequences of the counteractions that were not put in place 30 years ago are leading us to unprecedented and potentially disruptive changes. Looking ahead, it is virtually certain that if we are going to carry on emitting carbon into atmosphere, temperature will progressively heighten, and climate change impacts will get inevitably worse. In order to predict in broad terms what the world will look in the next future, the climate Science makes use of climate models. Climate models are parametric representations of the Earth system which try to account for all of its aspects, including both physical and thermodynamic (land, oceans, ice, atmosphere, etc.) and the socio-economic ones (economic growth, social inequality, technology development, etc.). These parameters are then bonded together by thousands of sets of differential equations, that are solved with numerical methods. A compromise between the computational time and the accuracy of the results is crucial for these analyses. The rationale beyond climate models and their main working principles will be discussed in depth in *Chapter 3.*

The outcomes of most climate models are outstandingly clear about the future we will have to face. Given the current rates of carbon emissions, deforestation, fossil fuels use and land exploitation, the world would reach 1.5 °C global warming by the decade 2040-2050. It is few decades from now. It is our generation. The point is that we are straight on a pathway to go towards the 2 °C (and more) before the end of century. According to the IPCC’s Special Report “Global Warming of 1.5 °C”, this would translate in more frequent storms, floods, droughts, heat waves and other extreme events and also stressed food production across the world, as certain types of cultivation would be no more fit for certain areas (triggering economic and social instability). The access to clean drinking water in some areas of the world would be even more difficult than now. In all of this, the parts of the world that are going to suffer the strongest impacts of climate change are the ones that have less responsibility on that, having been low-carbon emitters since the First Industrial Revolution.

Other than these general principles, there is uncertainty about the exact future development of the climate. The main source of ambiguity jointly with the intrinsic complexity of the Science is represented by current and future generations' behaviors. Science does not know at the moment what to expect: whether the climate crisis will start to be perceived as it should be, so as the biggest emergency of our time, or maybe if all the things will remain as they have been for decades and no further actions will be pursued. However, climate models are pretty clear on the tendency that we are going to face. They provide a quite large range of possibilities, taking into account all the various parameters of the climate system, and even the inherent ambiguities. According to this range of possibilities, it comes out that we may expect that by the end of this century the Earth's temperature will be higher than the pre-industrial levels between 3 and 6 °C. The outputs of the most important IPCC's climate models, gathered in different scenarios are presented in *Chapter 3, Section 3.3.*

- 1.6 - Seven different scenarios

In Chapter 5 a set of different scenarios are presented on the basis of the guidelines followed by the major climate and energy-related institutions such as the IEA, IRENA, IPCC, etc. Data constituting the boundary conditions are taken from the most recent findings in scientific literature and then fed to the climate model. Economic and social growth rates and parameters are taken from the last International Monetary Fund (IMF) and World Bank's estimates. The scenarios developed try to cover a wide range of possibilities for the evolution of climate system as well as the energy one.

Three stabilization scenarios (STs) are analyzed, bringing the world to a global net warming of 1.5, 2.0 and 3.0 °C by the end of the 2100. Other four scenarios are elaborated, highlighting the weight of the energy system different future developments. Two Current Policies Scenarios (CP) are carried on, assuming for the CP1 a development rather fossil-based, while for the CP2 a more balanced one. The New Policies Scenario (NPS) is then analyzed, accounting for the Paris Agreement pledges that have been put in place and the ones that have been announced only. Last but not least, the Sustainable Development Scenario (SDS) considers pathways that are fully in-line with the Paris Agreement goals. Remarkably, the SDS is the only one that actually manage to keep the global warming below the 2.0°C by the end of the century.

CHAPTER 2 - PHYSICAL FOUNDATIONS

In order to assess the climate change issue, crucial is to provide the physical framework. The Earth Global Energy Budget is discussed, and the various outflows and inflows are quantified. The basis of climate dynamics is explained focusing on climate sensitivity, feedbacks and controls. The geological backdrop is outlined stressing the evidences of human actions on climate. The Greenhouse effect is explained, as well as the carbon cycle, again focusing on human perturbations on it.

- 2.1 - THE PLANETARY MODEL

Key points

In order to address the issue of Climate Change, to understand deeply how the main drivers are involved and how models and scenarios for future climate pathways can be designed, a description of the primary components of the Earth's system must be provided. The first step that climatology – as any Engineer when assessing a problem does - is building a model of the system studied, making hypothesis, assumptions, listing its components and their features.

The Planet is composed by four different spheres or domains, representing the basic reservoirs for materials and energy:

a) Atmosphere: the set of layers of gases surrounding the Earth. Composed in terms of percentage with respect to volume in dry air by N_2 (78.084%), O_2 (21.046%), Ar (0.934%), CO_2 (0.04%) and traces of other gases (Ne, He, CH_4, O_3, CFC etc...). [2] H_2O in humid air ranges from 5% to virtually 0% in dry regions. Atmosphere is crucial because it contains the Greenhouse Gases (GHGs). Atmosphere is one of the features which distinguish a habitable Planet by a non-habitable one[6]. Besides gases, atmosphere contains multiple particles and droplets, collectively called *aerosols.* Some of these aerosols reflect the Sun's energy back to space. Some others are dark colored and absorb radiation instead (e.g., soot).

b) Lithosphere: the solid part of Earth, made by the upper portion of the mantle (called brittle) and the outermost layer of the Earth's structure: crust.[7] Rocks of the Lithosphere are important for climate because they interact with other parts of the Earth's system (e.g., they breakdown overtime in a process named weathering which ends up decreasing atmospheric CO2).

c) Hydrosphere: the sum of all the amount of water above the Earth's surface or into it. An estimated quantity of 1'386 km^3 [2] is subdivided in saltwater (97.5%) and freshwater (2.5%). Freshwater can be subdivided too: the 68.9% consists of ice, glaciers and permanent snow, and the 30.8% of fresh groundwater. Only 0.3% of this freshwater is in easily accessible sites like lakes or rivers. [3] Depending on its form, water exerts multiple influence on climate. For instance, dark oceans water absorbs incoming solar radiation, while light ice and cloud water reflects it.[8]

d) Biosphere: known also as *ecosphere,* it is the sum of all the ecosystems of the Globe. It integrates all living beings and considers their relationships with the former three Earth's components (e.g., living organisms exchange carbon and oxygen with the atmosphere, vegetation on land absorbs and release cyclically CO_2[9]…).

Fossil fuels that burns today have been formed by buried dead marine organisms and organic matters which are all Biosphere elements. Humans are part of the biosphere too, and influence climate in a strong way, as will be seen.

After this brief overview of the Earth's component, a focus on the other players involved in the climate dynamics must be provided.

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[6] The most important GHG are $H_2O_{(v)}$, CO_2, CH_4, N_2O, O_3. GHG are responsible for the GHG effect (see Section 2.5.1). For instance, Venus' atmosphere is thick and is composed for the 95% of CO_2, resulting in a strong GHG effect.

[7] Lithosphere can be *Oceanic*, typically about 50-140 km thick or *Continental*, ranging from 40 to 280 km. [53]

[8] See *Section 2.3.2*.

[9] See *Section 2.5.2*.

The primary source of energy for Earth's climate system is the Sun, which radiates energy coming from its core where the nuclear fusion of 600 million tons of Hydrogen (H_2) into Helium (He) take place every second [4]. This result in a large amount of energy reaching the Earth.

Two mechanisms intervene to moderate and change this flow of energy: *reflection*, which sends part of the energy flux directly back to space, and the so-called *GHG effect*, which regulate its passage through the atmosphere warming the Earth's surface as a result[10]. Atmosphere, Lithosphere, Hydrosphere and Biosphere are all involved in both the two processes.
The Earth in turn emits thermal radiation, as any object in nature with an absolute temperature >0 K does.
The two key relationships to quantify the powers emitted by Sun and Earth are respectively the Stefan-Boltzmann's and Wien's Law.
The first one relates the object's temperature and the energy that consequently emits, while the second one relates the object's temperature and the peak of the wavelength with whom the energy is emitted.

- ### 2.1.1 - The Sun

According to Wien's Law, the Sun's surface temperature can be measured by the characteristics of its electromagnetic radiation only by measuring the peak wavelength with whom the radiation is emitted[11]. Given the Wien's constant as $b = 2897.7729\ \mu mK$ and the maximum wavelength of the Sun's radiation as $\lambda_{max} = 0.5\ \mu m$, the Sun's surface temperature will be:

$$T_{Sun} = \frac{b}{\lambda_{max}} = \frac{2897.7729}{0.5}\frac{\mu mK}{\mu m} \sim 5800\ \mathrm{K}\ .$$

Then given the Stefan-Boltzmann constant:

$$\sigma = 5.67 * 10^{-8}\ \frac{W}{m^2K^4}$$

and the Sun's surface temperature T_{Sun} calculated above, the net energy flux from the Sun can be measured through the Stefan-Boltzmann's Law as follows:

$$I_{Sun} = \sigma * {T_{Sun}}^4 = 5.67 * 10^{-8}\ \frac{W}{m^2K^4} * 5800^4\ K^4 = 6.417 * 10^7\ \frac{\mathrm{W}}{m^2}$$

It means that each square meter of the Sun's surface gives off about 64 million Joules every second. Known the Sun's radius as:

$$R_{Sun} = 6.96 * 10^8\ m$$

the total power irradiated is:

$$P_{tot} = I_{Sun} * S_{Sun} = 6.417 * 10^7\ \frac{\mathrm{W}}{m^2}\ 4 * \mathrm{pi} * (6.96 * 10^8)^2 m^2 = 3.906 * 10^{26}\ W$$

This power propagates isotropically in the surrounding space, distributing uniformly on a spherical shell of radius:

$$R_{T\_S} = 1.496 * 10^{11}\ m$$

which is the Sun-Earth distance.

Solar constant[12] can finally be calculated as:

$$G_{sc} = \frac{P_{tot}}{S_{T\_S}} = \frac{3.906*10^{26}\ [W]}{4*pi*(1.50*10^{11})^2[m^2]} \cong 1380\ \frac{W}{m^2}.$$

[10] For a detailed focus on the GHG effect, see *Section 2.3.2*.
[11] Sun's wavelength of maximum emission is placed in the visible range, centered in 0.5 μm
[12] Solar constant (GSC) is defined as the total radiation energy received from the Sun per unit of time per unit of area on a theoretical surface perpendicular to the Sun's rays and at Earth's mean distance from the Sun [57]. Actual most prevalent value is 1.362 kW/m² [58].

- 2.1.2 - The Earth

The range of the Earth's radiation spectrum is mainly placed in the Infrared[13] zone. Given again the Wien's constant $b = 2897.7729\ \mu m$ and the peak wavelength at which the Earth emits thermal radiation as $\lambda_{max} = 11.4\ \mu m$, the Earth's estimated temperature is:
$T_{Earth} = \frac{b}{\lambda_{max}} = 2897.7729\ \mu \frac{mK}{11.4} \mu m\ \cong\ 255\ \mathrm{K}\ (-18\ °C).$
Again, according to the Stefan-Boltzmann's Law, putting

$$\sigma\ =\ 5.67 * 10^{-8}\ \frac{W}{m^2K^4}$$

and
$T_{Earth} = 255\ K$
the radiant energy given off by the Earth is in turn:
$I_{Earth} =\ \sigma * {T_{Earth}}^4\ =\ 5.67 * 10^{-8}\ \frac{W}{m^2K^4} * 255^4\ K^4\ \cong 240\ \mathrm{W}/m^2.$

Summarizing:

- The Sun gives off shortwave radiation with a peak wavelength placed in the visible part of the electromagnetic spectrum. The amount of energy per unit time that reaches the Earth's top of atmosphere, is the well-known *Solar Constant* (SC) and constitutes the so-called Earth's heat engine.
- The Earth gives off long wave radiation with a peak wavelength in the infrared part of the electromagnetic spectrum. An amount of energy per unit time (240 W/m^2) leaves the Planet towards open space.
  Because of the fact that Earth is spherical and rotates, the 1360 W/m^2 gets spread out to an average 340 W/m^2 received at the top of the atmosphere.

- 2.2 – THE EARTH'S GLOBAL ENERGY BUDGET (GEB)

<u>Key points</u>

Shortwave radiation from the Sun is the ultimate source of energy for the Earth's climate system. The Earth absorbs energy in two different ways: directly, through incoming solar radiation and indirectly, taking the energy re-emitted back by Greenhouse Gases from the atmosphere. The Earth heats up as a result until it reaches a certain temperature and consequently radiates energy according to the Stefan-Boltzmann's Law. The equilibrium on the Planet's control volume is gained when the energy radiated by the Earth's surface towards the atmosphere (the outflow), equals the one entering (the inflow). Life on the Earth is based upon this balance between inflows and outflows. The Planet is currently out of balance: inflows exceeds outflows. In other words, the amount of energy that is injected into the Earth's system is larger than the one that leaves it. That is at the core of the concept of Global Warming.

In order to understand the various mechanisms on which the climate system is grounded, a focus on how the incoming energy from the Sun is used and returned back to space must be provided. This is done by introducing the Earth's annual *Global Energy Balance (GEB)*. In line with the GEB model, the Earth is considered as a closed system14. The balance describes all the energy flows (or better, the power

[13] From 700 nm to 1 mm.
[14] "Closed system" is a thermodynamic system involving exchange of energy, not mass. [60]

fluxes) the ones coming from the Space, crossing the atmosphere and hitting the Earth's surface and the ones following the reverse path, starting from the Earth's surface, till leaving the atmosphere.

- 2.2.1 - Inflows

All these fluxes can be modeled and represented *(Figure 2.1).* The 1380 Watts per m^2 calculated above for the Solar Constant (SC) get spread and averaged out over the whole Earth's surface - which is spinning and spherical - and for this reason narrow down to about 341.3 W/m^2 [5]. This energy flux emitted by the Sun, reaches the top of the Earth's atmosphere and its wavelength is centered in the visible range with about the 8% in the Ultraviolet (UV) one [380-10 nm] [6].

About the 23% of this shortwave energy (77-78 W/m^2) gets directly reflected to space by clouds, tiny droplets and particles with the so-called *scattering* phenomenon. Examples of classic scattering particles are PM10, PM2.5 (or smaller), air molecules like nitrogen (N_2) or oxygen (O_2), etc. Besides driving the scattering phenomenon, the atmosphere also absorbs part of the incoming solar radiation, with different absorption coefficients in the different ranges of the electromagnetic spectrum depending on the type of the absorbing molecule considered; e.g., Ozone (O_3) absorbs in the UV range and particularly in the range [200-350 nm][15], water vapor (H_2O) absorbs mainly the Infrared wavelengths. Finally, dark particles (like soot) absorb radiation too. In conclusion, about 67 W/m^2 (the 19% of the incoming solar radiation) overall gets absorbed by atmosphere at various levels.

Atmosphere is mostly transparent to visible light, so the fraction of the incoming solar radiation belonging to that wavelength range (nearly 198 W/m^2, the 57% of the total amount), passes through it and reaches the Earth's surface. About 168 W/m^2 get absorbed by the Earth, while about 30 W/m^2 are reflected back to space by light-colored surfaces like ices and deserts. Total reflected incoming solar radiation summing the contributions both from Earth's atmosphere and surface amounts to 107 W/m^2 (31.2%), while the remaining part is absorbed either by the atmosphere of by the Earth's surface for a total of 235 W/m^2.

- 2.2.2 - Outflows

If the Planet continuously absorbed that 249 W/m^2, its temperature would go up progressively and systematically. This does not happen, because the Planet emits radiation too[16]. This creates an outflow that tends to equilibrate the balance.
As any object having absolute temperature > 0 Kelvin, the Earth emits thermal radiation. About 396 W/m^2 are radiated in the IR range by the Earth [7]. A portion of that energy flux having certain wavelengths of the electromagnetic spectrum passes directly through the atmosphere directed towards space, having no interactions with clouds or particles: it is the so-called atmospheric window and amounts to 40 W/m^2.

The other main part of *Surface Radiation* (350 W/m^2) gets absorbed by atmosphere (mainly by GHG and clouds). From there, radiation is then re-emitted isotropically. It can go both towards the Earth's surface, that is the *Back-Radiation* portion (324 W/m^2) ending up being absorbed by Earth's surface increasing its temperature, or towards space, following different pathways involving other multiple absorptions and re-emissions. The presence of greenhouse gases in the end, slows the passage of the radiation from the Earth's surface to space and makes around 324 W/m^2 to radiate back towards Earth's surface, which in turn ends up warming both the surface and the atmosphere[17]. Cloud and atmosphere are

[15] The so-called Hartley and Huggins-band. O_3 has also an absorption window in the visible, called Chappius-band [63].
[16] In the IR zone.
[17] GHG action on Climate occurs through the GHG effect. See *Section 2.5.1.*

responsible for the re-emission towards space respectively of 30 and 165 W/m^2, that summed up with the 40 W/m^2 from the *Atmospheric Window,* reach 235 W/m^2 forming the *Outgoing Longwave Radiation*.
Finally, there's also the *Latent Heat* portion (about 80 W/m^2) from evapo-transpiration: water evaporates from Oceans and Lands taking up energy, and then condenses in the atmosphere, releasing heat.

In the end, threating the Earth System as a control volume, including the atmosphere, handling the numbers with a higher accuracy[18] (including the first decimal as a significant figure), the three flows that must be considered become: *Reflected Solar Radiation* (104.9 W/m^2), *Total Incoming Solar Radiation* (341.3 W/m^2) and *Outgoing Longwave Radiation* (235.5 W/m^2). According to these numbers it is clear that, after an algebraic sum, the Earth System is slightly out of balance: 341.3-235.5-104.9 = + 0.9 W/m^2. In other words, as far as the Earth's Global Energy Balance (GEB) is concerned, the inflows slightly exceed the outflows.
Other estimates coming from other sources, studies and data, range from 0.1 to 1 W/m^2. The same applies when considering the Earth's surface as the control volume (thus not including the atmosphere). Performing the algebraic sum, five flows must be considered now: *Absorbed by Surface **share of *Incoming Solar Radiation* (168 W/m^2), *Thermals* (24 W/m^2), *Evapo-transpiration* (78 W/m^2), *Surface Radiation* (390 W/m^2) and *Absorbed by Surface* *re-emitted by the atmosphere (324.9 W/m^2). The same result holds true: 324.9+168-24-78-390 = + 0.9 W/m^2.

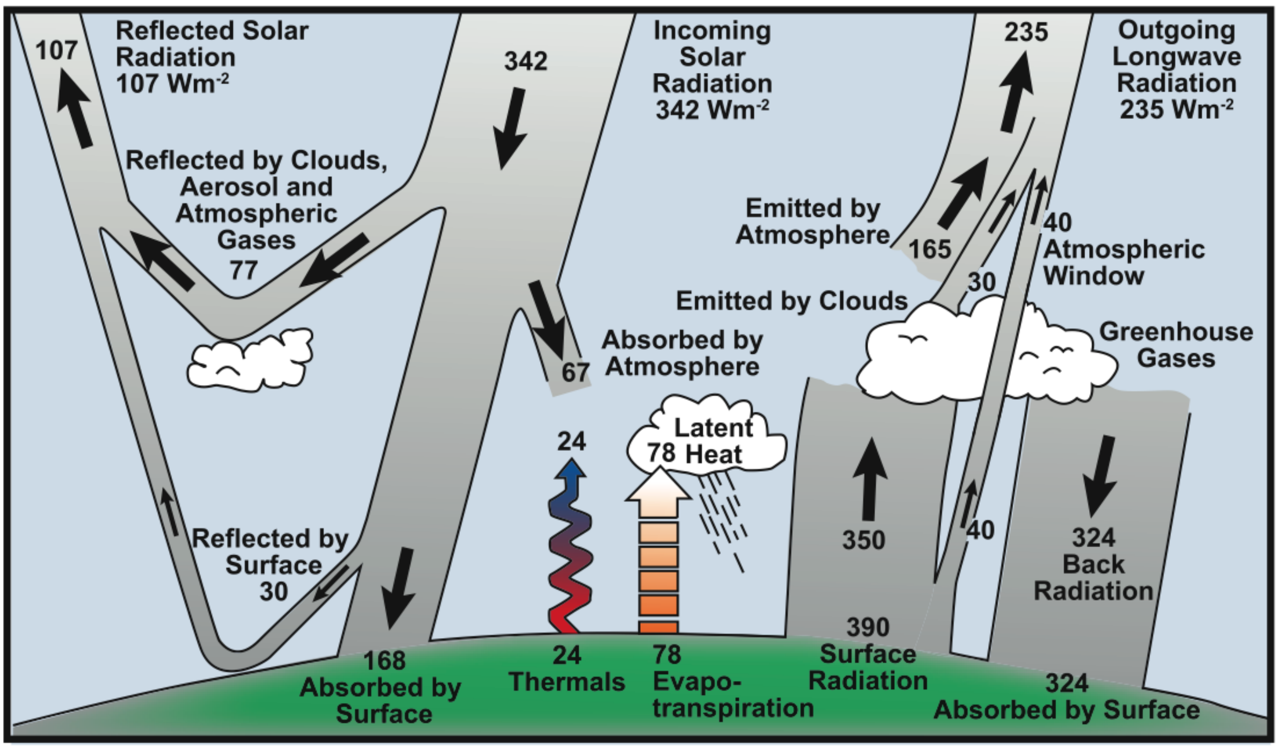

Figure 2.1 | The Earth's Energy Budget. Power fluxes and pathways describing the energy fluxes between the Earth's surface, the atmosphere and the Space.
Credits: Image adopted from IPCC Climate Change 2007, Working Group I: The Physics Basis. Updated with Trenberth et al. (2009).

[18] The numbers discussed above are integers, rounded for the sake of simplicity.

- 2.3 - CLIMATE DYNAMICS: CLIMATE SENSITIVITY, FEEDBACKS AND CONTROL

Key points

The Earth constitutes a dynamic climate system in which the various portions of it - described in Paragraph 2.1 - exchange matter and energy (one to each other) and energy alone (with the outside). As the Earth can be treated as su a thermodynamic closed system, if the Inflows equal the Outflows, the system is in steady-state. If not, its stock (matter or energy as well) will inevitably change, as it happens in any other closed system. The Earth's temperature responds to the exceeding energy flux occurring in the annual Global Energy Budget (GEB) with a re-equilibrating mechanism called Climate Sensitivity. Furthermore, the climate is subjected to multiple perturbations to which it responds by means of various feedbacks. Feedbacks can be both amplifying and stabilizing. Reflection of the Sun rays both by the light-colored Earth's surfaces or by the clouds and atmospheric aerosols is a classic example of a climate feedback. Changes in vegetation cover - the so-called Land-Use Change (LUC) - can alter reflectivity. Changes in cloud cover and stocks of reflective aerosols can change reflectivity too. Feedbacks involving clouds in a warming World are likely to be net amplifying, latest research suggests.

The amount of energy the Earth receives calculated from the Global Energy Balance (GEB) can change overtime and actually has changed in history. Various parts of the climate system respond to these imbalances as a result (i.e., the Earth warms up after the inflows exceed the outflow, etc…). The main issue at this point is how much temperature changes due to the sustained energy imbalance od 0.9 - 1 W/m^2 [19]. The IPCC reports and the climate science define this concept as *Climate Sensitivity* (CS). CS is defined broadly as the surface air temperature change resulting from an energy imbalance of the climate system, once it has adjusted and gained a new equilibrium [3]. Current best estimates existing in scientific literature of climate sensitivity, tend to converge to very similar results: a central value of 3/4 °C (three-quarters of degree Celsius) of temperature warming every W/m^2 added to the Earth's system [4]. In other words, the CS is about + 3 °C every 4 W/m^2 added[20].

- 2.3.1 - Climate feedbacks

Being treated thermodynamically as a dynamic system, the climate system considers inflows, outflows, stocks, balances as well as steady-state or transient conditions and feedback responses.

The concept of "feedback" is common to a wide gamma of disciplines ranging from control theory, mechanical engineering and biology but refers roughly to the same idea: "The outputs of a system are routed back as inputs as part of a chain of cause-and-effect that forms a circuit or loop" [5]. In the context of climate science, the term feedback refers to a process or a series of processes that both responds to a change (e.g., in temperature) and simultaneously influence the change. The climate feedback mechanism depends on the occurrence of perturbations to the climate system and it is characterized by a response of the climate system itself. The response can be an *amplifying* one or a *stabilizing* one. An amplifying perturbation pushes the system further towards the direction of the perturbation, while a stabilizing feedback is a response that pushes the system in the opposite direction of the perturbation, bringing the system towards the equilibrium again.

Considering the annual Earth's Global Energy Balance (GEB), multiple perturbations can occur both on the inflow as well as on the outflow side.

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[19] See *Section. 2.2.*

[20] The 4 W/m^2 added comes from the fact that it is about the energy added to the climate system, after doubling the atmospheric CO_2 concentration. The IPCC uses this case study as a possible future scenario for climate models.

One of the plainest examples of climate feedbacks is the link between glacier forming/melting and temperature levels[21]. Considering a single glacier as the control volume under equilibrium conditions, its ice stock remains constant. At steady-state there is an inflow coming from the snow of the precipitations and an outflow cause by its melting.
If a perturbation in Earth's temperature occurs (e.g., a small decrease), consequently there will be less ice melting. As a result, the glacier will increase its area, and this will cause that more solar radiation is reflected back to space. That ends up cooling the temperature of the Earth a little bit more. This phenomenon is a clear example of amplifying feedback[22].
Interesting is also the vice-versa, with the increase in temperature leading to a higher melting rate of the ice, causing a further increase in temperature since less reflective area of the glacier is left, resulting in a decrease in effectiveness of the ice-albedo feedback and an increase in absorption by the Earth's surface of the incoming solar radiation, ending up warming the temperature more. This phenomenon is an amplifying feedback again but pushing the system towards the opposite direction than before.

- 2.3.2 – Reflectivity: a focus

A deeper focus on the crucial process of reflection of the incoming solar radiation is of crucial importance in order to highlight what are the drivers for this process, whether they involve the Earth's surface or atmosphere and - most important - if it is a completely and only natural process or it can be influenced by human activity instead.

As discussed before, given the 341 W/m2 reaching the upper atmosphere, about 30% gets reflected back[23].
The measure of the diffuse reflection of solar radiation received by an astronomical body is called *albedo* [6]. Its values range from 0 (characterizing the classic black body behavior of absorbing all the incident radiation) to 1 (corresponding to a body that reflects all incident radiation instead). The effectiveness of the albedo phenomenon can be described by a parameter proper of the surface considered called *reflectivity*. Surfaces composed of different materials have different reflectivities.

Considering the atmosphere, clouds have the most efficient reflectivity leading to an albedo of 0.4-0.8[24]. Tiny particles and droplets, sulfate aerosols from volcanoes activity, pm10 from fossil fuel burning, sea salt particles from breaking waves are the other atmosphere reflectivity drivers. When referring to the Earth's surface instead, clean ice is the most effective reflectivity source providing an albedo of 0.8-0.9, while deserts are between 0.37 and 0.49 [12]. For dark forests and Oceans, the process is less effective and leads to albedos of 0.05-0.1 [7]. After considering all the possible Earth's surface material and their respective albedo coefficients, the Earth's overall albedo coefficient is about 0.3, matching the value of 30% reflected with respect to the total incoming solar radiation, found in Par. 2.2.

The point is that the stock of different reflective materials both in the atmosphere and over the Earth's surface can change overtime.

As regards the Earth's surface for instance, the view of an hypothetic cloud-free Earth shows on the one hand the light colored zones such as the light dry bands of deserts, the white ice on Antarctica, Greenland and on the main mountain glaciers mostly in the higher northern latitudes and on the other, the dark colored zones, such as the dark-green tropical forests, the Oceans and Seas, whose surface covers the 70% of the Earth. The formers reflect solar energy, while the latters mostly absorb the incoming solar radiation. Bands of different colors and consequently albedos are located at different

[21] This is the so-called *Ice-albedo* feedback.
[22] as clean white ice tends to reflect solar radiation, not absorb. A focus on the Reflection is done just below.
[23] See *Section 2.2.*
[24] Albedo 0.4 means that the 40% of the incoming solar radiation is

latitudes, according largely to atmospheric circulation, regional temperature and precipitation. The pattern with which the diversely colored zones are placed and especially their mutual extent are crucial factors that characterize our climate system intervening strongly in its perturbations. Taking the African microregion, the boundary between light desert and dark forest is clearly visible. *(Figure 2.2)* If the forest area expanded through the desert one, the macroregion's surface would be darker and reflectivity would decrease, increasing in turn the absorbed energy from the Earth and ending up warming the global average temperature.

The reflectivity of the different parts of the Earth is a driver for other important feedbacks. For instance, temperature warming at the higher latitudes of the Northern Hemisphere makes it possible for taller shrubs and trees to expand into tundra ecosystems. As they stick up more above the snow with respect to the classic tundra vegetation, it results in the net decrease in reflectivity of that area, allowing more solar energy to be absorbed. This helps promoting warmer temperatures, closing and feeding the feedback loop. This is another classic example of amplifying feedback, as it pushes the system towards the initial (warming) perturbation.

Going deeper on the climate feedbacks involving the Earth's atmosphere, 77-79 W/m2 of the total incoming solar radiation is reflected back to space mainly thanks to the clouds[25].
The major parameters influencing the reflectivity are the thickness for clouds (thicker clouds are more reflective and vice-versa rare ones are less reflective), size and concentration for droplets (higher concentrated, small sized ones are more reflective and vice-versa…).
Clouds are the major contributor to the Earth's overall albedo, accounting for a half of total energy reflected (77-79 W/m^2). In order to better understand the feedbacks involving the clouds it is relevant to highlight that clouds are the product of water cycles. The water cycle describes how water evaporates from the surface of the earth, rises into the atmosphere, cools and condenses into droplets or ice crystals in clouds, and falls again to the surface as precipitation in the form of rain or snow. The process is quick: the average time spent by a water molecule in the atmosphere is nine days [9].

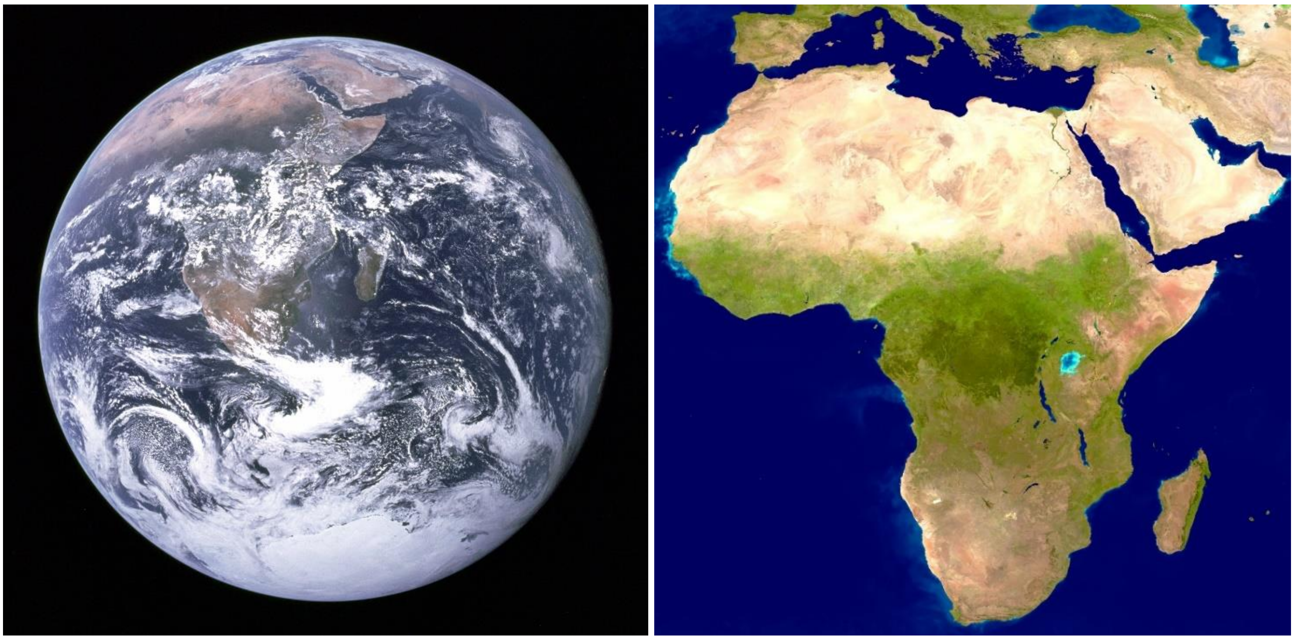

Figure 2.2 | The planetary model. (Left) Comprehensive view of the Earth in which are clearly visible all the elements taking part to the major climate feedbacks described in the Paragraph such as forests, deserts, the ice caps, the water vapor contained not the clouds. (Right) Focus on the African macroregion in a virtually cloud-free Earth. The boundary between the two areas (Northern desertic and Southern with vegetation) is clearly visible.
Credits: Image (left) taken from www.esa.int
Image (right) adapted from NASA, taken by Apollo 17 crew.

[25] See *Section. 2.2.1.*

Coming back to the climate feedbacks induced by the clouds, given an initial perturbation of the climate towards warming[26], more water would evaporate from the Earth's surface and therefore would be in the atmosphere, a greater surface in turn would be covered by clouds and consequently the overall reflectivity would increase. That would imply that more incoming solar radiation would be reflected, and temperature would cool down as a consequence, counteracting the warming. This is one of the best examples of climate stabilizing feedback. It must be highlighted that in this case, the water is considered to be into the atmosphere in the form of droplets and ice crystals.
The point here is that another (more likely) possibility is that water is into the atmosphere in the form of water vapor. In this second case, the climate feedback triggered by the clouds has a completely different evolution. Given again an initial perturbation towards warming, this would lead to an overall evaporation of liquid droplets into the atmospheric clouds, a consequent decrease in the surface covered by them and obviously to a lower reflectivity. Consequently, this would drive to an overall temperature warming as more energy would reach the Earth's surface. In this second case, the climate feedback set off by the atmospheric clouds would be an amplifying one.
Both the case considered and averaged the two different effects, the atmospheric cloud feedback on climate in a warming world, is tended on the whole to be considered mainly amplifying [10] [11].

Beside the clouds, one of the other major reflectivity agents is aerosol, defined as a suspension of fine solid particles or liquid droplets [8]. Volcanic activity, particles carried by winds and dusts from deserts taken several kilometers away through the atmosphere are aerosol sources. Larger aerosol particles (1-100 μm) such as volcanic ash and dusts tend to stay in atmosphere for hours or few days, and then to fall down. Smaller particles (0.1-1 μm) get removed from rain or snow, providing the nucleus around which droplets or ice crystals form during precipitations. Tinier aerosol particles can stay in the atmosphere for longer, from several months to years.

- 2.3.2.1 - Non-natural perturbations on reflectivity

As seen above aerosols and albedo drivers can be influenced by multiple natural factors. The tendency by the climate system to change dynamically in accordance to natural perturbations is called *natural variability*. Natural factors are absolutely not the only source intervening in the reflectivity feedbacks and defining their linked albedo coefficients: the anthropogenic ones can influence heavily the phenomenon too. The main anthropogenic contributions come from the so-called *Land Use Change (LUC),* clearing forests, urban and infrastructure development, mining and multiple other aspects whose effect increase as population and GDP increase, generally speaking. These mechanisms, together with fires and degradation of grasslands through grazing, are source of the so-called *anthropogenic variability.*

Focusing specifically on aerosols, their anthropogenic primary source is fossil fuel and biomass burning. It should be noted that all these anthropogenic emissions are overall highly reflective. In other words, larger anthropogenic emissions mean increasing the albedo effect which would result in a net temperature cooling [12].

Atmospheric soot and dusts, conversely can darken ice and glaciers surface, affecting their efficiency to reflect and resulting in a net increase of the Earth's absorbed energy. This would mean in turn a higher melting rate of ices themselves, triggering an amplifying feedback [13]. The most recent studies conclude that Land Use Change (LUC) have altered the Earth's surface albedo and caused a global decrease in the energy absorbed by the Earth of about 0.15 W/m^2 and a consequent temperature cooling. Uncertainties have risen instead about the overall effect of aerosols, but a net decline in the energy absorbed by the Earth is considered likely too [14]. In order to make this a little bit clearer, thinking in

[26] The climate perturbation is supposed towards warming, because - as it will be discussed in Section. - this is exactly what is happening right now.

terms of temperature, considering a relatively tiny change in Earth's overall albedo coefficient of 1%, this would result in a 0.01*341 = 3.41 W/m2 change in the Global Energy Budget (GEB) inflows. Given a *climate sensitivity* of 0.75°C per W/m2, a difference on the GEB's inflows of 3.41 W/m2 would mean a 2.5°C difference in the global mean temperature. This conveys the idea, on the one hand of the magnitude of the phenomenon and on the other, of the beautiful precariousness of the Earth and its climate system.

- 2.4 - THE GEOLOGICAL BACKDROP

Key points

Changes in the Earth's orbit have been altering for million years both the amount and the distribution of the incoming solar radiation that the Earth receives. The total incoming solar energy does not vary enough under these conditions to account for the large observed changes in climate from the Industrial Revolution until now, even if some feedbacks (e.g., the ice-albedo feedback) can amplify small perturbations and produce larger changes. The rate of change in climate that is registered right now, compared to the geologic backdrop on a timescale of million years, is by far the highest ever observed.

As discussed in ***Section 2.3*** natural and anthropogenic variability are both drivers for multiple climate feedbacks that have a quite immediate evolution. The mechanisms seen before are mainly fast response phenomena, re-acting to a certain perturbation. Nevertheless, multiple climate feedbacks have acted over the past million years (and are currently acting yet). By looking at the history of climate, evidences of Earth geologic variability and long-term feedbacks are clear. As will be seen, all these long-term periodical changes in the Planet's climate can be explained by the link between the Earth's orbital movements and the ice-ages.

In order to analyze the climate evolution over the past million years, human data obviously cannot be used. The geological temperature record has been rebuilt using sedimentary proofs. The most used one is the verification of the different shares of oxygen isotopes and specifically, defining the parameter "*$\delta^{18}O$*" or "*delta-O18*" as the ratio between the stable isotope *oxygen-18* (*^{18}O*) over *oxygen-16* (*^{16}O*). Given that ^{18}O is two neutron heavier than ^{16}O, water molecules (H_2O) containing the former oxygen isotope are heavier than the ones containing the latter. Considering the water cycle, this means that more energy is required for an Ocean's $H_2{}^{18}O$ molecule to evaporate, with respect to a $H_2{}^{16}O$ one. For this reason, the first water vapor originating from the evaporation of liquid H_2O is enriched in $H_2{}^{18}O$, while the residual liquid is enriched in $H_2{}^{16}O$. At the same time, water vapor molecules containing the heavier $H_2{}^{18}O$ condense more rapidly.

The Earth's climate had followed a long series of warm and cold period overtime ***(Figure 2.3).***

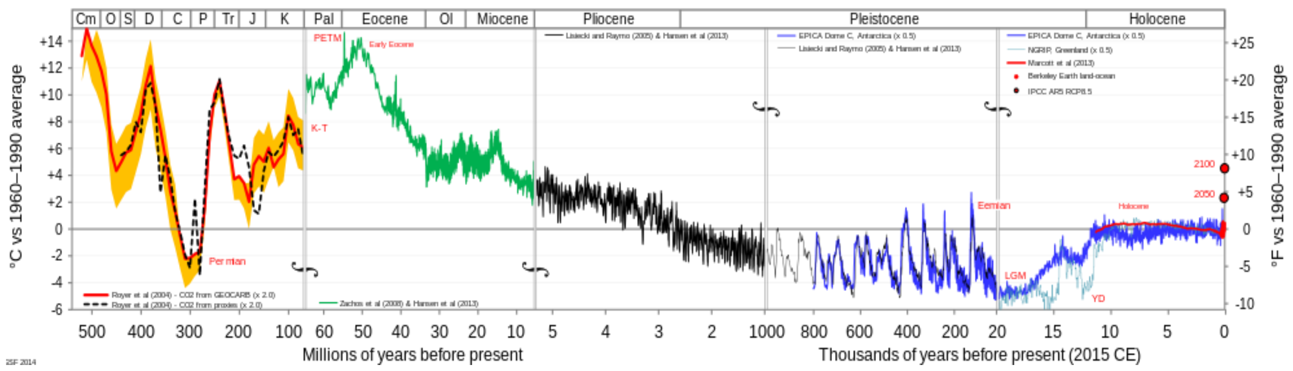

Figure 2.4 |The geological backdrop. Global Surface Temperature (GMT) history as a function of time with different timescales. **Credits: from Sato, J. E. Hansen and M. "Climate Sensitivity Estimatd From Earth's Climate History", (2012)**

The curve summarizes the evolution of the Global Surface Temperature (GST) during the last 500,000,000 years. What is most interesting for this purpose, is the right-hand side of it: the blue line that covers up the period ranging from 1,000,000 years ago, to the present days. During this relatively recent time, the trend shows a rather regular and systematic series of changes (consequent ups and downs).

By looking at the temperature difference between the cold and the warm periods it can be noted that it is in the order of about 5 °C. The very last bottom peak is the last ice cycle, occurred approximately 20,000 years ago [7]. At that time, the Earth was about 5°C cooler than today. Just to make it more tangible, Canada and part of northern Europe were completely covered with ice and sea levels were about 120 meters lower than today [8]. Back to the analysis of the geological GMT trend, although there is some variability it is clearly visible the exact periodicity of that variations: the largest and most important climate cycle has an amplitude of about a hundred thousand years.

- 2.4.1 – Earth's orbital periodicities influence

The pace, as well as the entity of the GMT geologic evolution is a crucial key in order to understand the dynamics of the Planet's climate and most importantly to seize the magnitude of the unprecedented changes that the Planet itself is undergoing right now. But what is the major driver of this periodic GMT fluctuation?

In order to answer to this question, it is crucial to focus on the time period of the fluctuation, taking into account at once the periodicity of the Earth's orbit[27]. According to the so-called Milankovitch cycles, the cyclical movement related to the Earth's orbit around the Sun affects the amount of solar heat incident on the Earth.

There are three different periodicities to consider:

a) <u>Eccentricity</u>: the eccentricity of an astronomical object is a parameter that determines the amount by which its orbit around another body deviates from a perfect circle. A value of 0 stands for a circular orbit, while values ranging from 0 to 1 varies respectively from an elliptic orbit to a parabolic escape trajectory. Values greater than 1 represent hyperbolic course. It takes nearly 100,000 years for the Earth's orbital path to change its eccentricity from approximately circular to its maximum value - which identify a slightly squashed course - back to circular again. This results in a change of the total amount of solar radiation reaching the Earth each year.

b) <u>Obliquity</u>: the obliquity address to the change of tilt axial angle which is defined as the angle between the object rotational axis and its orbital axis [9]. Angles are measured positive from the vertical. It takes about 41,000 years for the Earth's tilt angle to go from its minimum (22.1°) to its maximum (24.5°). Right now, the tilt angle is at 23.5°, getting smaller (with the axis on its way to standing more upright).

c) <u>Precession</u>: the precession is broadly defined as the change in orientation of the rotational axis of a rotating body. Axial precession is a gravity-induced process in which Earth's axis describes a circle in the space, completing one circle around 26,000 years (25,772) [10].

Season's patterns and seasonal contrasts are linked with obliquity. For example, if tilt axis was perfectly vertical, Earth would have no seasons and the majority of radiant energy from the Sun would be got

[27] In the 1920s the Serbian geophysicist Milutin Milanković made the hypothesis that the variations of the motions of the Earth's orbital paths resulted in the cyclic variation in the entity of solar radiation reaching Earth, influencing strongly its climate.

exactly at equator, vice versa for the poles. The maximum seasonal contrast occurs with the maximum tilt angle[28].

Earth orbit, tilt angle and seasons progression are shown in *(figure 2.4)*. The Earth passes closest to the Sun when Southern hemisphere is exposed to more direct Sunbeams with respect to the Northern one: in this configuration the Northern winter and Southern summer occur. The vice versa holds true with the Northern hemisphere summer and the Southern winter when the Earth is farther from the Sun. This means that basing only on the solar radiation coming in and orbital eccentricity, the largest seasonal contrast occurs in the Southern hemisphere. This state was completely reversed 11,000 years ago due to the precession of the equinoxes [11].

The point here is how to get from these multiple periodic motions to the GMT fluctuations observed. A first important link between the Earth's orbital cycles, the consequent seasonal contrasts and climate feedbacks is clear considering the growth of an *ice-sheet*[29].

In the Northern hemisphere, low seasonal contrast is the ideal condition for an ice-sheet to grow. After the snow has been piled up during the winter in fact, with high seasonal contrast, it will not be melting away during the following summer, as it would be with a warmer than average summer. In this case, an amplifying feedback takes place thanks to that: ideally more of the Globe's surface area is covered with white and reflective ice or snow so that more of the incoming solar radiation is reflected back and obviously less energy is absorbed by the Earth' surface. The Earth would get cooler as a result, allowing more ice and snow to be stored, closing the loop[30]. The initial perturbation in this case was towards cooling.

This type of climate feedbacks in combination to the incoming Sun's radiation changes are crucial to explain the amplitude of climate cycles recorded overtime.

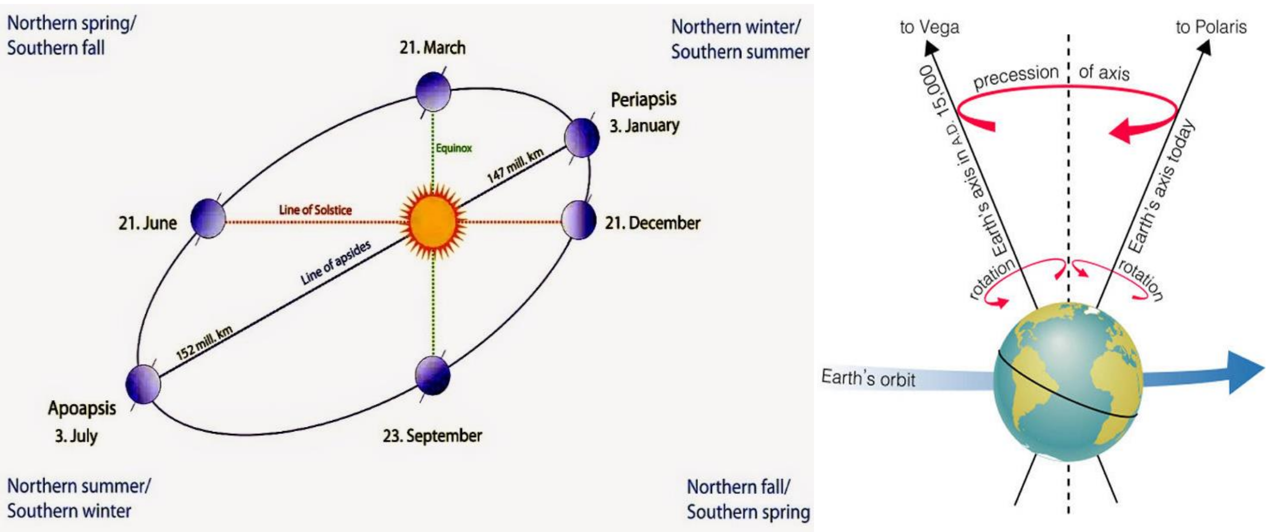

Figure 1.4 | Earth's Orbit Cycles. (Left) Scheme of the Earth's orbital trajectory. The three concept of seasons variability, eccentricity and obliquity are clearly visible. (Right) Sample of the precession of the equinox motion. Vega and Polaris are used as a reference direction for the Earth's axis. Credits:
Image (Left) from httpspeople.highline.eduiglozmanclassesastronotescycles.htm
Image (Right) from http://www.idialstars.com/jan2012.htm

[28] "Seasonal contrast" means for example particularly hot summers opposed to cold winters. Not only natural aspects are driving force for a marked seasonal contrast, but also anthropogenic ones [68].
[29] An ice-sheet is a is a mass of glacial ice that covers surrounding terrain and is greater than 50,000 km^2. For this reason, it is also referred to as "continental glacier".
[30] This is the so-called ice-albedo feedback. It involves ice caps, glaciers and sea ice. The effect has mostly been discussed (with some controversies) in reference to the declining Arctic sea ice [67].

By looking at the total actual change of energy received by energy over the past 10 million years *(Figure 2.5)*, two facts can be highlighted:

a) There is a periodicity in the cycles of about 100,000 years. As the eccentricity has a period of approximately the same time, it acts as the driver for this periodicity [12].

b) The value of energy from the Sun on the ordinate axis follows a quite restricted range of change overtime and most important, there is only 0.5 W/m^2 between the subsequent maximum and minimum peaks.

Considering the *Climate Sensitivity* (CS) as introduced before[31], if the only drivers of climate change over the past million years were these small variations in incoming solar energy, a tiny change in Global Mean Temperature (GMT) about 0.5 [W/m^2] * 3/4 [°C/W/m^2] = 0.375 °C would have been noticed. As seen, the geological records show fluctuations in the order of 5-6 °C, instead. This means that these orbital parameters' influence on incoming radiant energy from the Sun has a slight effect on a quantitative side. However, the combination of tilt, precession and eccentricity determines strongly the timing and the distribution of that energy around the Globe.

The overall effect on the climate ultimately observed with the geological records, is a combination between these small changes in the incoming solar energy and climate feedbacks that amplify these changes, depending on the direction of the initial perturbation. In other words, the periodic variations in Earth's orbit can nudge preventively the climate system towards cold or warm and consequently the action of multiple climate feedbacks - like the ice-albedo ones - magnify those nudges.

Another feedback mechanism of great importance that operates over such long timescales (hundreds of thousands years) is the one linking the atmospheric CO_2 and the Global Mean Temperature (GMT). Data from geologic records are used again.
The most complete dataset is the one reported by EPICA (European Project for Ice Coring in Antarctica). EPICA is one of the most important projects of this kind, whose main goal was to provide information about the natural climate variability and rapid climate changes during the last glacial epoch. Proxy climate indicators include oxygen isotopes (as seen before), methane concentrations, dust content, as well as many other indexes.
These measurements are obviously not only valid for Antarctica but are a consistent representation of the global concentrations, because the atmosphere mixes quickly and therefore no big differences between different locations are expected at this timescale on concentrations.

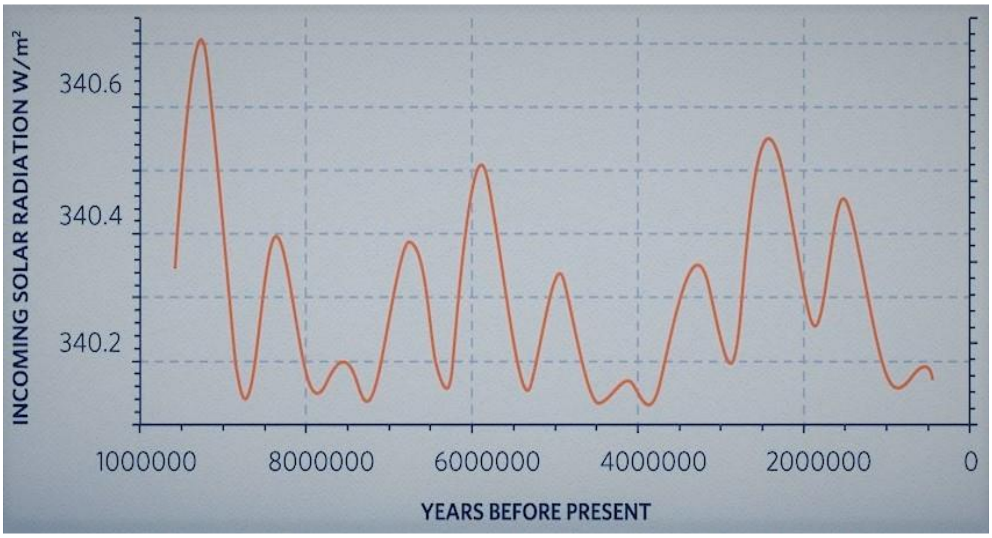

Figure 2.5 | Actual change in total solar energy received by Earth on average over a time period of 1,000,000 years. The periodicity of these cycles is about 100,000 years. That make sense, as the Eccentricity is the only among the orbital parameters that changes the Earth-Sun distance and consequently the amount of energy received as well. Credits: Image adapted from https://cleanet.org/clean/literacy/principle_1.html

[31] 3/4°C every W/m^2 added to Earth's System, in line with *Section 2.3.*

Making the use of deep ice core drilling, an analysis on the air trapped inside is performed measuring CO2 concentrations (and many other parameters) [13].
(Figure 2.6), shows the data record with two lines: the red one that represents the difference between the Earth's temperature in a specific time (on the x-axis) and the average temperature of the past 1,000 years and the blue one, that represents the atmospheric carbon dioxide concentrations, according to measurements from ice cores.
The two curves are clearly correlated: warmer temperatures are linked to higher concentrations of atmospheric CO2 and vice versa.
The phenomenon is explained by the occurrence of another climate feedback: Ocean's water captures and stores the dissolved CO_2[32]. As the efficiency of this process gets lower at warmer temperatures, given a perturbation of climate towards a slight warming of the Earth's GMT (e.g., a change linked to orbital pathways, causing a different distribution of incoming solar radiation, as seen before), less CO_2 can be kept dissolved in solution resulting in more CO_2 outgassing into atmosphere. More carbon dioxide in the atmosphere means that the strength of the GHG effect will be higher[33], promoting further warming closing the loop. This is another example of amplifying climate feedback.

In conclusion, the Earth's geological backdrop during the past million years shows a cyclic course, with warm and cold periods, with cold periods about 6 °C colder than warm periods. These cycles follow a precise periodicity that matches the periodicities of the major variations of the Earth's orbital pathway. Furthermore, considering the CO_2 history records[34], the swing in CO_2 concentration ranges between highs of about 285 ppm and lows of about 175 ppm. It has never reached 300 ppm. No time during the last 800,000 years has the Earth's atmospheric CO_2 been anywhere near as high as the todays 411.75 ppm[35]. The current value is highly unusual, and even most importantly the rate of change (the abrupt increase) is highly unusual too, both compared to the geological context. According to the IPCC, the Earth is almost halfway to the 2 °C GMT increase and the trend is strongly on track. What will the future be like in the next decades? A "small-sounding" 5-6 °C difference drove the Planet from ice-age conditions to a relatively livable climate. What will around half an equivalent quantity of heating produce?

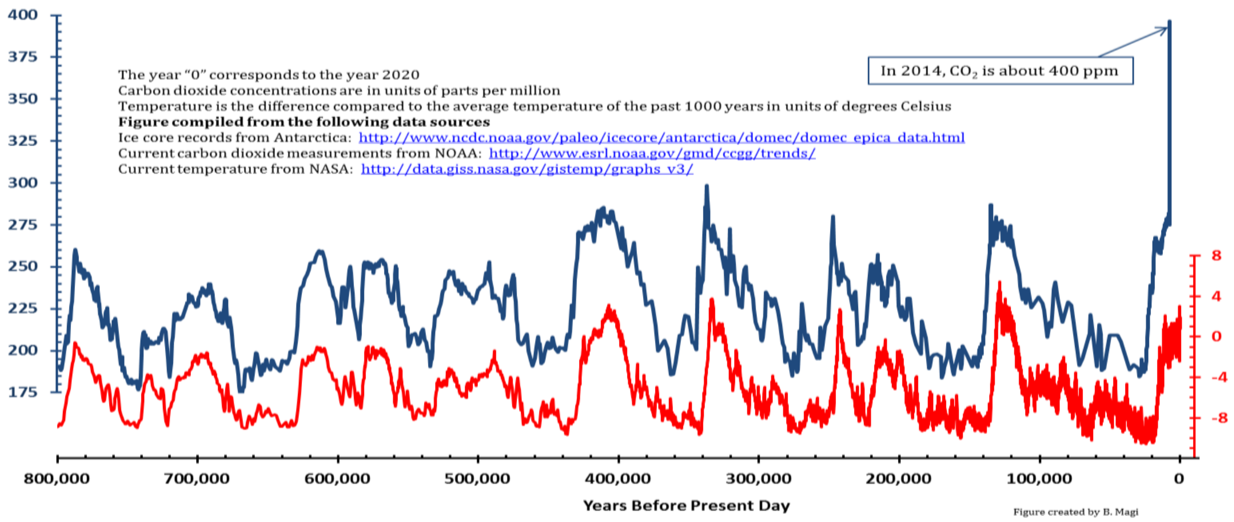

Figure 2.6 | The geological backdrop. Carbon dioxide and the Global Mean Temperature (GMT) from 800,000 years ago until the present day.
Credits: Image adapted from https://environmentcounts.org/ec-perspective-accounting-for-800000-years-of-climate-change/

[32] The whole process is explained in *Section 2.5.2.1*.
[33] See *Section 2.5.1.*
[34] Data are undeniable. A lot of other important datasets exists in scientific literature, other than the EPICA's ones: see [14], [15], [16].
[35] For the current updated value, see https://www.co2.earth/

- 2.5 – GREENHOUSE GASES: STOCKS AND FLOWS

key points

The Greenhouse Gases (GHG) are those that can absorb and re-emit the infrared radiation in the wavelength rage of energy emitted by the Earth's surface. The so-called GHG effect slows the passage of infrared energy from Earth's surface to space, warming the Planet. The GHG effect is a conditio sine qua non of life on our Planet. The atmospheric carbon taking part in the GHG effect is stored and exchanged mutually into the atmosphere, biosphere, hydrosphere and lithosphere. This continuous mutual exchange give birth to the Earth Carbon Cycle. Carbon Cycle can occur on a yearly basis as it happens during plant's photosynthesis and respiration (Fast Carbon Cycle) or can be slower, with timescales of thousands of years (Slow Carbon Cycle).

- 2.5.1 - The GHG effect

Besides the quantity of energy coming from Sun and the multiple feedbacks involving the Earth's reflectivity, one of the most important climate controls is the *GHG effect.* The mechanism is known by the XIX century and was quantified for the first time by Svante Arrhenius[36].
As seen in *Section 2.2*, the wavelengths of received solar energy by the Earth is mainly placed in the Ultraviolet (UV) zone, with a peak in the visible and near Infrared (IR) one. The Earth in turn, emits with a much larger wavelength (mainly the IR one) since it is cooler, according to the Wien's Law[37]. The atmospheric GHGs interactions occur mostly within this range.
Without the natural GHG effect and the albedo effects as the only climate controls, the average temperature at the Earth's surface would be below the freezing point of water (-18 °C) [26]. Thus, the Earth's natural Greenhouse effect makes life as we know it possible [26].

A "good" Greenhouse Gas is one that can absorb and emit radiation within the same range of infrared wavelengths as the one emitted by the Earth. A proper chemical structure is required in order to do this task. Gas molecules vibrates at certain frequencies that are function of some parameters such as the number of atoms, the type of chemical bonds, etc... Vibrations can produce small asymmetrical charge imbalances, electrically neutral overall: the dipoles. When one of these kind of molecules hits the infrared radiation with a frequency that matches the one at which the molecule vibrates, it absorbs (and then re-emits) radiation at that exact wavelength.

Molecules made of two atoms vibrate with symmetrical stretch instead: the center of charge and mass are in the same place and therefore no localized charge imbalance occurs. This type of molecule does not interact with infrared radiation and cannot be a GHG (e.g., N_2 and O_2 are not GHG). Molecules made by three atoms can stretch symmetrically and bend. A charge imbalance is created also in this case. Triatomic molecules do interact with infrared radiation as long as the frequency of vibrational motion matches the wavelength of IR radiation. CO_2 and H_2O are two of the most important greenhouse gases existing in nature.

More specifically, after a GHG molecule absorbs IR energy from the Earth's surface, it must radiate back in order for the Global Energy Budget (GEB) to maintain the equilibrium and consequently re-emit in a random direction. After being re-emitted, the radiation can encounter other GHG molecules which in turn can exert the GHG effect until part of it gets absorbed[38], resulting in a net warming of the Earth atmosphere until a new equilibrium is reached.

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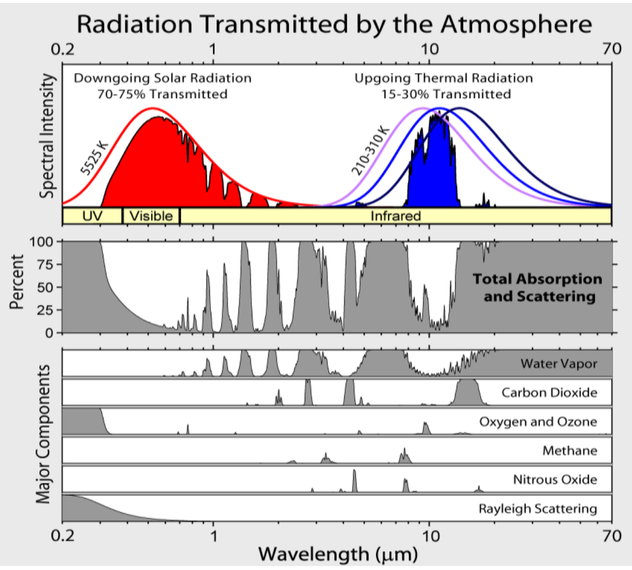
[36] The Swedish chemist predicted even a global warming due to a hypothetical doubling of atmospheric CO2 [28].
[37] See *Section 2.1*.
[38] About 324 W/m2 gets absorbed by the Earth's surface after GHG effect, according to the Global Energy Balance, **see** ***Section 2.2.***

Globally, in order for the whole Planet to be in equilibrium and not to cause a net warming or cooling, the share of energy radiated back to space by atmosphere must match the one entering in it coming from the Sun. As atmosphere is more concentrated next to Earth's surface and gets thinner moving up, the higher the radiated energy moves, the more likely it is that it does not interact with GHG and escape to space.

(Figure 2.7-Left) shows the main greenhouse gases and the characteristic wavelength each gas interacts with.
Water vapor (H_2O) is a great greenhouse gas, it has multiple different absorption bands, especially placed at the longest wavelengths. Carbon dioxide (CO_2) has one major absorption band centered at 15 µm, situated at around the middle of the Earth's emission spectrum. Ozone (O_3) mainly absorbs in the ultraviolet (UV) range but it has also a window at 10 µm, in the infrared (IR) one. Methane (CH_4) and dinitrogen monoxide (N_2O) have narrow absorption bands.

Every single GHG is responsible for a quote of the overall GHG effect and contribute to it with different efficiencies, that are function of the associated absorption band. The IPCC's 2001 Third Assessment Report defines a way to weight those contributions considering the amount of heat trapped in atmosphere due to the GHG effect exerted by these different gases: the Global Warming Potential (GWP). GWP provides a relative measure of how much energy the emissions of 1 ton of a specific greenhouse gas will absorb over a given period[39] with respect to the emissions of 1 ton of carbon dioxide (CO_2) [29]. The value of GWP depends on the spectral location of the absorption wavelengths and on the atmospheric lifetime of the specific GHG. For instance, a high GWP is linked to a high efficiency absorption in the IR zone and a long atmospheric lifetime.

The GWPs for the main GHGs considered above and for the *Fluorinated gases (*F-gases)[40] taken from multiple Assessment Report from the IPCC are summarized in (***Figure 2.7-Right)***



Substance	AR1 (1990)	AR2 (1995)	AR3 (2001)	AR4 (2007)	AR5 (2013)
Carbon dioxide, fossil (CO_2)	1	1	1	1	1
Methane, fossil (CH_4)	21	21	23	25	28
Methane, biogenic (CH_4)	18.25	18.25	20.25	22.25	25.25
Dinitrogen monoxide (N_2O)	290	310	296	298	265
HCFC-141b	440	-	700	725	782
HFC-134a	1200	1300	1300	1430	1300
HCFC-22	1500	-	1700	1810	1760
HCFC-142b	1600	-	2400	2310	1980
CFC-11	3500	-	4600	4750	4660
CFC-12	7300	-	10600	10900	10200
Sulfur hexafluoride	-	23900	22200	22800	23500

Figure 2.7 | The geological backdrop. (Left) The upper panel shows the emission spectra for the Sun (visible centered range) and for the Earth (IR based range). The lower panel shows the most important greenhouse gas absorbing and emitting wavelengths. (Right) Progression of the GWP potential for the main greenhouse gas in each Assessment Report by the IPCC from the first one in 1990 to the last one in 2013.
Credits: (left) image taken from https://ghginstitute.org/2010/06/28/what-is-a-global-warming-potential/
(right) image taken from https://www.pre-sustainability.com/news/updated-carbon-footprint-calculation-factors

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[39] The time horizon considered goes from 20 to 100 years, but 100 years is the most widely used.

[40] F-Gases can be of four types: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3). They are commonly used in a lot of applications including refrigeration, electronics, cosmetics etc…

- 2.5.2 - The carbon cycle

In order to better understand the GHG effect and examine the linkage it has with the anthropogenic activity, a focus must be done on the carbon cycle.
Carbon is both the foundation of life on the Earth and the source of the majority of energy consumed by human civilization[41] [30]. Carbon is also a component of carbon dioxide (CO_2), which acts as a GHG as seen above. As for the energy budget, carbon cycle has been studied with a system dynamics method since its discovery by Antoine Lavoisier [31]. Not including human activity at first, carbon flows are exchanged naturally between the four Planet's constituents: atmosphere, hydrosphere, biosphere and geosphere.

Just as what happens for the Global Energy Budget, in order to analyze the carbon cycle, inflows, outflows and stocks must be considered *(Figure 2.8)* [32]. According to these medium estimates, on an annual basis the atmosphere retains about 800 GtC, deep Oceans 37,000 GtC while plants store some 550 GtC. Photosynthesis from land takes about 120 billion tons of C from the atmosphere, while plant respiration gives off 60 GtC/yr, and air-sea exchange swaps about 90 GtC/yr. Carbon Cycle can be divided into two subsets:

a) Fast Carbon Cycle;
b) Slow Carbon Cycle.

The first one operates with time measured in a lifespan on a magnitude of ~ 100 Gtons of carbon every year, while the second goes through a series of reactions with a longer timescale (in the order of 100-200 million years) moving between 0.01 and 0.1 GtC/yr [33]. A focus is made for the main exchanges of both the two types.

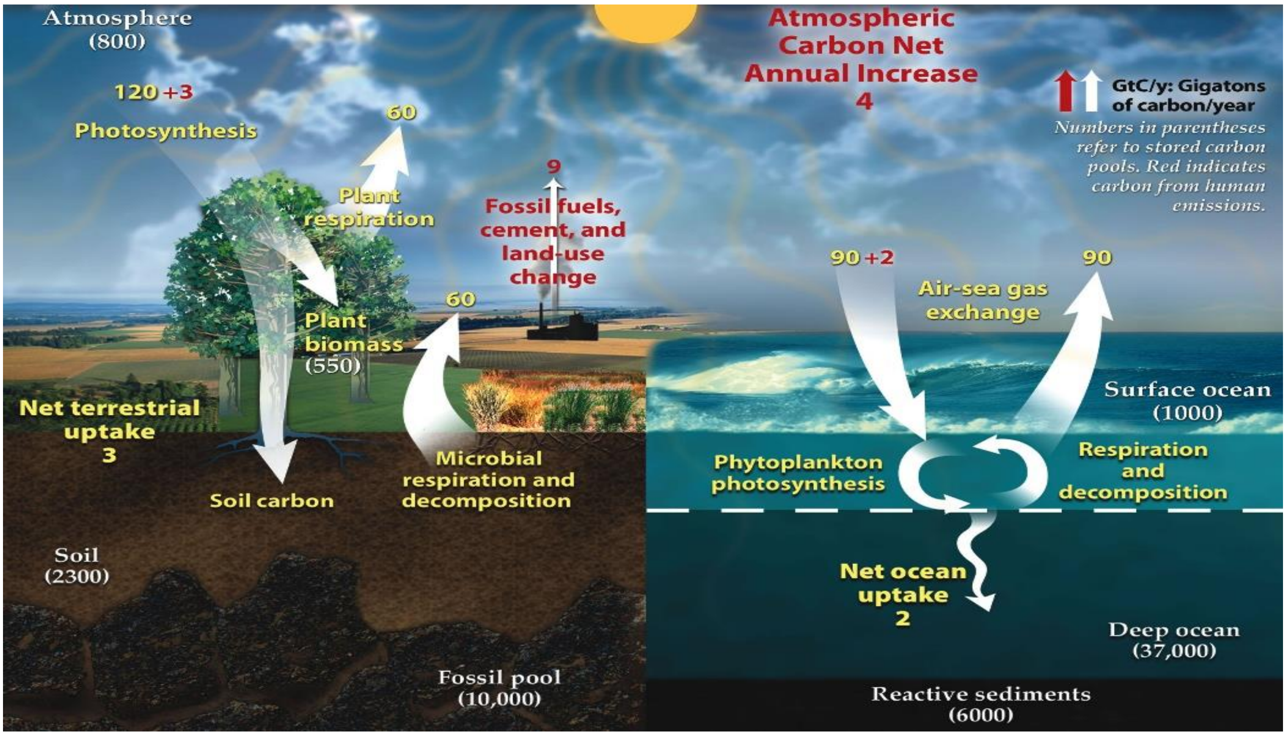

Figure 2.8 | GHG effect and carbon cycle. Diagram of the carbon cycle. The numbers in parenthesis are the reservoirs of carbon. Numbers in yellow are the flows instead. Measures are in gigatons of carbon (GtC). Contributions in red are the human activity linked one (primarily burning of fossil fuels, cement production and land use change). **Credits: Office of Biological and Environmental Research of the U.S. Department of Energy Office of Science.**

[41] The vast majority of the World's Total Primary Energy Consumption (TPEC) comes from fossil fuels, that are mainly composed of carbon.

- 2.5.2.1 - Atmosphere-Biosphere exchange

Through *photosynthesis*, plants use energy coming from the Sun to let the following reaction take place:

$$CO_2 + H_2O + nutrients + energy \rightarrow CH_2O + O_2$$

The process makes use also of nitrogen and phosphorous nutrients[42] in order to produce organic matter which builds up biomass for the plant's structure and release oxygen to the atmosphere. As the photosynthesis occurs on annual basis, it is considered a part of the *fast carbon cycle*.

Through *respiration (*or *decay)* vegetation dies in fall and winter, returning carbon dioxide to the atmosphere. Organic matter recombines with oxygen (O_2), water (H_2O), nutrients and energy too, reversing the reaction seen above. The average annual flows of carbon, considering both the photosynthesis and the respiration, are in balance with an uptake of 120 Gtons from photosynthesis, equalized by a release of the same amount from respiration (60 Gtons from plant and 60 Gtons from microbial decomposition) [34].

- 2.5.2.2 - Atmosphere-Oceans Exchange

The other player in the *fast carbon cycle* is the Ocean. Gases are constantly exchanging across the boundary between air and water, going back and forth depending on the relative pressures of atmosphere compared to the Ocean's. The process is basically the same as the one that occurs on land, with photosynthesis and respiration. It occurs below, but close to the Ocean surface, where there is still light available. Marine plants (e.g., algae) take up carbon to photosynthesize which is then released with respiration and decomposition, as marine organisms die. Globally there is a balance between carbon inflows and outflows (90 GtC each one), except for a net uptake from deep Oceans of around 2 GtC as a portion of dead organisms sinks down [35]. The Oceans carbon stock is therefore increased forming one of the so-called *Carbon Pools*[43]. It takes approximately several hundreds to thousands of years for the circulation to mix the bulk structure of Oceans bringing back CO_2 to surface, restarting the process again.

- 2.5.2.3 - Atmosphere-Geosphere Exchange

There is also some geological process involved in the carbon cycle. Volcanoes activity adds about 0.1 GtC/yr [36]. Weathering on older carbon-rich rocks exposes them to the atmosphere, to which ultimately carbon is returned. At the same time, the downward leakage of organic matter which gets buried every year, stores carbon and gives birth to another fossil carbon pool. These other mechanisms establish the *slow carbon cycle*, since they all act on timescales much longer than a lifespan. Flows from slow carbon cycle are tiny in a year timescale, compared to the flows exchanged within Fast Carbon Cycle [36].

- 2.6 – SOMETHING NEW AFTER THE FIRST INDUSTRIAL REVOLUTION

<u>Key points</u>

Anthropogenic activities have increased the inflows of carbon into the carbon cycle and consequently in our atmosphere. Some of this excess is taken back by natural sinks like plants and Oceans but about the 45% of human emissions remains in the atmosphere each year. Chemical data from carbon isotopes and oxygen provide solid evidence that the recent rise in atmospheric CO_2 is due to human activities. It is extremely likely that we have begun altering the atmosphere approximately 8'000 years ago with the

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[42] Nutrients can be mineral and non-mineral ones. The first come from the soil, while the second are found in air and water. Examples of mineral nutrients are: N, P, K, Ca, Mg, S, B, Cu, Fe, Cl, Mn, Zn. H, O, C are examples of non-mineral nutrients.

[43] Carbon Pools are natural reservoirs of carbon. Besides Oceans, the Earth's crust and terrestrial eco-systems are carbon pools as well.

first technological advances and the largest changes that have occurred since the Industrial Revolution, until now. Carbon cycle responses to its perturbations include multiple feedbacks. The near-term ones are likely to be mainly amplifying, pushing the system towards its perturbation. The long-term ones tend to bring the carbon emitted in the atmosphere today on its way back to other natural carbon stocks through processes involving geosphere, hydrosphere and biosphere.

The balance of carbon cycle has been substantially steady during the last million years, excepting from the huge volcanic eruptions. During the last 150 years, something changed.

In addition to the multiple exchanges of inflows and outflows between the various elements of the Earth seen in ***Section 2.5.2.1***, ***2.5.2.2*** and ***2.5.2.3***, the carbon cycle undergoes to a periodic variability on a yearly basis. In ***(Figure 2.9-right),*** data of the atmospheric CO_2 concentration in the Northern Hemisphere are shown relative to a 60 years' time period. Following the evolution of the zoomed diagram - covering one single year - the peak occurs in May (springtime), while the valley is in October (autumn). This singular pattern is explained by the fact that inflows and outflows of carbon are in balance[44] only considering the whole year and not instantly. In other words, during autumn, winter until spring, the rate of plants and Oceans' respiration exceeds the rate of photosynthesis: the CO_2 concentration goes upwards; the vice-versa occurs in growing seasons from spring to fall, with photosynthesis bursting out and CO_2 concentration going downwards [37].

- 2.6.1 - Human perturbations on carbon cycle

The carbon cycle is intrinsically fragile because as any other mass balance can be perturbed as the equilibrium between inflows and outflows is no more valid. The additional burden of CO_2 added to the atmosphere by human activities often referred to as *anthropogenic CO_2*, leads to the current perturbed global carbon cycle [38].

By looking to the history records of human carbon emission from fossil fuels, cement and land-use change, a total cumulative of anthropogenic CO_2 emissions of 2040 ± 310 $GtCO_2$/yr were added to the atmosphere between 1750 and 2011 ***(Figure 2.9-left).*** About half of the cumulative anthropogenic CO_2 emissions between 1750 and 2011 have occurred in the last 40 years. Nearly the 40% of these emissions

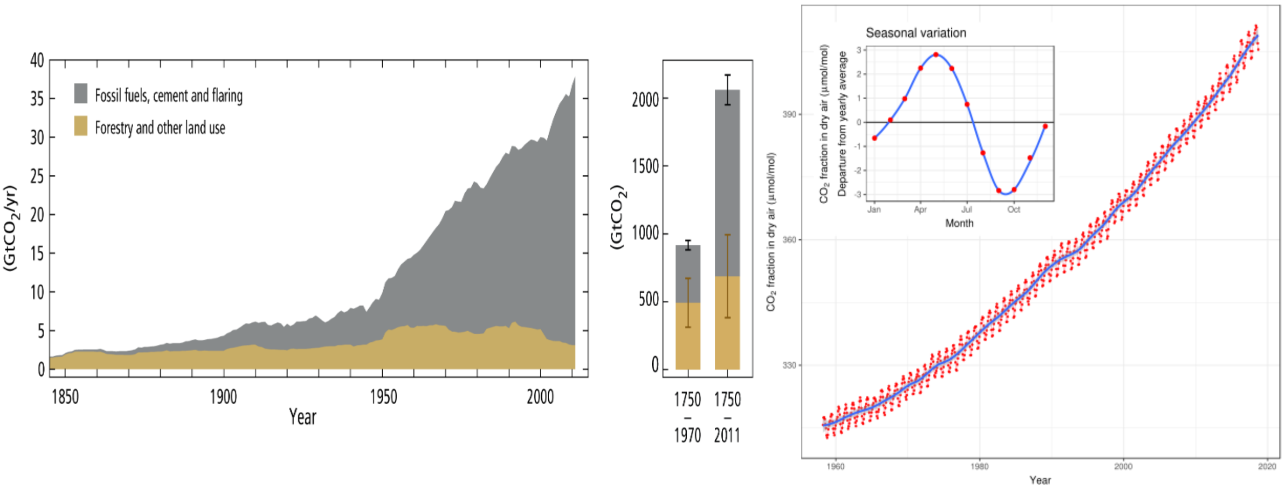

Figure 2.9 | Human perturbations of the carbon cycle and consequent responses. (left) Progression of annual global anthropogenic carbon dioxide emissions in Gigatonnes per year from fossil fuel combustion, cement making and FOLU (Forestry and Other Land Use). Data back to 1850 are based on written records, while since the 1970s satellite ones are used. (right) Most recent series of monthly mean atmospheric CO_2 concentration. The period of observation ranges from 1958 to 2018. The zoomed trend shows the seasonal variation along one single year. **Credits: (left) IPCC, 2014: Climate Change 2014: Synthesis Report, (right) Scripps CO_2 Program (*http://scrippsco2.ucsd.edu/*)**

[44] In line with ***Section 2.5.***

remained in the atmosphere since 1750, while the rest has been removed and stored in natural sinks and carbon cycle reservoirs [39].

In terms of carbon Gigatons[45], 540 ± 60 GtC is the amount of carbon emitted since 1850 until now [40]. Given the volume and the concentration of CO_2 in the atmosphere, it takes about some 2.1 GtC released in order increase by 1 ppm the atmospheric carbon dioxide concentration [40]. This means that, if all the 540 GtC stayed in the atmosphere since 1850 the today's CO_2 atmospheric concentration would have risen by 540/2.1 ≅ 257 ppm. Comparing the current real data with the 1850's levels, the concentration actually rose only by 110 ppm [42]: it means that there is another imbalance between the known inflows available in historical records of human activities, the measured stock (the atmospheric carbon dioxide) and the outflows. Specifically, Land, Plants and Oceans take up almost the 55% of extra CO_2 that humanity currently adds into the carbon cycle[46]. The majority of projections suggest that Land and Oceans' uptake will slow down; assuming that emissions will continue at the actual pace[47], a larger percentage of emitted CO_2 will stay in the atmosphere.

But how can the anthropogenic activity be called undeniably responsible for the majority of these emissions? An approach based on the study of the stable isotopes of carbon helps to identify their source without any doubt. In nature, the 98.9% of carbon atoms have an atomic mass of 12 (^{12}C) while about the 1.1% has an extra neutron which makes its mass slightly heavier (^{13}C)[48]. CO_2 in atmosphere can have both ^{12}C or ^{13}C as carbon atoms. By measuring the so-called $\boldsymbol{\delta_{13}C}$ ratio (or "*delta-C-thirteen*") as the ratio between the respective concentrations of ^{13}C over ^{12}C in different samples (e.g. atmosphere, vegetation, rocks etc...), it turns out that they have different values. With a relatively high ratio, the ^{13}C prevails and consequently the sample is "heavy", with the vice-versa, the ^{12}C prevails and the sample is "light".

Plants prefer to absorb ^{12}C compared to what is available in atmosphere; this implies that the atmosphere shows a ^{13}C dominance over ^{12}C, meaning that it is isotopically "heavier" than plants[49]. At this point, it has to be highlighted that what we often call "human emissions" derive in the end largely from plants in some way: the action of Land Use Change (like deforestation) returns back to the atmosphere the stocks of carbon dioxide previously stored in plants; the same applies for fossil fuels - which of course used to be vegetation or other organic material – and, while burning, release in the atmosphere all the carbon that was stored there. That said, the carbon in the CO_2 coming from human emission, being plant derived, has a light $\boldsymbol{\delta_{13}C}$ ratio. Looking to measured data, a decreasing trend in the value of atmospheric $\boldsymbol{\delta_{13}C}$ ratio can be noted overtime, meaning that the carbon in CO_2 has become lighter and lighter, with an abrupt and clear increment in steepness from 1980 until now *(Figure 2.10-left)*. The timing of this unprecedented and sudden decrease in $\boldsymbol{\delta_{13}C}$ ratio matches perfectly the one with which the pace of carbon emission by human activity has started to increase significantly. Besides this, another atmospheric behavior aligns well with the fact that the major responsible for the increase in atmospheric CO_2 concentration. Besides this, another atmospheric behavior aligns well with the fact that the major responsible for the increase in atmospheric CO_2 concentration. Burning fossil fuel or biomass means oxidize carbon, releasing energy and carbon dioxide. In order to the reaction of combustion to take place, oxygen is obviously consumed. This means that a decrease in atmospheric O_2

[45] In order to switch from $GtCO_2$ to GtC, a multiplication/division for a factor 3.67 is needed. For instance: 1 Gton of CO_2 is equivalent to 1/3.67 Gton of C.

[46] CO_2 absorption from Oceans is the most remarkable share (30% of total anthropogenic emissions) and it is the cause of the ocean acidification [45].

[47] Global CO_2 emissions hit a two years in-a-row rise, increasing by 2% in 2017 and 2.7% in 2018 after the 2014-2016 plateau [46], [69].

[48] Carbon actually has got 15 known isotopes. Only C-12 and C-13 are stable and therefore used in this approach.

[49] The $\delta^{13}C$ of plants is 0.33-0.24 [47].

concentration is expected. By looking at the measured data, a progressive decrease - with the exact same pace of the $\boldsymbol{\delta_{13}C}$ ratio - in O_2 atmospheric concentration can be seen *(Figure 2.10-left).* This is just another evidence that fossil fuel and Land Use Change (LUC) are the main responsible for what is going on right now.

But that is not all: human activity started to act on carbon cycle approximately 8,000 years ago, when the split between the curve of expected CO_2 concentration based on past climate cycles and the observed one starts *(Figure 2.10-right)* [43]. This time corresponds to when humans begun to clear forests and lands for agriculture, starting to release carbon dioxide into the atmosphere. Then, the exponential increment placed approximately during the Industrial Revolution is clearly visible in the upper part of *(Figure 2.10-right)*. The atmospheric concentration of methane (CH_4) follows the same pattern with the reversal of the observed data curve with respect to the expected one, placed 5'000 years ago. This timing corresponds well with the initiation and expansion of irrigation and forming of artificial wetlands, which are both huge source of methane production. The same exponential increment started with the Industrial Revolution can be noted also for the atmospheric CH_4 concentration [43], reaching the todays 1,867,5 ppb [45].

In conclusion, solid evidences attribute the increasing atmospheric carbon dioxide concentration and the climate change itself to the alteration of the natural carbon cycle. There is absolutely no doubt that these alterations are mainly of anthropogenic origin, driven by human activities that have been affecting the climate system for thousands of years, but have begun to disrupt it only 150 years ago.

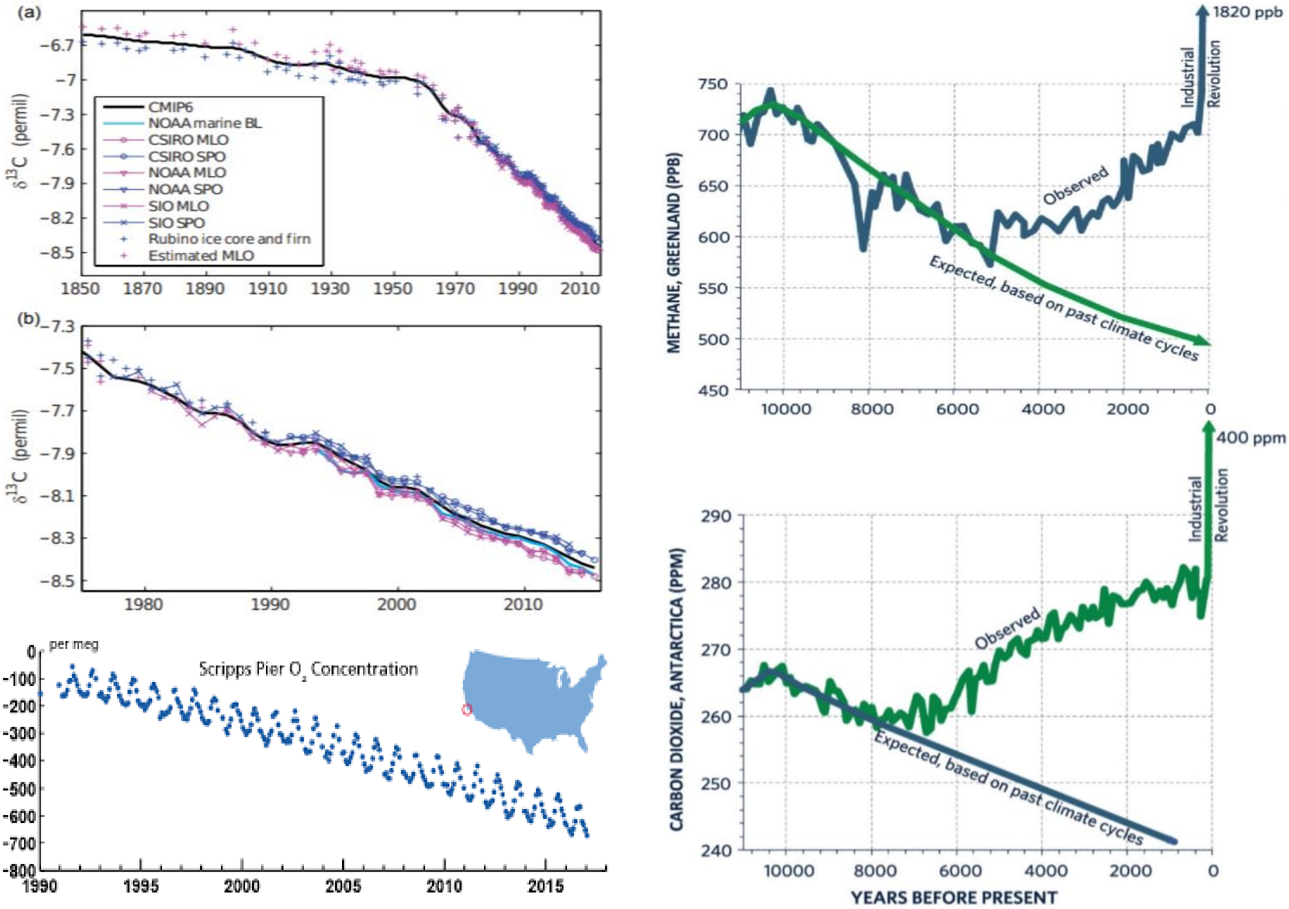

Figure 2.10 |Human perturbations of the carbon cycle and consequent responses. (left, up) Observations of $\delta^{13}C$ ratio over the full time period 1850-2017 and over the most recent period 1970-2017. (left, bottom) Atmospheric O_2 concentration measured in Scripps Pier, California. (right) Atmospheric CH_4 and CO_2 concentrations respectively in Greenland and Antarctica, observed vs expected. Credit: (left, up) H. Graven et al. in "Compiled records of carbon isotopes in atmospheric CO2 for historical simulations in CMIP6", 2017. (left, bottom) ***http://scrippso2.ucsd.edu/*** (right) Ruddiman, William F. in "The Anthropogenic Greenhouse Era Began Thousands of Years Ago", 2003.

- 2.6.2 - Carbon cycle responses

Human perturbations on carbon cycle are clear and undeniable. An important aspect of the issue is of course how much and within what timescale does the Planet respond to these perturbations. As seen in *Section 2.3*, feedbacks are the main responses from the climate system to a perturbation to which is subject. General examples of climate system feedbacks have been provided yet, but the following are some of the most important involving specifically the carbon cycle. All of them are responses to an increased atmospheric CO_2 concentration.

- 2.6.2.1 - Vegetation feedback

Plants grown up exposed to higher level of CO_2 concentrations in the air, grow more. Since they grow more, they take up more CO_2 from the atmosphere, storing it as biomass, decreasing the stock of atmospheric CO_2. This is the so-called *CO_2 fertilization effect*, a stabilizing feedback. In natural ecosystems the entity of CO_2 fertilization effect on the magnitudes of the Global Energy Budget (GEB) is quite unclear, since also other variables (e.g., plant species, temperature, availability of water and nutrients, etc…) must be considered [45].

- 2.6.2.2 - Forest Fires

With increased levels of atmospheric CO_2, some areas experience warmer temperatures and longer periods of drought which are both good conditions for forest fires. As forests burn, more carbon is released to the atmosphere, amplifying the perturbation. This effect is mostly prevalent at mid-latitudes [46].
In a future with higher CO_2 levels, this kind of feedbacks involving land biology are mainly amplifying, pushing the climate system towards the direction of the perturbation (the initial increase in both CO_2 concentration and Global Mean Temperature) [47].

- 2.6.2.3 - Permafrost feedback

The high latitudes (Arctic and Antarctic regions) permafrost[50] stores large amount of CH_4 and CO_2. As atmospheric CO_2 increases, so temperature does – particularly at higher latitudes - resulting in a higher rate of permafrost thawing and consequently CH_4 and CO_2 are then released after the melting. Clearly the permafrost feedback is an amplifying one, pushing towards the initial perturbation (the increase in the atmospheric CO_2 concentration) [48].

- 2.6.2.4 - Oceans: Stabilizers – $CaCO_3$

As CO_2 interacts with water in the Oceans, it dissolves. Then the following reaction takes place:

$$CO_2 + H_2O + CO_3^{2-} \rightleftharpoons 2HCO_{3-}$$

The carbonate ion (CO_3^{2-}) is one of the reactants. The main product is the bicarbonate ion (HCO_3^-), but there are also percentages of carbonic acid (H_2CO_3) and carbonate ion as well. With all these reactants gathered together, this other reaction occurs:

$$CO_{2\,(aq)} + H_2\mathrm{O} \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^{2-} + 2H^+$$

As this reaction takes place, water becomes more and more acidic (the H^+ ion concentration in the Ocean increases, thus decreasing its pH) [49]. The climate system response here is represented by calcium

[50] Ground made of frozen soils and rocks which remains at 0°C for two or more years [54].

carbonate ($CaCO_3$) from marine organisms' shells: as they dissolve overtime, carbonate ion is produced with the following reaction:

$$CaCO_3 \rightleftharpoons Ca^{2+} + CO_3^{2-}$$

This helps buffer the Oceans' pH and keeps it from getting too acidic. Another source of carbonate calcium is limestone rock on lands (e.g., The White Cliffs of Dover). In conclusion, $CaCO_3$ acts as a stabilizer tending to neutralize the acidifying effects of CO_2 in the Ocean. This process has a long timescale (hundreds of thousand years) [50].

- 2.6.2.5 - Silicate weathering

An even longer time frame process involves rocks like granite or basalt. In the atmosphere, the CO_2 combines with water to form a slightly acidic rain. The rainwater interacts with rocks near Oceans, causing weathering (the slow dissolution of solid minerals into dissolved ions). At this point, multiple reactions take place in what is called carbonate-silicate cycle. The one that can sum up all of them is the following:

$$CaSiO_3 + CO_2 <-> CaCO_3 + SiO_2$$

It must be highlighted that wollastonite ($CaSiO_3$) represents general calcium silicate minerals. At the end of the cycle of reactions, calcite ($CaCO_3$) and silica (SiO_2) end up flowing off the land into the Oceans, where are used by marine critters to make shells, which in the long period will be buried in sediments on the bottom of the Oceans feeding the long term natural storage. Silicate weathering is another response of the climate system to its perturbations, as a certain amount of CO_2 ultimately is taken up from the atmosphere by the process. The timescale for this cycle, ranges from 170 to 380 kyr [51].

- 2.6.3 - The Paleocene-Eocene Thermal Maximum

About 55 million years ago something perturbed strongly the *carbon cycle*. The atmospheric CO_2 increased fast, as global temperature did; Oceans got acidic, lots of shells from marine organisms

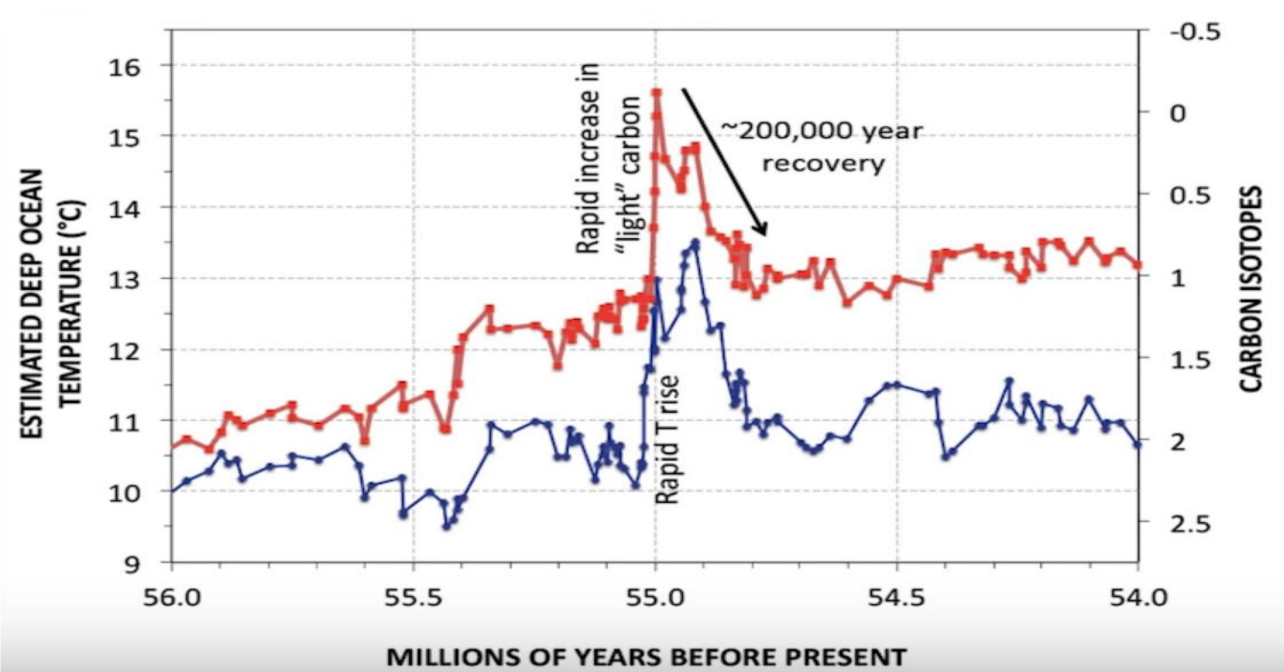

Figure 11 | Carbon cycle perturbations and consequent responses. The Paleocene-Eocene Thermal Maximum in two parameters: the estimated deep Ocean temperature (blue line) and the trend in carbon isotopes (red line) over a 2 million years' time period. Credits: Hansen, J.E., and M. Sato in "Paleoclimate implications for human-made climate change", 2012.

dissolved and multiple species went extinct. In order to make it clearer the Global Mean Temperature (GMT) increase d by 5-8 °C. The massive carbon release occurred then is surprisingly in line with current values [59]. Deep Oceans temperature experienced an abrupt rise corresponding to a rapid change in carbon isotopes towards lighter values *(Figure 11)*.

The Paleocene-Eocene thermal maximum is exceptionally important because it offers a good analogy to us with what is happening nowadays. Most importantly it shows a scenario that can be realistic within a lifespan: what can happen to the Planet if the GMT rise, the GHGs concentrations and the other climatic parameters exceed certain values? Well, the Paleocene-Eocene thermal maximum leaves no room for ambiguities.

The relatively small peak of the GMT (5-8 °C) during the Paleocene-Eocene thermal maximum is considered to have lasted 20,000 years, but there is some uncertainty [52]. The only undeniable fact that is quite significant to us is that a recovery from climate conditions that can be reached now, carrying on with the business as usual development, took for climate system feedbacks and controls an impressively long time with respect to human timescales.

Oceans taking up excess CO_2, carbonates dissolving to neutralize acidity and silicate weathering brought ultimately the system back to equilibrium, but this took approximately 200,000 years [53]. The current carbon cycle anthropogenic perturbations may have similar recovery times, if GMT rise and atmospheric CO_2 concentrations reaches comparable values.

- 2.7 - ANTHROPOGENIC VERSUS NATURAL INFLUENCE ON CLIMATE: METRICS FOR THE ATTRIBUTION OF THE BURDEN

Key points

The concept of Radiative Forcing (RF) is introduced, aiming to idenify the different wheight of the multiple drivers' contribution to the overall climate system variation. The RF is measured in W/m^2 and is assigned to each one of the substances (or processes as well) that can alter the climate system in some way. The RF can be positive, meaning that pushes the Earth system towards a net warming and negative, viceversa pushing towards a cooling. RF' agents can be both of antropogenic or natural origin. Other important metrics of the various drivers' influence on climate are Global Warming Potential (GWP) and Global Temperature change Potential (GTP). Both GWP and GTP provide a measure of how severe is the influence of a single GHG compared to the reference gas CO_2.

Once that a brief overview of the main principles of the climate system has done and all its major variations occurred during the last 150 years has been summarized, there is the need to assess the responsibility of these variations. What has caused the GMT to increase? What has caused the sea levels to rise? What has *caused our cities' air to be polluted?*

- 2.7.1 - The radiative forcing concept

As seen in ***Section 2.3***, a lot of different agents exists perturbing the climate system. These perturbations drive the climate change and have determined various transformations.
The most widely used way to estimate the relation between cause and effect of these mechanisms is the Radiative Forcing (RF). RF is defined as "the net change in the energy balance of the Earth system due to some imposed perturbation, measured in W/m^2" [16, p. 668] and provides an immediate way to quantify the potential response of climate to the different agents and compare the weight of each of them. Any sustained RF impose a temperature difference $\Delta T=\lambda*RF$ with λ being the climate sensitivity

parameter[51]. However, RF is not an accurate indicator for responses from all forcing agents. Effective Radiative Forcing (ERF) is defined to include also the effects of rapid tropospheric adjustment related to humidity and clouds, which are constant phenomena. Many compounds cause a certain RF as their atmospheric concentration changes. In order to better understand what the RF effectively is, two different groups of RF components are defined by common properties: Well-Mixed Greenhouse Gases (WMGHGs) and Near-Term Climate Forcers (NTCFs) [16, p. 668]. WMGHGs are those sufficiently mixed in the troposphere, such that emissions do not depend on the geographic locations as their lifetime in atmosphere are much greater than the timescale (of few years) needed for atmospheric mixing. WMGHGs include CO_2, N_2O, CH_4, SF_6 and others. NTCFs instead, are compounds with a climate impact occurring primarily within the first decade after their emission. NTCFs include O_3, aerosols and others. WMGHGs are long-lived greenhouse gases while NTCFs are short-lived ones.
RF compare the influence that these different emissions have on Global Mean Temperature GMT and can be both positive, leading the climate system to a net warming or negative, leading to a cooling.

- 2.7.2 - Anthropogenic Drivers

The RF of all Well-Mixed Greenhouse Gases (WMGHGs) is about 2.83 W/m^2 [2.54 to 3.12] W/m^2, with CO_2 being the dominant contributor with 1.82 W/m^2 [17], growing 0.3 W/m^2 per decade. CH_4 accounts for about 0.48 W/m^2. N_2O atmospheric concentration increase causes a RF of about 0.17 W/m^2, while the one of dichlorodifluoromethane (CF_2Cl_2)[52] is decreasing. Concerning Near-Term Climate Forcers (NTCFs), tropospheric ozone (O_3) accounts for about 0.40 W/m^2 and the stratospheric one for a negative -0.05 W/m^2. O_3 is not emitted directly in the atmosphere, but it is formed by photochemical reactions starting from a variety of natural and anthropogenic sources. It also has detrimental effect on vegetation physiology, leading to a reduction in the CO_2 uptake from plants, increasing its atmospheric concentration even more[53]. As regards aerosols, the so-called aerosol-radiation interactions are estimated to exert a negative RF overall with -0.35 W/m^2, while the RF from Black Carbon (BC) on snow and ice weights about 0.04 W/m^2. Anthropogenic Land Use Change (LUC) such as deforestation, increases the land surface albedo resulting in a negative RF of about -0.15 W/m^2.

- 2.7.3 - Natural Drivers

Solar and volcanic forcings are the two main natural contributors to climate change. As regards Total Solar Irradiance (TSI), a RF change of -0.04 W/m^2 has been observed with satellites between the most recent minimum in 2008 and the 1986 maximum. On the other hand, volcanic eruptions inject both mineral particles, sulphate aerosols precursors and CO_2 as well in the atmosphere. A negative RF of [-0.15 to -0.08] W/m^2 is given mainly by particles and sulphate, as the total average amount of CO_2 coming from volcanic eruptions ranges from 65 to 319 million tonnes per year (depending on the activity on that specific year), which is more than 100 times smaller than the yearly anthropogenic rate of emission. This is quite a remarkable fact.

- Focus 1 – Global Warming Potential vs Global Temperature change Potential

Considering this variety of climate change agents and forcings, the necessity to compare emissions from different substances has been raised overtime both by the UNFCCC and the IPCC. Different metrics can be used to quantify and provide relative and absolute contribution to climate change from different emissions.

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[51] See *Section 2.3*.

[52] Dichlorodifluoromethane, also CFC-12, has been the third largest contributor to RF for several decades. Its atmospheric concentration is decreasing during the last years due to the phase-out under the Montreal Protocol.

[53] This means that a fraction of RF from CO_2 can be attributed to ozone, but uncertainties emerge over quantitative estimates [16].

The primary way is using the Global Warming Potentials (GWPs) which are based on the relative effect that any agent's emission has on climate change with respect to the reference gas: carbon dioxide (CO_2). GWP accounts both for the radiative forcing of the various substances and their lifetime. The main concern about GWP is that it is measured on a fixed time horizon affecting the comparison between short- and long-lived gases. An increasing focus has been posed on the Global Temperature change Potential (GTP), which is based on the change in Global Mean Temperature (GMT) at a specific time, again relative to that caused by the reference gas, which is CO_2. While GWP integrates the effect on a chosen time horizon, the GTP is calculated just on one chosen year.

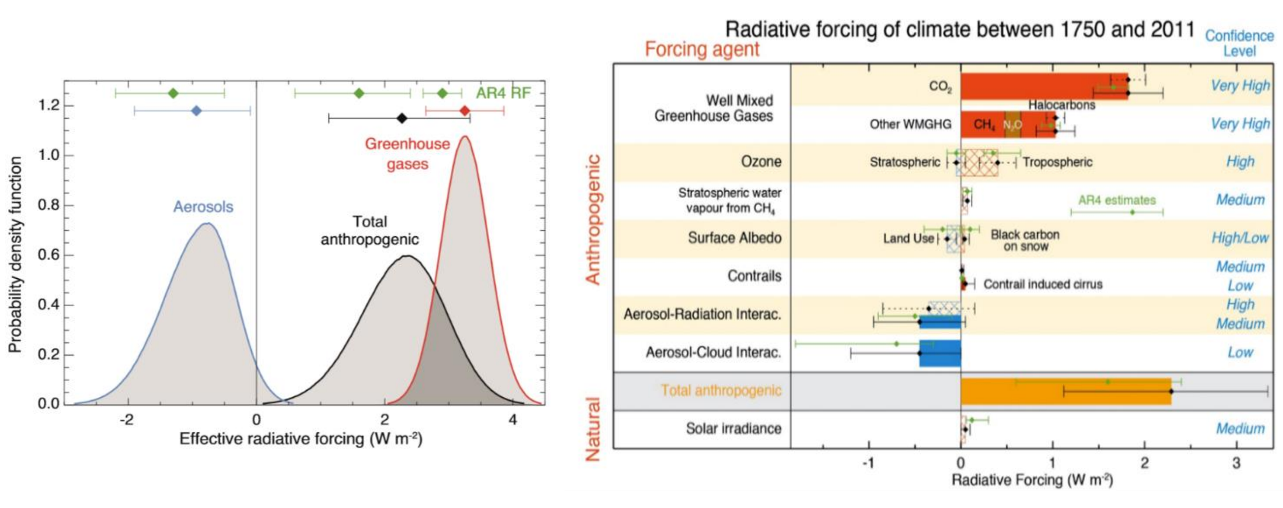

Figura 2 | Radiative Forcing and other metrics: anthropogenic versus natural influences on climate. (a) RF by concentration change between 1750 and 2011. (b) Probability density functions for the main contributions for the ERF. **Credits: graphs adapted from IPPC Climate Change 2013: The Physical Science Basis, (2014).**

CHAPTER 3 - PAST AND FUTURE: OBESRVED CHANGES AND CLIMATE MODELS

The last climate developments are pretty clear: the World is warming undoubtably. The tangible effect are multiple, starting from sea level rise, Arctic sea ice, ice sheets and glaciers regression, increased frequency of extreme weather events such as floods, drought or heavy rainfalls. Understanding deeply what the future of climate will look, becomes crucial in such conditions. Climate models are used for this purpose. The strong point of climate models is that they represent future with equally likely scenarios, that aim to cover a wide range of possibilities. Climate models' outputs are constantly checked against real observations and contribute to make Governments and Institutions to take specific decisions on specific climate policies. The climate scenarios provided until now by the International Panel on Climate Change (IPCC) are then provided.

- 3.1 - OBSERVED CHANGES IN RECENT PAST AND DRIVERS FOR CLIMATE CHANGE

Key points

The Global Mean Temperature (GMT) has been increasing since the late 19th century. The warming has interested basically the entire globe during the period 1901-2012, with a steep growth in the last three decades (80s, 90s and 00') each successively warmer in turn. The current decade is going to be the warmest by far, with a temperature anomaly of about +0.75 °C with respect to the average GMT, given 1901-2000 as a baseline period. Ocean has been warming since 1870, especially in the upper layers (above 700 m). The Global Marine Sea Level (GMSL) had risen by 0.19 ± 0.02 m over the period 1901-2010. The perennial sea ice extent as well as the multi-year ice (the one surviving two or more summers) and Greenland ice sheet thickness decreased over the period 1979-2012 and keeps decreasing. The five smallest Arctic sea ice winter peaks in the satellite era occurred between 2015 and 2019. The atmospheric concentration of GHGs has been constantly increasing, reaching a record on a monthly average basis in April 2018 exceeding 410 ppm for the first time in history records. Since the 1950s an increasing number of extreme events has been observed, leading to millions of premature deaths and major socio-economic losses.

- 3.1.1 - Temperature

Direct observations of climate metrics (e.g., GMT, GMSL, CO_2 concentration and emission, ect…) have been started to be collected only recently. Surface thermometer records goes back approximately to 1880, while satellite records only to 1970s. In order to collect data prior to those times, other sources like samples from ice sheets or deep Oceans sediments are used.

According the series of temperature anomalies measurements from 1850 to now, a discrete variability from year to year occurs ***(Figure 3.1)***. Subsequent oscillations can be easily noted in the sequence of data. This variability is expected, as it happens due to natural climate events. For instance, 1998 was an unusually warm average year with respect to the long-term trend because there was a large El-Nino event[54]. In addition to this year-to-year variability, it is also clearly visible a long-term trend on GMT that

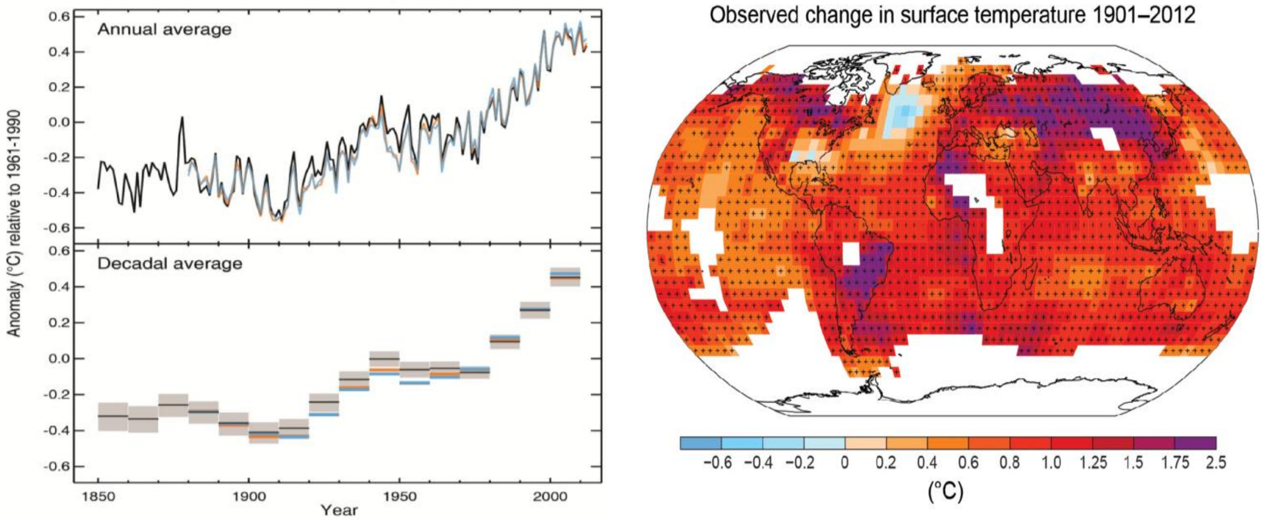

Figure 3.1 | Observed indicators of a changing climate system. (left) Up: observed globally averaged combined land and ocean surface temperature anomalies from 1850 to 2012, with respect to the baseline of 1986-2005 period. Bottom: decadal averages on the same period. (right) Map of the observed surface temperature change from 1901 to 2012. **Credits: IPCC 2014: Synthesis Report, 2014.**

[54] El Nino Southern Oscillation (ENSO) refers to a cycle of warm and cold sea surface temperature of the tropical and eastern Pacific Ocean.

tends to a gradual increase. The globally averaged combined land and ocean surface temperature shows a warming of 0.85 [0.65 to 1.06] °C over the period 1880-2012. Each of the last three decades has been progressively warmer than any other preceding decade since 1850. It must be highlighted that we are currently in the middle of a tremendous climax: the period from 1983 to 2012 is the warmest 30-year period from the last 1400 years [1]. The last 5 years are the hottest globally on records [2], the 2016 is the warmest in history with an average temperature anomaly of 1.12 °C with respect to the period 1951 to 1980[55]. Focusing on a greater detail, in a general context of warming, some regional differences occur. Extreme changes are dominant over lands, with some of the strongest warming at the higher latitudes in the Northern Hemisphere. In the Oceans, a considerably smaller area has been warming instead, with lower increasing rates, while in some places the sea surface has even slightly cooled. Generally speaking, the Northern Hemisphere has warmed more (and faster) than Southern Hemisphere.

- 3.1.2 - Ocean warming and rising sea levels

As seen, the Earth's surface temperature has been warming with unprecedentedly fast rates during the last decades, but it certainly did not warm at the same pace as it might if the Planet did not have vast Oceans on it. Due to the high heat capacity of water, Oceans have acted overtime as huge heat sinks, absorbing the imbalances between Inflows and Outflows in the Global Energy Budget (GEB)[56], increasing the stock of energy stored by the Earth.

Ocean warming accounts for more than 90% of the energy accumulated between 1971 and 2010 by the Earth system, dominating the increase in energy stored with respect to other climate system constituents. Just to give an idea, the portion of the extra energy resulting from the GEB imbalance that has warmed the atmosphere results to be only the 1% of the total [3][57] (*Figure 3.2-left).* Ocean warming is strongest near the surface: the upper 75 m warmed by +0.11 °C [0.09 to 0.13] °C every decade during the period 1971-2010 [4]. Evidences from latest researches proof that a net Ocean warming has occurred also down to 3000 m water depth.

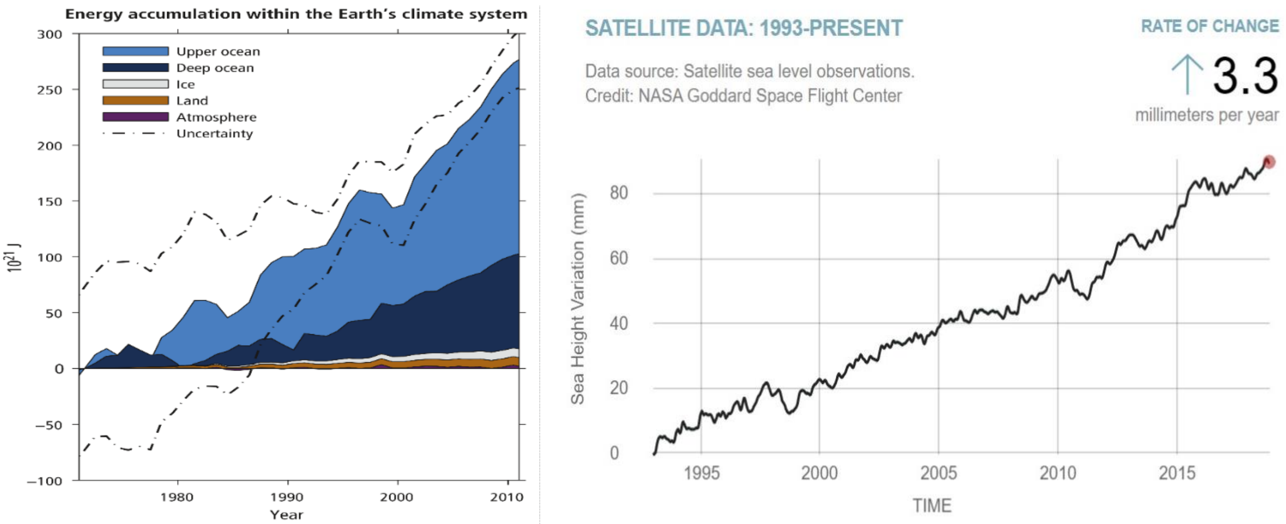

Figure 3.2 | Observed indicators of a changing climate system. (left) Energy accumulation within the Earth's climate system from 1971 to 2010 relative to 1971. (rigth) Sea level rise: model versus observations trends for projections made by the IPCC First Scientific Assessment, 1990. **Credits: (left) IPCC 2014 Synthesis Report, 2014. (right) Adopted from "The Copenhagen Diagnosis", 2009.**

[55] Different base periods are typically considered based on different purposes: during the period 1951-1980 for instance, the Global Mean Temperature (GMT) did not trend upward or downward in a significant way.

[56] See *Section 2.2.*

[57] This fact is pretty remarkable and should worry even more: it means that the atmosphere has been relatively spared from the full extent of global warming for now. Heat already stored in the Ocean will eventually be released, exposing the Earth to additional warming in the future.

As obvious, as water heats up, it expands in volume: Oceans and Seas water levels are raising as a consequence. This expansion of water accounts for approximately one third of the global seal level rise, while melting ice is responsible for the remaining part (one-third from land ice in Greenland and Antarctica and one third from melting ice on mountains) [5]. Since the early 1970s, both thermal expansion and glaciers mass loss contributed together to the 75% of the observed mean sea level increase[58]. Global sea level rose by +0.19 [0.17 to 0.21] m over the period 1901-2010, with a pace of +1.7 mm/yr between 1901 and 2010, increasing to +3.2 mm/yr considering only the period 1993-2010. [4, pp. 40-41]

By comparing projections on sea level rise made in IPCC Scientific Assessment (1990) with the measured data, it turned out that the 1990's estimates were quite conservatives, with the real trend curve overlapping with upper edge of the projections made. According to the most recent and reliable findings, sea levels rose approximately by 9.07 cm only during the period 1993-2018 and the rise is ongoing at a rate of 3.3 mm/yr *(Figure 3.2-right).*

- 3.1.3 - The Cryosphere

Even if the increase rate of sea level has been systematic in the last few decades, has not been constant - extending the timeframe - during the transition from the last ice age to the present days, due to the influence of the major ice-sheets melting and collapsing. Over the last two decades, the Greenland and Antarctica have been losing ice mass and glaciers are keeping shrinking worldwide. [4, p. 42] This is another quite remarkable fact. To give a reference, if the 2,850,000 km^3 of ice of Greenland were to melt entirely, a global sea level rise of 7.2 m would be seen [7]. Another type of ice is the floating sea ice, which do not influence the sea level rise but plays a fundamental role in climate feedbacks[59]. The annual mean Arctic sea ice extent has decreased over the period 1979-2012 with a rate of decrease varying in the range 3.5-4.1% per decade. Arctic summer sea ice minimum decreased more rapidly in the range 9.4%-13.6% per decade, reaching a loss of -1.07 million km^2 per decade. Given the observed rates of change, it is very likely that the Arctic will be virtually ice-free in summer within 30 to 40 years according to the majority of the models [8]. The annual mean Antarctic sea ice extent increased instead in the range 0.13-0.2 million km^2 per decade between 1979 and 2012, with strong regional differences [4, p. 42]. Permafrost in most regions of Northern Hemisphere suffered a reduction in thickness and areal extent since the early 1980s. [4, p. 42] The extent of snow cover in Northern Hemisphere has decreased since 1950 by 1.6% per decade in winter period and by 11.7% in summer period [9].

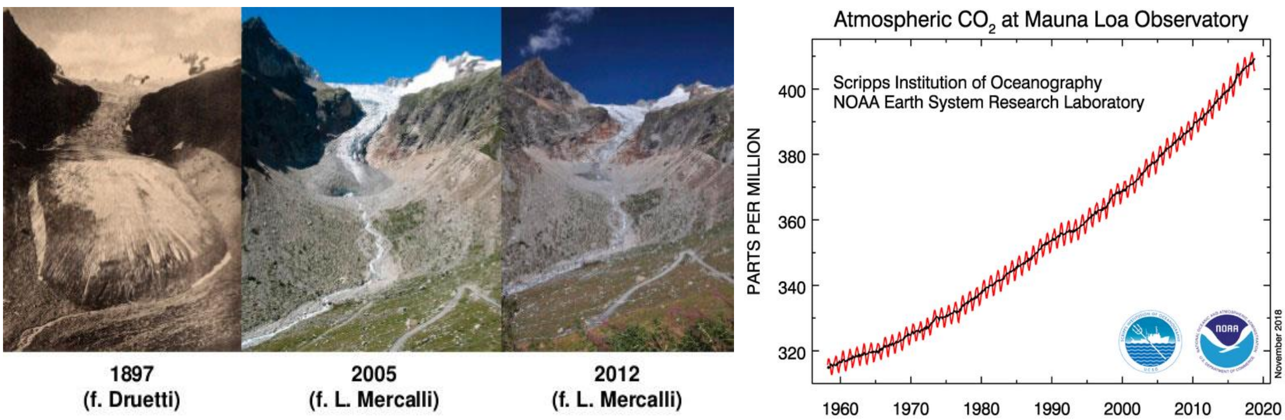

Figure 3.3 | Observing indicators of a changing climate system. (left) Mont Blanc Prè de Bar glacier extent in three different years. Pictures from F. Duretti (1897) and L. Mercalli (2005, 2012). (right) Keeling curve: atmospheric concentration of CO_2 at Mauna Loa between 1950 and 2018. **Credits: Luca Mercalli (left) and NOAA Earth System Research Laboratory (Mar, 2019) (right).**

[58] Even if some uncertainties have emerged in recent studies [40].

[59] See *Sections 2.3 and 2.6.2.3.*

- 3.1.4 - The atmosphere

Atmospheric CO_2 has been increasing constantly and esponentially since the starting of the records by Charles David Keeling in 1950[60]. The increment goes from the 1950's 315 ppm, to the today's 412.33 ppm [9]. Carbon dioxide concentration increase is a result of the imbalance in the carbon cycle driven by human activities since the Industrial Revolution[61]. Furthermore there has been an accelleration in the increase of CO_2 concentration in recent decades, with 1.87 ppm per year during the 1995-2004 decade, 2.11 ppm per year during the 2005-2014 decade and a final 2.6 ppm per year in the period 2014-2017 [11].

Methane has been increasing with the same pace from the 722 ± 25 ppb in 1750 to the nowadays' 1850.5 ppb, with an approximately constant growth rate of ~ 550 Tg/yr [12]. Nitrous Oxide (N_2O) increased too, from an estimate of 270 ± 7 ppb in 1750 [13], to 327.7 ppb in 2015 [14], with a growth rate of about +0.75 ppb/yr since the late 1970s. Hydrofluorocarbons (HFCs) concentration peaked in the 2000s and begun a slow decrease thanks to Montreal Protocol and Clean Development Mechanism (CDM) from UNFCCC[62]. Perfluorocarbons (PFCs), Sulphur Hexafluoride (SF_6), Nitrogen Trifluoride (NF_3) has generally longer lifetimes than CO_2, ranging from 3 to 50 kyr and their concentration has continued to increase rapidly, but their contibutions to the Radiative Forcing (RF) are less than the 1% of the total GHGs [12].

- 3.1.5 - Extreme Events

Changes in many extreme weather and climate events have been observed since about 1950. These changes were linked to human influences that had driven the increase in temperature extremes, in sea levels and in heavy precipitation events in some regions [12]. The frequency and intensity of heavy precipitations has increased in North America and Europe [15] leading to a consequent greater risk of flooding on a regional scale. It is certain that intense tropical cyclone activity has increased in the North Atlantic since 1970. Impacts from these climate-related extremes (e.g., heat waves, droughts, floods, wildfires, cyclones etc…) have been increasing substantially in the last decades.

- 3.2 - CLIMATE MODELS: AN OVERVIEW

Key Points

Climate models act as an attempt to represent Earth's climate system in order to better understand its working principle, to conduct experiments and to make predictions about its future progress. Climate models are based on physics, chemistry and biology laws implemented mathematically on multiple computer languages. Equations are solved with numerical methods using different time and spatial schemes depending on the level of accuracy needed. Choices must be done about what variables and processes are to be included in the model. Reasonable assumptions, hypothesis and parametrizations must be done, likewise any other scientific model development. Computer power is the major constraint: a trade-off against accuracy must be done. Climate models are constantly refined by technological improvements and checked against real world observations.

After an outline of the Planet's constituents, the climate driving forces, the geological backdrop - that suggest that global warming actually is human-made - and the detailed overview of the observed changes in the near past, at this point the focus goes on the near future. What is going to happen? How will the climate develop? To give an answer, climate models are introduced.

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[60] Charles David Keeling, of the Scripps Institution of Oceanography was the first person to make measurements on carbon dioxide concentrations. Data from Mauna Loa Observatory are commonly used.

[61] In line with *Section 2.5*.

[62] CDM is a part of the policies adopted within the Kyoto Protocol aiming at making industries and stakeholders to evolve in developing countries in a sustainable way (e.g., reducing emissions etc.)

- 3.2.1 – Overview

Climate models work in the same way as the first model invented in the history: the language.[63] Models are used in Architecture, Engineering, Agriculture, Economics and basically in every context which needs future estimates or an easier representation of a complex system. It usually starts from present conditions, a set of hypotheses and relies on multiple assumptions and expectations. With respect to climate, models allow to try out all sorts of the so-called *what-if scenarios*, turning the various forcings on and off, considering or not feedbacks etc., starting from what is known: historical data and present observations. Climate models in the end provide a wide range of possibilities, describing what the future climate is likely to be. Their boundary conditions, assumptions and equations are constantly revised and refined, as new insights are gained.

According to the Intergovernmental Panel on Climate Change (IPCC), the development of climate models involves multiple steps [19, p. 749]:

- Expressing all the system's physical laws in the mathematical terms that best describe the system;
- Implementing these mathematical expressions on a computer, making use of numerical methods discretizing the mathematical equations with time and spatial grids depending on a tradeoff between accuracy and computational time;
- Building and implementing conceptual models using parametrizations for those mechanisms that cannot be represented explicitly due to complexity or spatial and/or timescales inconsistent with the discretized model.

The basis of climate models are the physical and chemical laws like the conservation of mass, energy, gravity, chemical balances, the First Law of Thermodynamics, the Clausius-Clapeyron equation, the Stefan-Boltzann Law, Navier-Stokes equations, etc. These laws apply to the major components of the Earth's climate system, with a grade of precision depending on the case, and identify the flows of mass and energy exchanged between them changing overtime dynamically[64].

Other than the equations, the information about the major phenomena (physical, thermodynamic, chemical, biological etc.) are provided besides the timescales of each of them. All these data are fed to the climate model, available in multiple programming language such as C, Python, R, Matlab, IDL and especially Fortran [18]. Once that the model is run and has reached reasonable stability, perturbations are added in order to study how they affect the system (e.g., how fast and what effect with the system approaches equilibrium again, turning on an off a single perturbation to isolate its influence).

The crucial part then is to test the model outputs with real observations and measurements to see if the model aligns well with them or not: real world provides the constraints for the progressive development of the climate model[65]. So, observation builds the model, the model provides plausible information about the real world and observation again, eventually *verify or falsify*[66] the output of the model itself with a mutual feedback loop. An example comes from the study of the CO_2 emitted from human activity. Models and observations together provide more specifically the various carbon pathways, incorporating observations about carbon dioxide emission and concentration in multiple zones into models of *atmospheric circulation*[67] and finally infer which constituents are responsible for the uptake of CO_2 from the atmosphere.

[63] When you talk (or write) you are representing in a practical and coded way, what you are thinking; the aim is to get with that process as close as possible to communicate the ideal thought, even if it can never be what you are exactly thinking.
[64] Global Energy Budget (GEB) and Carbon Cycle provide multiple equations composing a climate model. See *Section 2.2 and 2.5*.
[65] An example of a simple real-world constraint is the relation between the ambient temperature and the water pressure.
[66] Verification and Falsification here are intended in a Popperian sense [45].
[67] Atmospheric circulation is a large-scale movement of air by which heat is distributed on the surface of the Earth [46].

- 3.2.2 - A brief example

The following lines are dedicated to a brief development of one easy model built to simulate the Global Energy Balance (GEB), gradually including processes and approaching to the real world. The model relies on different hypotheses and provide one single parameter as outcome: Global Mean Temperature (GMT). The difference between the various GMTs obtained depending on the hps considered is quite remarkable.

A) *Hypothesis: no Sun.*

The Earth is subject only to geothermal energy coming from the core (0.06 W/m²). In order to reach equilibrium, it must emit 0.06 W/m². The Earth GMT would 32 K (or -241 °C) [20].

B) *Hypothesis: Sun "turned on". No reflection, no GHG effect, meaning that the Earth absorbs all the radiation.*

The energy received from the Sun is about 341 W/m². An imbalance rises. The Earth warms up as a consequence and passes from an equilibrium temperature of 32 K emitting 0.06 W/m², to 278 K (or 5 °C) emitting 341 W/m².

C) *Hypothesis: Sun "turned on". Reflection "turned on". No GHG effect.*

Earth absorbs only the 70% of the 341 W/m² coming from the Sun (i.e.: 239 W/m²). The equilibrium is reached at 255 K (or -18 °C) [21].

D) *HP: Sun "turned on". Reflection and GHG effect "turned on". Simplifying assumption: GHGs absorb all the radiation emitted by the Earth's surface, re-emitting it for an half towards Space and for the other half towards the Earth's surface.*

In order to reach the equilibrium, the energy emitted out of the atmosphere by GHGs must be equal to the difference between the inflow from the Sun (341 W/m²) and reflection (102 W/m²), that is 239 W/m². Emission towards the Earth's surface is 239 W/m² too. Summarizing, the Earth is absorbing 239 W/m² directly from the Sun and 239 W/m² from GHG effect. Therefore, the Earth must emit 2*239 = 478 W/m² to balance the flows in turn. Under these conditions, the GMT would reach approximately 303 K (or 30 °C).

From this basic state, more and more processes can be added to the climate model with an increasing grade of accuracy and complexity. Phenomena that can be included in the climate model range from the Carbon Cycle with its multiple components, to the effect of sulphates and carbon injected into the atmosphere by human activities[68]. This is an example of a simple climate model that averages over the whole Earth its energy balance under a few elementary assumptions. From there it may be needed for instance to study the time the Earth might take to regain energy equilibrium after these perturbations.

- 3.2.3 – A further step

A first broad terms climate model can be built using the above elementary assumptions, but in order to make reliable predictions about the future climate, a further step must be done. A deeper degree of complexity can be reached by dividing the atmosphere into different layers, adding the other terms of the GEB, such as the *atmospheric window*, *latent heat* and *thermals* ones[69] as well as the influence of the various constituents of the Earth's surface (e.g., rocks, Oceans, land etc.). The development of a climate model needs then the Globe to be divided by means of a spatial grid according horizontally (on a 2D-plane) to latitude and longitude and vertically to height or pressure. The third dimension, that is

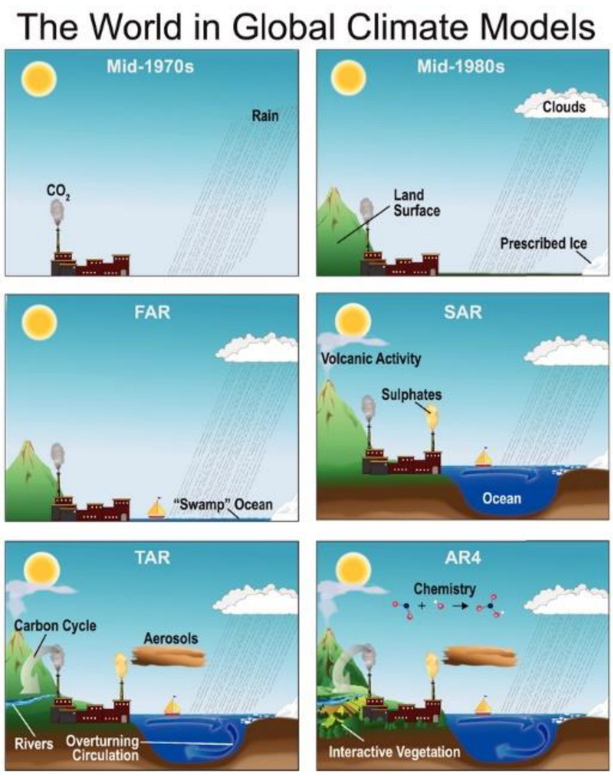
[68] As seen in *Section 2.3* any process or constituent added to climate model is a perturbation that breaks the equilibrium; a certain time interval is needed to the system to reach the equilibrium again.
[69] See *Section 2.2*.

the height, extends upward in atmosphere and relatively deep downward the Oceans, creating ultimately a three-dimensional grid. The size of the cells in the grid is called *spatial resolution*. A rather coarse global climate model has grids of 100 km in latitude and longitude; smaller and smaller cells better approach the reality, increasing the computational cost [22]. A more refined spatial resolution is adopted in the atmospheric and Oceans' layers near their respective boundaries, in which the major exchanges occur and the best accuracy is needed.

The same applies to the choice of the timestep. As for any numerical simulation, the correct approach is to keep decreasing the timestep until simulation has converged and the results stop changing. In the operation of the most recent climate models, a timestep of about 30 minutes seems to be a reasonable compromise between computational time and accuracy. It means that a climate model produces simulations of the whole climate system at 30-minutes interval, over decades [22]. At this point, each variable of the model (e.g., temperature, humidity, pressure, atmospheric mass, sea ice salinity etc.), is determined then for each cell, at each timestep.

One of the other biggest issues for climate models is the level of the scale adopted. The climate system has way more constituents and links that any model can explicitly track. Reasonable approximations and assumptions, the so-called process of *parametrization,* must be done in order to describe multiple and complex small-scale processes in a global and aggregate study[70]. From here, individual components and processes of the model (e.g., the ocean, the forests, the effect of photosynthesis on carbon cycle etc.) are firstly evaluated in insolation and subsequently they are assembled into a comprehensive model, which is studied in a systematic evaluation.

Even the period covered by the model is crucial. Climate models can be specifically designed to simulate short-time periods of the order of decades (the highest resolution ones), they can develop century-scale



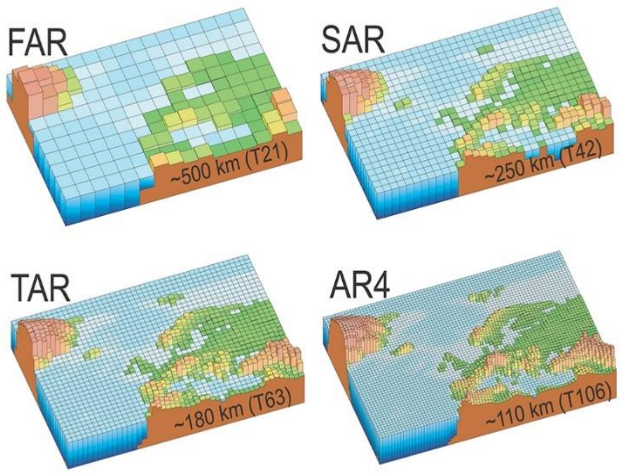


Figure 3.4 | Climate models: an overview. (left) Progression of processes added to global climate models over the decades from the mid-1970s to the ones implemented in the IPCC assessment report: FAR (1990), SAR (1995), TAR (2001), AR4 (2007). (right) Increasing spatial resolution of climate models for FAR, SAR, TAR, AR4. **Credits: IPCC Fourth Assessment Report: Climate Change 2007.**

[70] An example of climate model parametrization is the representation of clouds. As they are smaller than the grid cell size and formed by deeply small-scale processes like evaporation and condensation, they cannot be realistically modeled considering every raindrop. Climate models describe clouds instead assigning measurable variables (e.g., temperature, relative humidity etc.) to each cell.

estimates, or they can be designed to simulate thousands of years. The final choices about level of detail, accuracy, timestep, timescale is a trade-off with the computational cost of the evaluation. The time to run the model is the product between computer time needed to perform a single operation, the # of operations per equation, the # of equations per cell, the # of cells in the model and the # of timesteps.

$$Time_{model} = Time_{op} * \#_{\frac{op}{eq}} * \#_{\frac{eq}{cell}} * \#_{\frac{cell}{model}} * \#_{timesteps}$$

As technology progresses, more processes and constituents can be added to a single climate model, aiming to include ideally every single component of climate system at all possible scales. The main issue is that as the climate model increase its complexity getting more and more adherent to reality, a single small-scale variable error can translate into a dramatically huge error on the aggregate large-scale outcome[71].

In conclusion, climate models are not replicas of climate system, but tools which require a constant and systematic check against real world observations. A schematic progression of the climate models refinements overtime is shown in *(Figure 3.2).* After the proper setting, any individual simulation represents only one of the possible pathways followed by the climate system: it is necessary to carry out several evaluations with several different models in order to decrease the effect of uncertainties on the final outputs.

- 3.2.4 - The main models

Now a quick overview of the most used type of climate models is done. The most basic climate models are the Energy Balance Models (EBMs), which consider only inflows and outflows of energy exchanged between Earth and Sun. They are zero-dimensional considering the Earth as a whole, without distinguishing between its various constituents. The climate variable provided by the EBMs is the surface temperature.

The next step is with Radiative Convective Models (RCMs), which add the convection in atmosphere among the energy exchanges. Typically, RCMs are one-dimensional. A further development is

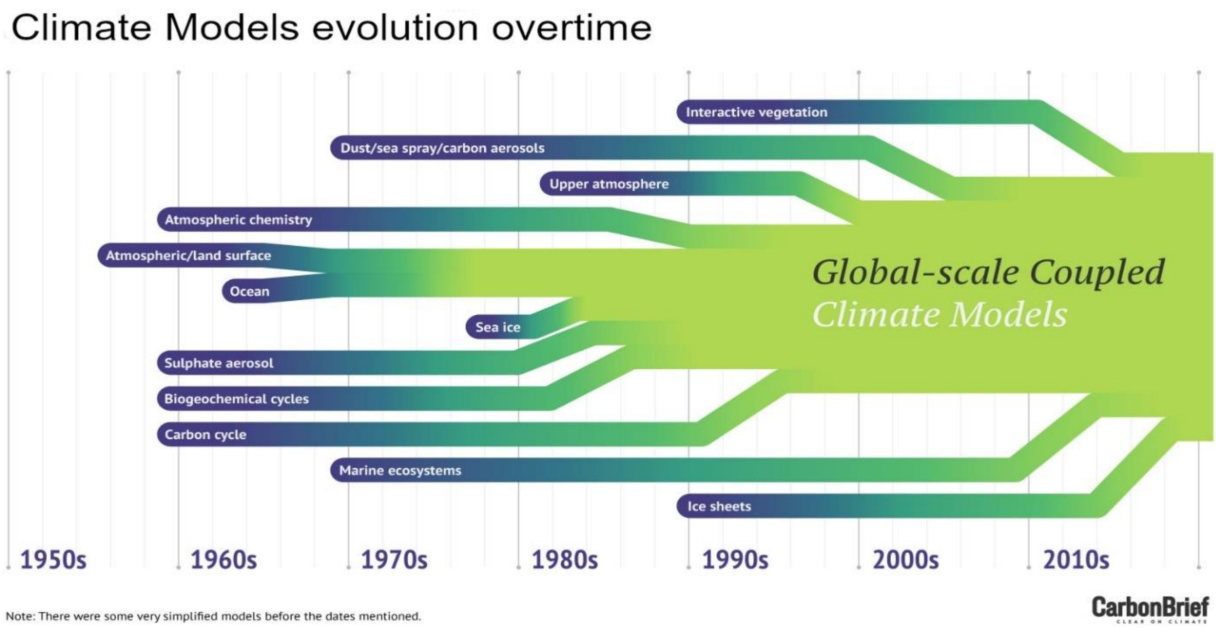


Figure 3.5 | Climate models: an overview. Progression of processes added to aggregate global scale climate models. Credits: www.carbonbrief.org, 2018.

[71] It is the so-called "complexity paradox". The concept comes from the Harvard historian of Science Naomi Oreskes. A complex model may be more realistic as more factors are added, but the certainty of its predictions may decrease as a result [42].

represented by General Circulation Models or Global Climate Models (GCMs), that simulate multiple phenomena aggregated in a comprehensive representation such as the Atmosphere-Ocean General Circulation Models (AOGCMs). As discussed above, climate models have gradually added phenomena that were before studied in different standalone models (e.g., land hydrology, sea ice etc.). An idea of the complexity of the models overtime can be given by *(Figure 3.5)*.

The most recent GCMs include also biogeochemical cycles of livings and their habitats. These are called Earth System Models (ESMs) and can simulate carbon cycle, ocean ecology, land use and vegetation changes etc.
The Regional Climate Models (RCMs) are the local-scale akin of GCMs, providing higher resolution information for a specific area. Finally, Integrated Assessment Models (IAMs) are climate models which take into account also socio-economic issues (e.g., population growth, GDP, energy use, social stability etc.)[72] [21].

The projections about future climate pathways, emissions and scenarios from the Intergovernmental Panel on Climate Change (IPCC) relies mainly on the Coupled Model Intercomparison Project Phase 5 (CMIP5). The CMIP is defined as a "standard experimental framework for studying the output of coupled atmosphere-ocean general circulation models" provided by the World Climate Research Program (WCRP) [23]. The *Phase 5* is the most extended and updated model of this series. CMIP provides a framework for climate change experiments including decadal and long-term simulations in order to evaluate the effectiveness of model simulations of recent past changes recorded and supply near-term projections (out to 2035) and long-term ones (up to 2100 and beyond).

The current ultimate series of climate models is CIMP Phase 6. CMIP6 is foreseen to take operation within 2020. With CMIP6, many of the models will be run at higher resolutions and will include additional processes that were not simulated in the previous models. The Phase 6 will also rely on a better consistency, as it will be organized on the so-called Diagnostic Evaluation Characterization of Klima experiments (DECK experiments). The CMIP6 timeline is shown in *(Figure 3.6)*. The CMIP6 products will represent one of society's most important sources of high-quality reliable climate information.

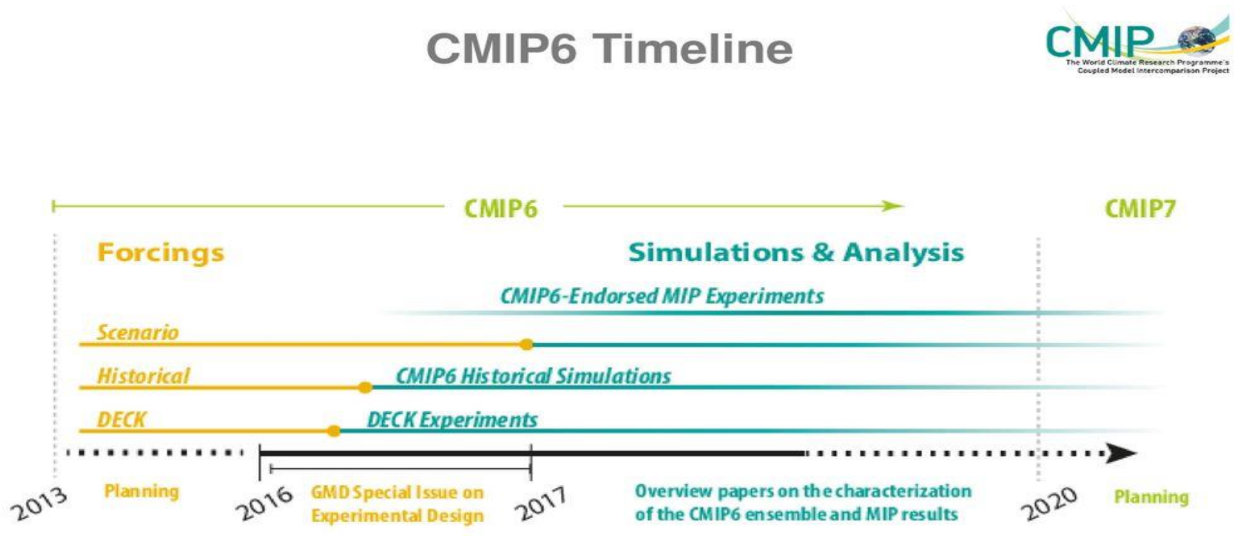


Figure 3.6 | Climate model: an overview. CMIP6 timeline for the preparation of forcings, the realization of experiments and their analysis. Credits: V. Eyring, S. Bony et al., "Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization", Geoscientific Model Development, 2016.

[72] IAMs are implemented by the IPCC's Assessment Reports to track future scenarios with the aim to display plausible policies against climate change and to proof the impact of those policies on climate system.

- 3.2.4 - Input, output and checking against the observations

Once that the general characteristics of climate models have been outlined, it is important to focus on the simulation's strong linkages between inputs, outputs and observations. As previously said, the main inputs of climate models are the parameters describing and quantifying the external agents that perturb the Earth's energy balance. These external factors have been identified as the *Radiative Forcings* (RFs) from the various GHGs, aerosols, land use change etc.[73]. Estimates on how RFs are linked to the change in a specific variable or part of climate system are based on historical observations and empirical constraints recorded (e.g. GHGs concentration, temperature trends etc.) that plausibly can explain the occurrence of similar future processes. It must be remarked once again, that climate models are not tuned to match a particular future scenario but are referred to a relatively wide range of possibilities.

The outputs of climate models can be future long- or short-term variables, generating an overall picture of Earth's climate system. As previously said, real observations are crucial to check climate model outputs; by looking at them the temperature anomalies series displays a substantial match between the measured data and the average of the 58 simulations from 14 different models, each constructed with different assumptions and parametrizations ***(Figure 3.6-left)***. The trend is markedly tracked. The effect of particular climate events at a global scale, as the influence of the four large volcanic eruptions in the 20th century of Santa Maria (1992), Mount Agung (1963), El Chichon (1982) and Mount Pinatubo (1991)[74] is tracked as well both by observations and models.

Besides the use for projections and future scenarios, climate models are decisive to sort out attribution for climate change between natural and anthropogenic agents. As shown in (***Figure 3.6-left)***, both natural and anthropogenic agents are included in the models[75], while in ***(Figure 3.6-right)*** are displayed outputs from models which include natural variability only, and no human activities. If the climate system were subject only to natural agents, the trend in temperature anomalies would have been a slight net cooling rather than the warming that was actually observed. In other words, the models which consistently reproduce the observed warming best are the ones that include the RF's anthropogenic factors among the initial assumptions.

Projections made in 1988 by Jim Hansen[76] [26] are a probably one of the best benchmarks to gauge the effectiveness of climate models, after three decades by their release. Hansen provided three future

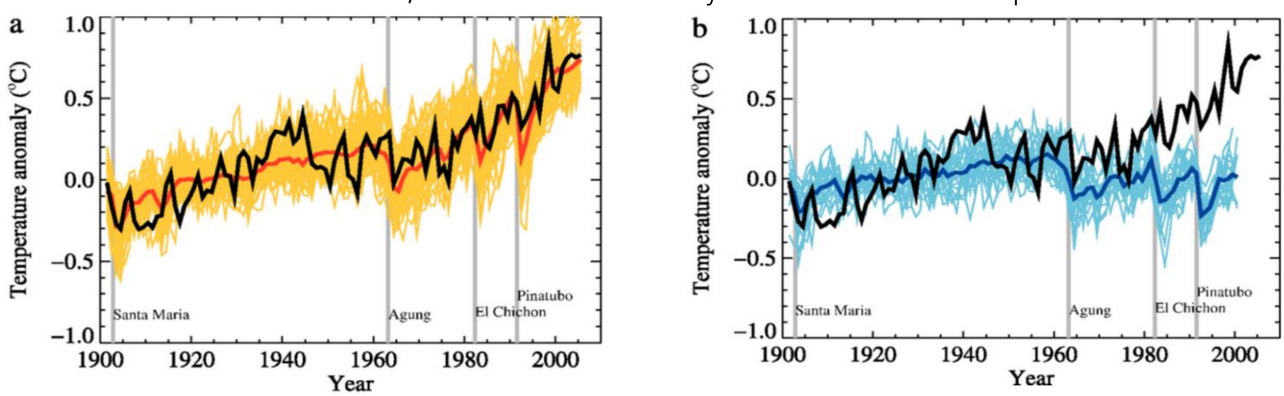


Figure 3.6 |Climate models: an overview. (left) Comparison between GMT anomalies (°C) between observations (black) and Atmosphere-Ocean General Circulation Model (AOGCM) simulations. (a) Anthropogenic and natural RFs are considered. (b) Natural RFs are considered only. Data relative to the baseline period 1901-1950. Credits: IPCC Fourth Assessment Report, 2007.

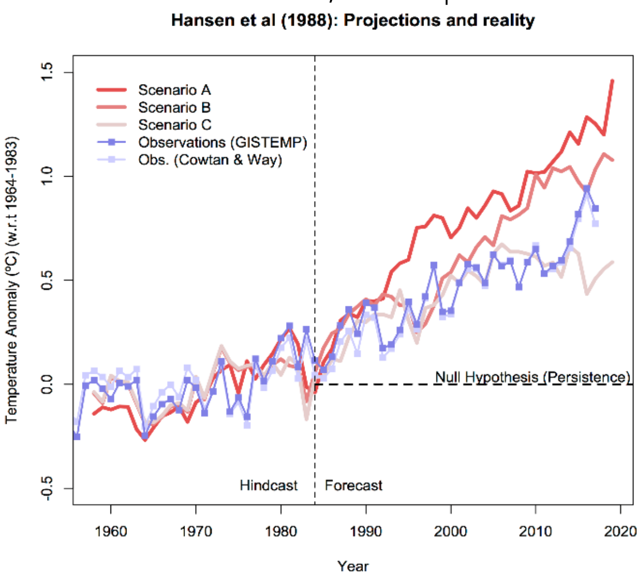
[73] See *Section 2.7.1.*
[74] Volcanic eruptions emit sulfate and other particles which are reflective and therefore cause temporary cooling at a global scale.
[75] For natural and anthropogenic variability factors see *Section 3.2.*
[76] The first transient climate projections using GCMs were performed by astrophysicist and climatologist Jim Hansen from NASA's Goddard Institute for Space Studies, one of the most important scholar of climate change and global warming by GHG effect [47].

scenarios representing three different human CO_2 (and other GHGs) emission pathways. Scenario A assumed exponential growth in emissions, scenario B considered an emission growth rate slowdown, stabilized but still increasing in the amount and scenario C assumed GHG emissions to start decreasing by 2000 [25]. Estimates of RFs were related to CO_2, N_2O, CH_4 and CFC[77] and provided three different warming rates for each scenario:

- Scenario A: 0.33 ± 0.03 °C/decade
- Scenario B: 0.28 ± 0.03 °C/decade
- Scenario C: 0.16 ± 0.03 °C/decade

The observed real changes on the period 1984-2017 are 0.19 ± 0.03 °C/decade from Goddard's Global Surface Temperature Analysis (GISTEMP) [26], or 0.21 ± 0.03 °C/decade from Cowtan and Way [27] staying in between scenario B and C with some deviations due mainly to the higher value used for *climate sensitivity* compared to the today's one[78] *(Figure 3.7-left)*. In short, estimates by Hansen reproduced well a range of trends, which real observations have resulted falling in after more than three decades right now [30].

Another example of checks between observations and models is related to another major climate parameter: the September sea ice extent. Well, a certain agreement between observations and the average of 18 different models from IPCC 2007 AR4 [30] is clear in the early part of the data record measurements, while there is discrepancy over the last decades *(figure 3.7-right).* Models show a more conservative decline with respect to the steep decrease of the real observations. In other words, the Arctic ice is retreating more rapidly than what estimated by IPCC: the models were underestimating the phenomenon. The fastest rate of decline in September sea ice cover provided by models was 5.4% per decade over the period 1953-2006, but satellite measurements showed about a 7.8% instead [29]. This happened due to an increased weight of the anthropogenic GHG emissions in the assessment of the causes of ice loss overtime, with respect to the assumptions made by IPCC. Impacts of GHG loading on



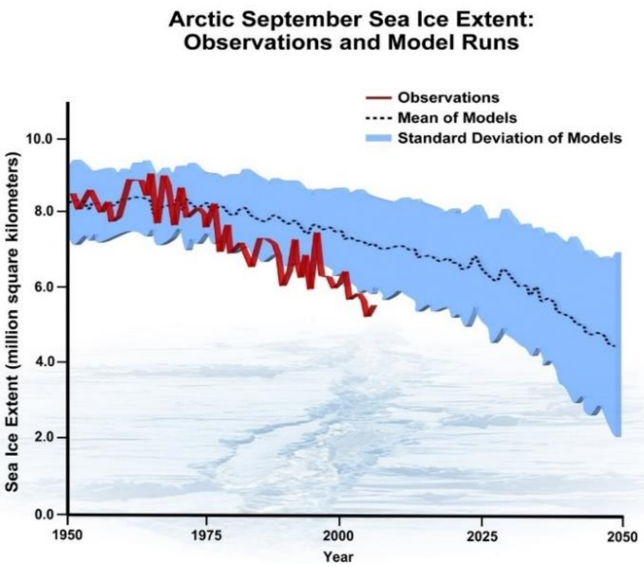


Figure 3.7 | Climate models: an overview. (left) Check between temperature anomalies projections (three scearios) from Hansen et al. in 1998 [25] (redish solid lines) and observations from GISTEMP (2019) [26] and Cowtan and Way [27] (bluish dotted line). (right) Check between Arctic September sea ice extent from IPCC AR4 models and real observations from Nationl Center for Atmospheric Research (NCAR) (solid red line). Credits: (left) http://www.realclimate.org, 2018. (right) spacemath.gsfc.nasa.gov

[77] These scenarios were developed in 1983. The Montreal Protocol had yet to be signed, so projections on CFC were "pessimistic".
[78] Hansen's climate sensitivity was ~1 °C/W. Today's one is ¾ °C/W. See cap. Par.

Arctic sea ice in September are stronger and faster-growing than projections of previous climate models. In this case improvements must be done adding information from measured data, updating the share of the effect of anthropogenic RFs with respect to assumptions that were made. According to the new assumptions coming from the check with real observations "Arctic sea ice may disappear considerably earlier than the IPCC projections" [29].

To conclude, comparing model outputs to observations checks the grade of accuracy with whom the climate model represents the Earth's climate system. Evidences show an elevated match between global temperature models and observations. Finally, once again: climate models are not developed to predict exactly parameters or trends, but rather ranges of possibilities.

- 3.3 - CLIMATE MODELS: OUTPUTS AND FUTURE SCENARIOS

<u>Key points</u>

Information about plausible emission scenarios are needed by climate models to provide outputs on climate future. Two main approaches exist to defining those scenarios. The first one is the Special Report on Emissions Scenarios (SRES), that starts by determining different possible histories based on human and society choices and consequently outlines emission pathways and parameters for climate models. The other approach is the Representative Concentration Pathway (RCPs) one, which instead starts by defining certain endpoints within 2100 in terms of Radiative Forcing (RF) above pre-industrial times and then infers backwards what is the representative pathway leading to that endpoint. Again, this information feds the climate model which will give the climate response as output. All the approaches are what-if scenarios, providing expectations given the pathway followed. Through Transient Climate Response to Cumulative CO_2 Emissions (TCRE) a relationship between carbon cumulatively emitted from now to pre-industrial period and temperature change is established. Every 1000 Gigatons of carbon emitted yield to about 1.8°C temperature warming. According to this metric, the quantity of carbon left for humanity to emit can be assessed with the so-called carbon budget. Some uncertainties arise when quantifying the humanity's carbon budget exact amount. Given that the hypothesis is far to be plausible, according to climate models even the "stop-all-emissions" overnight scenario would be not be capable of kick-starting a breakthrough in reversing the Global Warming. The GHG's long atmospheric lifetime and the slowness of the climate response to perturbations due to oceans large thermal inertia, would lead to a near constant temperature for many centuries even if emissions were suddenly halted.

- 3.3.1 – Forecasts: next week vs coming decades

Taking a further step and going to focus ultimately on the climate model's outputs, it must be clarified that weather and climate – which are the two main objects of the model forecasts - are two different concepts. The term *weather* indicates the condition of the atmosphere in one area at a particular time and place. It can change day by day and hour to hour. The term *climate* instead refers to statistics and parameters linked to weather, but with decadal or multi-decadal timescales. In order to make predictions about weather, information on the current state of atmosphere are needed, these kinds of forecasts are subject to the so-called *butterfly-effect*[79]. Climate predictions instead do not focus on a detailed day-to-day trend of future weather, but rather deals with long-term climate variable averages, the so-called *climatological averages*. These projections are subject to the *butterfly-effect* too, but its influence on climate is slower and weaker owing to the naturally-driven phenomena included in climate internal variability which act on longer timescales[80].

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[79] Meaning that the tiniest error on assumptions and initial conditions reflects on inaccurate forecast within one week or so.
[80] The Carbon Cycle is one of the most important examples. See *Section 2.5.*

- 3.3.2 –Scenarios modeling: the different approaches

As discussed in the previous section, climate change projections are not like weather forecast. It is not possible to make deterministic prediction about the evolution of climate over the next century as it is for the short-term weather forecasts. Therefore, as yet said, climate models provide a range of likely possibilities which can explain different pathways that climate evolution can take. Each of these pathways is affected by the wide series of perturbation drivers seen - both natural and anthropogenic - and has different likelihood to occur, depending on the way that the Planet will then act to counteract these drivers[81]. Information about emissions, land use, social, economic and cultural developments are fed to climate models, which then provide the future trends of the main climate parameters such as temperature, sea levels, precipitation patterns, etc.

The Intergovernmental Panel on Climate Change (IPCC) uses two different approaches to address this issue:

- Special Report on Emissions Scenarios (SRES);
- Representative Concentration Pathways (RCPs);
- Shared Socioeconomic Pathways (SSPs).

- 3.3.3 – The Special Report on Emissions Scenarios (SRES)

Special Report on Emissions Scenarios (SRES) is a report from the IPCC released in 2000 which poses the guidelines for an approach to make projections which was utilized in the IPCC's Third (2001) and Fourth (2007) Assessment Reports. This approach defines different future storylines based on a wide range of human driven plausible changes in the future including socio-economic, demographic, geo-political, as well as energy demand and supply mix, resources use, technology developments and policies pursued. The SRES approach estimates ultimately the implications of these different storylines reflecting on the level of GHG emissions: it defines a linked "emission scenario" that is then fed to the climate model which provide in the end the various parameters as outputs.

The emission scenarios are organized into four *Families* ***(Figure 3.8)*** outlining frameworks of common

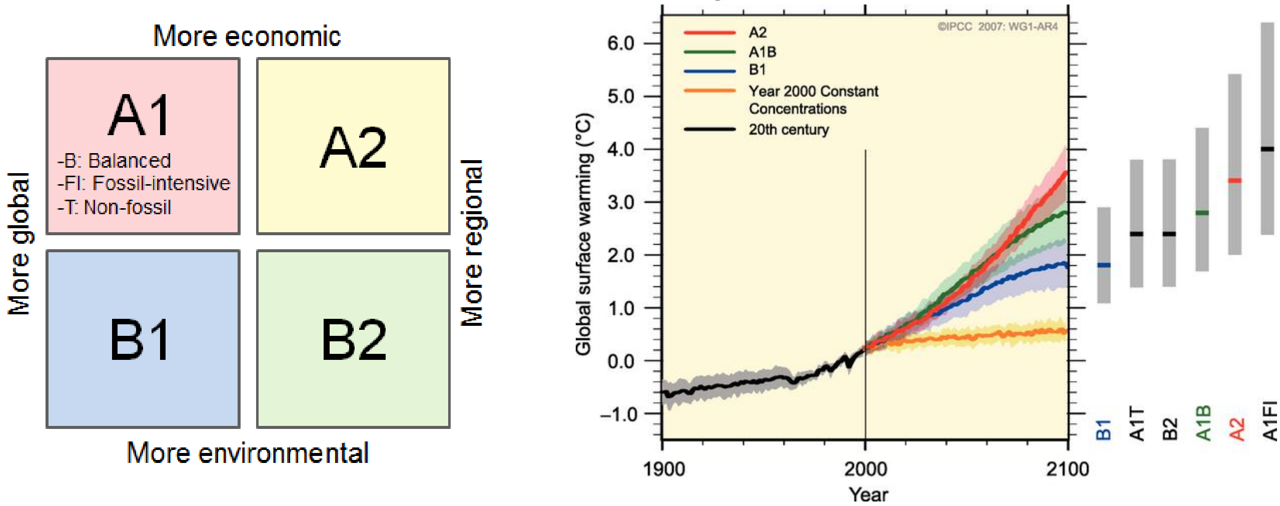

Figure 3.8 | Climate models (left) Families and sub-families subdivisions in SRES approach by IPCC. (b) Global surface warming by 2100 for three SRES scenarios (A2-red line, A1B-green line, B1-blue line) and one additional one considering year 2000 constant concentrations (yellow line). Image (a) adapted from https://climate4impact.eu/drupal/?q=scenarios_different Image (b) adapted and modified from https://www.ipcc.ch/publications_and_data/ar4/wg1/en/figure-spm-5.html

[81] Counteractions here are meant to be not only climate feedbacks and natural mechanisms discussed in *Section 2.3*, but also policies for mitigation and adaptation, change in behaviors, mind view and perceptions from public opinion.

themes and features.

- ### 3.3.3.1 – SRES: the families

Generally speaking, A1 and A2 tend towards a more economically centered development while B1 and B2 vice versa towards a more environmental protection. A1 and B1 describes a more globally interconnected World, while A2 and B2 tend to a more regional growth scheme. A brief description of the main single families' parameters is to follow:

- *A1*: outlines a rapid economic and demographic growth, extensive social and cultural interactions worldwide. A1 has three subsets, differing on the technological emphasis of the development.
    - *Fossil Intensive* (*A1FI*) nicknamed *business-as-usual*, with intensive fossil fuel use;
    - *Balanced Energy* (*A1B*), characterized by a balanced energy mix between fossil and non-fossil sources;
    - *Transition to non-fossil fuel* (*A1T*), the eco-friendliest one;
- *A2*: profiles a world of self-reliant nations and a regionally oriented, strong growing economic model of development. A2 projects a continuously increasing population;
- *B1*: account for a World more integrated and ecologically friendly, a rapid economic growth tending to a development more services and information centered. B1 sees population peaking to 9 billion in 2050 and then declining as in A1. Clean and efficient technologies for energy and resource supply are assumed; social and economic stability issues are globally assessed;
- *B2*: outlines a more local, fragmented and eco-friendly development. B2 projects a growing population but with a slower growing rate than in A2. Local rather than global solutions to socio-economic and environmental instabilities are pursued.

None of these scenarios is more likely to occur than the others. The goal is to provide a wide range of divergent futures taking into account the uncertainties on the main driving forces. According to this scheme, SRES made projections until 2100 using IAMs[82]. As regards Global Surface Warming SRES identified the temperature pathways for four different scenarios. By 2100, A2 outlines the highest temperature rise of 3.2°C above 2000's levels, the pretty optimistic A1B scenario projects anyway a temperature rises by about 2.3°C and the only one remaining below the 2°C threshold is B1 with the temperature still rising by 1.4°C. Akin trends for CO_2 and other GHG were identified.

- ### 3.3.4 - The Representative Concentration Pathways (RCPs)

The newer approach to defining emission scenarios is the Representative Concentration Pathways' one, which is based on a reversed mindset with respect to the SRES. According to RCPs, an "endpoint" is defined (i.e., the value of Radiative Forcing in the year 2100) in terms of the amount of extra energy that can be added within the climate system by 2100 compared to the pre-industrial levels[83]. The *Representative Concentrations* are the different trajectories that future climate can take to get to the endpoint estimated, depending on the GHG concentration, rather than emissions. In other words, rather than outlining a "story" first and then infer the implications for the GHG emissions, the RCP approach defines firstly some GHGs emission trajectories and then sets the variety of human scenarios corresponding to these trajectories.

Ongoing exchange of information between concentration pathways and the corresponding human choices makes the RCPs a far more flexible and updatable approach compared to the SRES. The RCPs goal is to identify magnitudes and rates of climate change in order to assess "the risk of crossing

[82] See *Section 3.2.4.*

[83] The RCP approach has been implemented in the IPCC Fifth Assessment Report (AR5). The baseline to which projections are referred is the period 1850-1900. Claims have been done about this choice, as GHG concentrations have been increasing – altering climate - since the very begin of industrialization (around 1750) [52].

identifiable thresholds in both physical change and impacts on biological and human systems" [30]. RCPs models, likewise SRES ones have been developed through Integrated Assessment Models (IAMs). RCPs' trajectories are identified by the approximate value of the RF (W/m^2) by 2100, relatively to the pre-industrial period. The RFs considered by the RCPs include multiple factors such as the predicted solar output, every single of the GHGs involved in the Global Energy Balance (GEB), aerosols, Land Use Change (LUC), black carbon on snow, etc.[84]. The value of the RFs coming from the GHG emissions define the different scenarios (e.g., *RCP6* stands for a Radiative Forcing of 6 W/m^2 higher than prior to the Industrial Revolution by 2100, RCP2.6 stands for a RF of 2.6 W/m^2, etc.).

- 3.3.4.1 - RCPs: primary characteristics

The four types of RCP scenarios are then described:

- RCP2.6 (also referred to as RCP3-PD): is the stringent mitigation[85] scenario and the best-case one. It outlines a future leading to very low GHGs concentration levels. It is one of the so-called *peak-and-decline* scenarios: its RF peaks at 3.0 W/m^2 by mid-century and then declines by 2100 at 2.6 W/m^2. It requires a major policy turnaround, which seems absolutely not on the current agenda [35].

- RCP4.5 and RCP6: are intermediate *stabilization scenarios* without overshoot[86] tending to stabilize respectively at 4.5 and 6 W/m^2 by 2100. The two scenarios differ from the timing of the stabilization, occurring earlier for RCP4.5 than RCP6 thanks to the application of strategies and policy for mitigation and adaptation which reduce GHG emissions [36].

- RCP8.5: is the "nightmare" scenario. It is characterized by GHG's RF reaching values greater than 8.5 W/m^2 by 2100, following a progressively rising trajectory [37]. RCP8.5 is the *non-climate policy* scenario, highly energy intensive and is characterized by the highest rate of population growth reaching 12 billion by end-century.

The RCPs are designed to provide information on all radiative forcing component needed as models' input and are based on scenarios published in the existing literature and revised yet. RCPs refer to a time

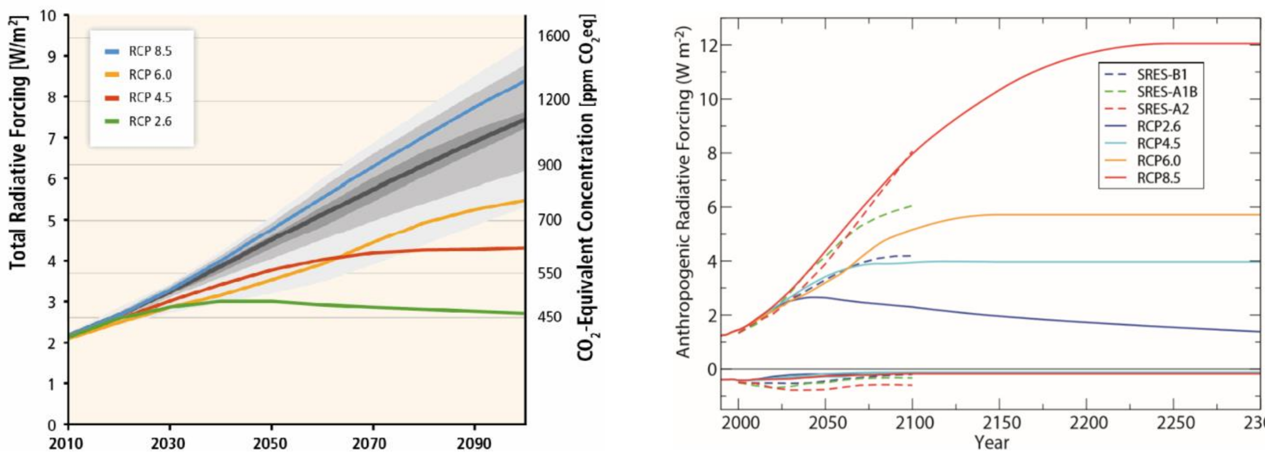

Figure 3.9 | Climate models: future scenarios. (left) Total radiative forcing by 2100 compared to pre-industial levels: the RCPs. RCP 8.5 (light blue), RCP 6.0 (yellow line), RCP 4.5 (red line), RCP 2.6 (green line). (right) Anthropogenic Radiative forcing comparison between SRES (dashed lines) and RCPs (solid lines) approach. **Credits: http://climatechangenationalforum.org/what-is-business-as-usual/ (left). "An exploration of building energy performance and financial value with demonstration on UK offices", Aidan Thomas Parkinson (2016) (right).**

[84] For the RFs factors see *Section 2.7.*
[85] The concept of "mitigation" will be discussed in *Section 4.3.*
[86] Emissions, concentrations or temperature can temporarily exceed or *overshoot* the long-term goal. RCP4.5 and RCP6 are defined "without overshooting" the long-run RF target level.

period up to 2100, but projections are also available thereafter with multi-century extensions for the 2100-2300 period: the so-called Extended Concentration Pathways (ECPs). ECPs were highly stylized and designed with the aim to provide rough simulations.

The RCPs - complementarily with Shared Socio-Economic Pathways (SSPs) - not only focus on the climate system description, but also provide a crucial benchmark for the estimates on mitigation/adaptation policies and socio-economic conditions that would be needed to reach a particular scenario, and inform on the extent of the impact of climate change as well[87]. RCPs "should not be interpreted as forecasts or absolute bounds, or be seen as policy perspective" [35] but rather as a set of possible developments in climate and socio-economic parameters consequent to natural and human driven future changes.

- 3.3.4.2 - RCPs: population, GDP, Land Use and Primary Energy Consumption

As *globally*, *economic and population growth continue to be the most important driver* of climate change, the RCPs scenarios project firstly different trends for population and GDP. The RCP8.5 outlines approximately 12.6 million people on the Earth by 2100, while only 9.8 million for RCP6, 8.5 for RCP4.5 and 9.0 for RCP2.6 are foreseen. All the four scenarios provide for an increasing GDP with RCP2.6 leading, reaching 363 T$ by 2100.

Land use is a crucial driver for climate change as well[88]. RCP8.5 emphasizes the use of cropland and grasslands as a result of growing population and GDP. RCP2.6 sees croplands increase too because of the widespread of bio-energy, while a more-or-less steady use of grasslands. The RCP4.5 shows a turnaround in land use, with a decline in both grassland and cropland due to reforestation programs. RCP6 outlines instead a decline in pasture and an increasing use of cropland.

As for energy use, the RCP approach differentiates also for the Primary Energy Consumption (PEC), Oil consumptions and Primary Energy Use (PEU). RCP8.5, the highly energy-intensive scenario, far exceeds the 1500 EJ of PEU by 2100 and provides for a lower rate of technology development with a massive use of coal and the others fossil fuels accounting for a half of PEU by 2100, with a peak-add-decline trend for Oil. RCP2.6, RCP4.5 and RCP6 are all intermediate scenarios in terms of PEU, leading to values between 750 and 900 EJ by 2100 with a more differentiated sources mix, but with all scenarios agreeing on fossil fuel share to be greater by 2100 than in 2000.

Oil consumption is nearly constant for the mid-RCPs while declines only for RCP2.6 due to both depletion and climate policy. Non-fossil fuel use increases for all scenarios especially renewable as wind and solar due to the increasing energy demand, climate policies and fossil-fuel prices rising [34].

Turning to pollutants emissions[89], all the RCPs exhibit a declining trend. Air pollution is influenced by the change in the multiple driving forces (fossil-fuel use, land use, fertilizers or other agricultural chemicals, etc.) and also by the effectiveness of air control and climate change policies with the goal of reducing emissions.

All the RCPs assume more rigid policies in the years to come. A strong correlation between a high fossil-fuel use and higher levels of pollutants is found. In contrast, a massive use of renewables, an increasing efficiency in the power sector coupled with a strong electrification of the whole energy system and a slowdown in the demand would drive to a reduction of air pollutants.
The following charts in *(Figure 3.10)* show the multiple RCPs parameter trends.

[87] Mitigation, adaptation and impact on climate change concepts will be addressed in *Chapter 4.*
[88] See *Section 2.7* for the various influences of land on climate.
[89] With the term "pollutants" a lot of agents are included. However, the ones of which the impacts on urban population have been deeply studied are Sulphur dioxide (SO_2), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), particulates and Volatile Organic Compounds (VOCs) [53].

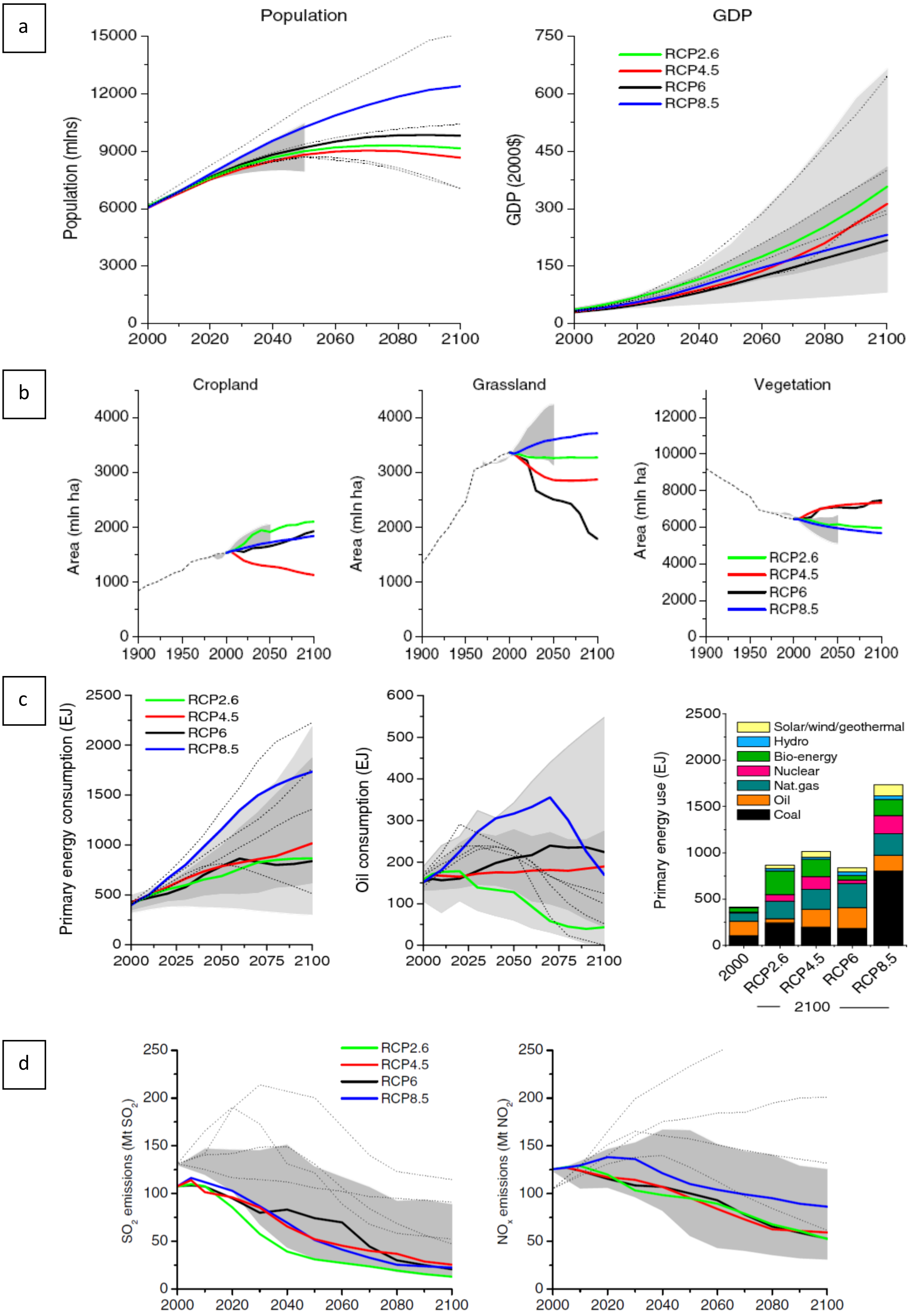

Figure 3.10 | Climate models: future scenarios – RCPs. (a) Population and GDP projections. (b) Land use changes (crop and grassland) and vegetation. (c) Development of primary energy consumption, oil consumption and share of the primary energy use by 2100. (d) Pollutants emissions (SO_2 and NO_x trends are displayed but the remaining pollutants show coherent curves). Credits: "The representative concentrations pathways: an overview", Van Vuuren et al. (2011)

- ### 3.3.4.3 - RCPs: GHGs annual emissions, concentrations, GMT

Focusing on GHGs emissions - concerning the CO_2 - RCP8.5 trends increasingly to reach about 30 gigatons of carbon (GtC) every year by 2100. RCP6, RCP4.5 and RC2.6 peak and then start to decline prior to 2100, with different timings *(Figure 3.11-up)*. RCP2.6 peaks by 2020 and starts to decline gaining net negative emissions by 2080 thanks to CCS[90] and bio-energy use.

As regards CH_4 and N_2O, emissions show a rapid increase for RCP8.5 due to non-climate policy and strongly growing population. A peak and a more-or-less stable tendency for RCP6 and RCP4.5 scenarios is foreseen. RCP2.6 outlines a reduction by around 40% by 2100 [35].

Turning from atmospheric emissions to concentrations some grade of inertia by the climate system is visible. The only pathway contemplating a decline in CO_2 atmospheric concentrations is RCP2.6, peaking at around 440 ppm by mid-century. As for RCP4.5, concentration continues trending up until 2070 reaching 520 ppm and then keeps increasing but with a slower rate. RCP6 shows a continuously increasing concentration with high rate until 2060, reaching 620 ppm by 2100. RCP8.5 finally, projects a CO_2 concentration exponential acceleration, reaching 950 ppm by 2100, continuing to increase for 100 years [35].

The different scenarios' N_2O and CH_4 concentration is influenced by the choice in climate policy too. Trend for CH_4 is similar to the one of CO_2 but more pronounced, due to the relatively short methane

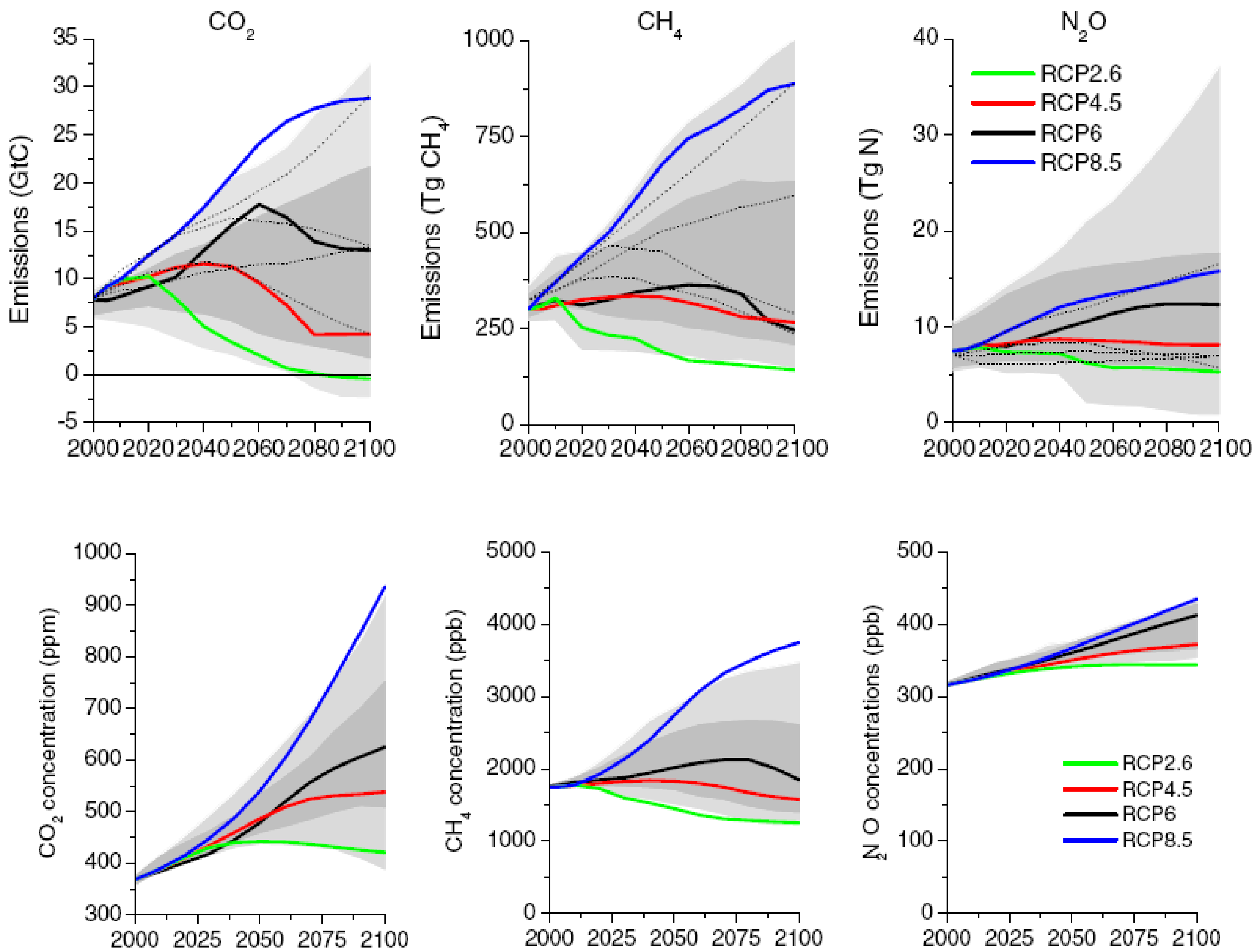

Figure 3.11 | Climate models: future scenarios – RCPs. (up) Emission pathways for major GHGs: CO_2, CH_4 and N_2O. (bottom) Concentration projections for the same gases. **Credits: "The representative concentrations pathways: an overview", Van Vuuren et al. (2011).**

[90] CCS stands for Carbon Capture and Storage. See **Cap. Par**.

atmospheric lifetime. RCP2.6 and RCP4.5 lead to an earlier peak and consequent decline, while RCP8.5 projects increasing levels reaching almost 4000 ppb by end of century. Trend for N_2O concentration in contrast, is increasing for all scenarios, given the modest reduction potential[91] and the relatively long lifetime.

RCPs finally, give four different outputs also for the Global Mean Surface Temperature (GMST). GMST is projected to rise under all four scenarios over the 21th century ***(Figure 3.12-left).*** RCP2.6 is the only pathway in which temperature stabilizes by 2100 and the temperature increase do not exceed 2 °C warmer than pre-industrial values[92]. GMST change until 2035 is similar for the four RCPs, likely in the range 0.3-0.7 °C. After that period the three scenarios diverge, with RCP8.5 reaching a warming of 3.7 °C and the two intermediate scenarios rising until +2.2 °C (RCP6.0) and +1.8 °C (RCP4.5) by 2100 [1]. Temperature change will not be regionally uniform with the Arctic region projected to warm more rapidly than the global mean.

- 3.3.4.4 – RCPs: other changes, extremes, ocean and sea level and warming

On a general basis, temperature extremes will be more frequent. More hot extremes and fewer cold extremes are expected as GMST rise. Number of days with temperature above 20 °C will be rising for all scenarios with the only RCP2.6 staying under 20 days/yr, while exceeding for RCP8.5 the 50 days/yr by 2100[93] [35].

Precipitations are projected to increase globally, but with regional differences: the higher latitudes are likely to increase the annual precipitation rate, while in mid-latitudes and subtropical regions a decrease is expected, drying more these areas as a result. Extreme precipitations will be more likely in a warming world. Under RCP8.5 droughts and soil moisture shortage are projected to increase in presently dry zones.

Flood projections are uncertain to due to lack of observations. Global ocean temperature and global mean sea level will continue to rise in the 21th century under all RCPs scenarios. Ocean warming is projected to increase on a rather wide range, going from +0.6 °C (RCP2.6) to +2.0 °C (RCP8.5). Sea

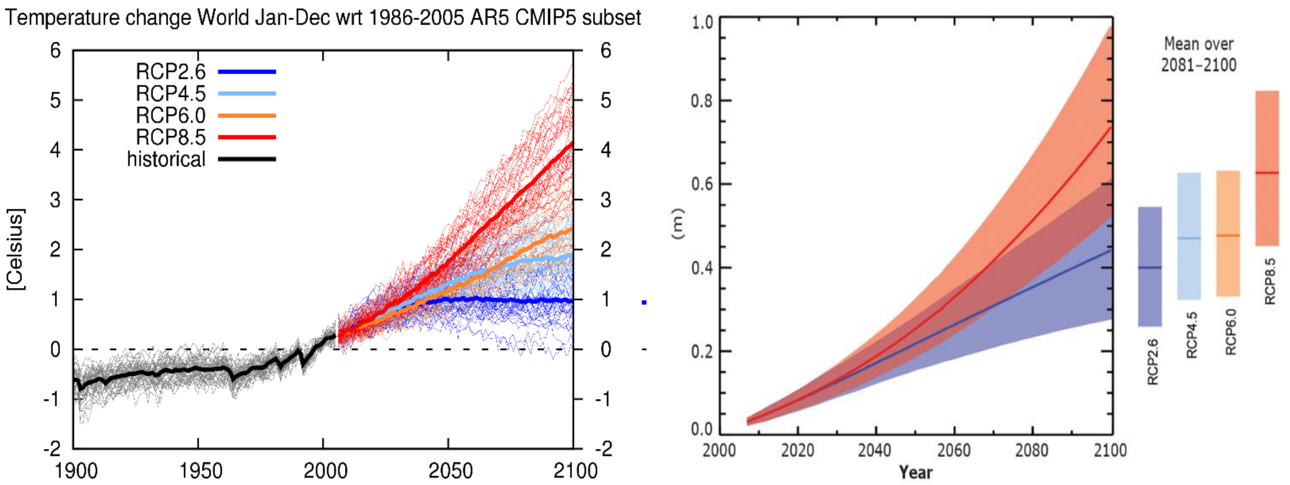

Figure 3.12 | Climate models: future scenarios – RCPs (left) Temperature changes for RCP2.6 (dark blue), RCP4.5 (light blue), RCP6.0 (orange) and RCP8.5 (red) with respect a baseline period of 1986-2005. (right) Sea level rise projections according to the four scenarios. **Credits: https://global-climat.com/2015/12/21/la-sensibilite-climatique-reevaluee-par-la-nasa/ (left). IPCC Fifth Assessment Report (2014) (right).**

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[91] Main sources of N_2O are agricultural. They are projected to grow modestly but they are also difficult to abate [35].
[92] In ***Figure 3.12***, 1986-2005 is used as baseline period so warming is less remarkable. "Pre-industrial level" means since 1750, unless otherwise indicated.
[93] To give an idea of the phenomenon, during the period (1961-90) only *three to four days above 20°*C on average occurred per year.

level rise will stay between the 0.26-0.82 m by 2100, with regional differences and yearly increasing rates hitting 16 mm/yr for RCP8.5. [1, p. 60]

Reductions in Arctic sea ice extent are likely for all the RCPs. The most adherent-to-observations scenario is RCP8.5 providing a nearly ice-free Arctic Ocean in September before mid-century[94]. Northern Hemisphere total spring snow cover will decline by 7% for RCP2.6 and by 25% for RCP8.5 by 2100. Permafrost area is projected to decrease by 37% (RCP2.6) to 81% (RCP8.5). Global glaciers volume is likely to decline by 15 to 55% for RCP2.6 and by 35 to 85% for RCP8.5 by the end of the century [36, p. 62].

- 3.3.4.5 - RCPs: a link between concentrations and temperature

As stabilizing CO_2 does not translate into stabilizing temperature in a short time[95], the IPCC defines two other metrics needed to identify the link between CO_2 concentrations and temperature changes: Transient Climate Response to Cumulative CO_2 Emissions (TCRE) and Equilibrium Climate Sensitivity (ECS). Multiple and undeniable evidences show a near-linear relationship between net cumulative emissions and projected GMST change by 2100 got once Earth has adjusted, after the climate perturbation.

Transient Climate Response to Cumulative CO_2 Emissions (TCRE) estimates the warming expected at a given time per unit cumulated CO_2 emission. The reference unit of cumulated CO_2 is usually taken as 1000 GtC. TCRE provide the information on the transient climate response linked to the fraction of total CO_2 released remaining in the atmosphere. One of the most likely value of TCRE is in the range 0.8-2.5 °C per 1000 GtC emitted as CO_2[96] [37, p. 1033]. Through the TCRE, a relationship between cumulative carbon emissions and the consequent temperature change is used to estimate the remaining carbon emission budget for humanity, considering the warming not to exceed 2 °C (preferably 1.5 °C) as the COP 21 pledges state. According to this benchmark, 2 °C more in GMST corresponds approximately to 1100 GtC cumulatively emitted. Given the 540 GtC released from the start of the recording in 1850 until now, humanity have a carbon budget of 560 GtC left in order to stay below a 2 °C warming.

RCP2.6 is the only scenario projecting cumulative emissions < 560 GtC not breaking the limit by 2100. The two intermediate scenarios estimate the carbon budget reached by 2064 (RCP4.5) and by 2062 (RCP6.0), while the RCP8.5 outlines the carbon budget shortage by 2048 [38]. These numbers have been updated in the IPCC SR15 according to which the budget for staying below the 2 °C is 1070 GtC and will be exhausted in 26 years at the current rate of GHG emission. 1.5 °C corresponds to around 420 GtC left. They will be used up in nine years at current rate of GHG emission.

The Equilibrium Climate Sensitivity (ECS) is the equilibrium change in annual GMST following a doubling of atmospheric CO_2 concentration. Estimates based on CMIP models indicate an ECS mean value of 3.2 °C [41]. ECS evaluates the eventual warming in response to a stabilization of atmosphere composition.

- Focus 2 - An additional scenario: what if we stopped emission today?

After having covered the whole set of climate model scenarios available now in scientific literature, just to give the idea of the current situation, it is important to clarify one last thing: what if the World suddenly stopped all kind of emission today?

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[94] "Ice-free" here means when sea-ice extent is < 1 Mkm^2 for at least five consecutive years [1, p. 62].
[95] In order to stabilize temperature, it is required a balance between energy inflows and ouflows within theGlobal energy Balance (GEB). See *Section 2.2.*
[96] The most commonly used value is 1.8°C every 1000 GtC.

Well, even if the "stop-all-emissions today" scenario is not absolutely plausible at the moment, it can be an idealized case useful to display the timeliness of the climate system and carbon cycle responses. Due to the Oceans' large thermal inertia and to the long lifetime of many GHG[97], the warming would persist for centuries after the emissions have stopped.

Aerosols have a short lifetime of weeks, methane (CH_4) of 10 years, nitrous oxide (N_2O) of 100 years, hexafluoroethane (C_2F_6) of about 10,000 years. Carbon dioxide's lifetime is more complicated to assess as it is exchanged continuously within the carbon cycle. It can be said that roughly the 15 to 40% of the CO_2 stays in the atmosphere for about 1000 years, whereas the remaining part is absorbed by land, plants and oceans[98]. Therefore, GHG concentrations would not return at pre-industrial levels at timescales consistent for today's human society: methane (CH_4) would return to pre-industrial levels in approximately 50 years, nitrous oxide (N_2O) in several centuries and carbon dioxide (CO_2) even more [37, p. 1106].

To conclude, if the pace of the Earth's recovery from the GHGs intoxication would be slow in terms of return to pre-industrial level concentrations, the climate response would be even slower, because of the huge heat capacity of oceans: it would take several centuries for the Oceans temperature to reach an equilibrium with the new radiative forcing corresponding to the halted GHG emissions. In other words, projections show that - contrary to what everyone thinks - the long-term global temperature is controlled by the total CO_2 emitted and accumulated overtime, rather than by the right-now concentration levels. For this reason, stopping the GHG emissions overnight would lead the climate system to a near constant temperature for many centuries [37, p. 1106].

[97] See *Section 2.5.*
[98] See *Section 2.5.2.*

CHAPTER 4 – DESTRUENS (IMPACTS) AND COSTRUENS (MITIGATION AND ADAPTATION ACTIONS)

Once that all the mechanisms and processes driving the climate system and causing the climate to change have been addressed, it is fundamental to refer to a human dimension of this century's major issue. "Human dimension" means to move from the series of scientific numbers and facts shown in *Chapter 2 and 3* to consequences that are human-related, which may affect deeply our everyday life. This implies to understand the concrete impacts on human settlements and society all around the World of sea level rise, droughts, deforestation, air pollution, warming, etc. The major intergovernmental institutions have been trying to provide policy frameworks, roadmaps, timetables to Governments and public opinions, in order to act against the biggest challenge of nowadays' world. With the aim to mitigate the poisonous activity of climate change, ways to reduce GHG emissions by working with the energy systems must be explored and at the same time - as an undeniable awareness exists that these changes are inevitable and even yet occurring - strategies to adapt to the impacts of climate change must be pursued.

For this reason, one of the major themes of this Chapter will be action. Action which is carried on by individuals, companies and governments around the world. The first part of the Chapter will discuss the biophysical and human impacts of climate change, with a focus on the repercussions on human life that sea level rise, floods or heat waves can have. The magnitude of these impacts on communities can be really different as a function of their degree of development, wealth, access to services, literacy, etc.: climate change impacts are not democratic. The related concepts of vulnerability and resilience will be introduced.

After that, the second part of the Chapter addresses the solution part of the climate change issue. A focus on technologies, cultural and behavioral drivers underpinning the climate change mitigation is provided.
The third section deals with adaptation. Community vulnerability, links with poverty and humanitarian crisis, ethical questions and building up resilience are addressed. The scale of this challenge is pretty dramatic, but all the technologies, innovations and solutions to heal the wounds of climate change are already available.

- 4.1 – UNDERSTAND CLIMATE CHANGE IMPACTS CORE CONCEPTS

<u>Key points</u>

Impacts are only second and third-order effect of a changing climate, often referred as the damage report. In order to focus on the climate change impacts, some concepts must be introduced. Vulnerability is defined as the degree to which a system is susceptible to and unable to cope with adverse impacts; it represents the convergence of exposure and sensitivity towards them and it is influenced by adaptive capacity and resilience. Adaptive capacity is the ability of a system to successfully respond to climate variability, while the strictly related concept of resilience is the amount of change the system can undergo without changing its state fundamentally. Uncertainties exist about the assessment of climate change impacts, but real actions towards them must be taken now.

- 4.1.1 – Vulnerability

The phrase "climate change impact" refers to those phenomena occurring as a result of the processes discussed in *Section 3* such as rising temperatures or precipitation changes. In other words, these are the so-called first-order effect of a changing in the climate system. Second and third-order effects are the ones that are directly experienced, providing a tangible signal of climate change such as longer growing seasons, human health repercussions during heat waves, endangered species, etc. The Impact of climate change can be thought as a cause-effect chain: rising sea level for instance is a second-order impact of global warming, occurring mainly due to the melting of land-based glaciers and thermal expansion of water[99], sea levels rising can lead in turn to floods, erosion damage or altered ecosystems. These last ones are the third-order impacts of climate change.

These effects are said to be the damage report of all the anthropogenic drivers that have altered yet and are currently altering the climate system, the most important of which is the mass combustion of fossil fuels. Depending on the magnitude of the global warming, the extent of the impacts will be varying accordingly. A rule of thumb often reported in this context estimates standard impacts as a function of the Global Mean Surface Temperature (GMST) rise: it starts from the bleaching of all coral reefs at about + 1.5 °C, sharp declines in crop yields at + 2.5 °C, and species extinctions starting at + 3.0 °C [2].

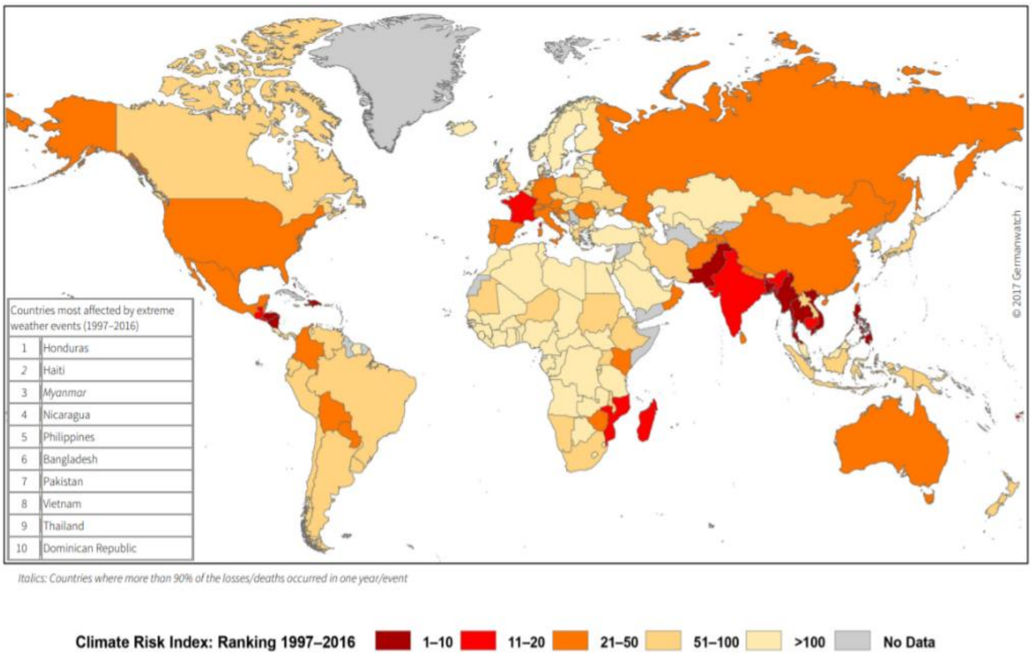

Figure 4.1 | <u>Climate Change Impacts: Vulnerability and Resilience.</u> The map comes from a deep analysis to what extent countries and regions worldwide have been affected by impacts of weather-related loss events (storms, floods, heat waves, droughts, etc.). The most recent data are taken into account for the period from 1998 to 2017. Most affected countries are ranked in a decrescent way. Credits: Germanwatch's "Global Climate Risk Index", 2019.

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[99] See *Section 3.1.2.*

However, the definition of the impacts requires a cross-sectional approach taking into account not only the magnitude of the climate change drivers, but also the interaction of climate-related risks with other biophysical and social drivers.

A key concept to deeply focus on this interaction is ***vulnerability***. An exhaustive definition of vulnerability is provided by IPCC as the "propensity or predisposition [of the climate system, ed.] to be adversely affected" by climate change. Vulnerability to climate change impacts is the convergence of exposure to impacts and the sensitivity towards them. According to the risk analysis theory, by which the risk of an unwanted event is the product of severity (the amount of damage assigned to a hazard) and frequency (the likelihood of occurrence of the hazard), vulnerability considers both the level of sensitivity of climate system and the likelihood to experience related impacts. In other words, a system is not considered highly vulnerable if it is highly sensitive, but at the same time unlikely undergoing to climate change impacts *(Figure 4.2-left and right).* To give the idea, a house built low to the ground without drainage systems and ditches protecting it, but not even near the coastline or floodplain, would be considered "sensitive" but not "vulnerable", being not exposed to damage. In the context of climate change impacts, vulnerability allows to assess the degree to which a system is susceptible to and on the other hand unable to cope with, adverse impacts.

A distribution of different vulnerabilities around the globe in a high temperature future can be identified as a function of multiple factors, including geographical position, pollution, degree of development and socio-economic parameters. A key concept of vulnerability clearly visible in *(Figure 4.1)*, is that it is not democratic. Poorer and developing countries are more likely to be affected by climate change impacts, that are yet caused mainly by the developed ones. Based on the *Global Climate Risk Index, 2019* - released at Katowice Summit - Puerto Rico, Sri Lanka, Nepal, Bangladesh, Honduras and South Asian countries in general, are ranked as world's top most vulnerable countries. The extent of the impacts of climate related events can be conveyed by the 526,000 people died worldwide and the (USD) $3.47 trillion as a result of extreme weather events in the period between 1998 and 2017 [3].

- 4.1.2 - Assessing system's vulnerability and adaptive capacity

As moving into uncertain future – but certain concerning the fact that will be warmer and generally unhealthier – criteria must be identified to assign different levels of vulnerability to different human and

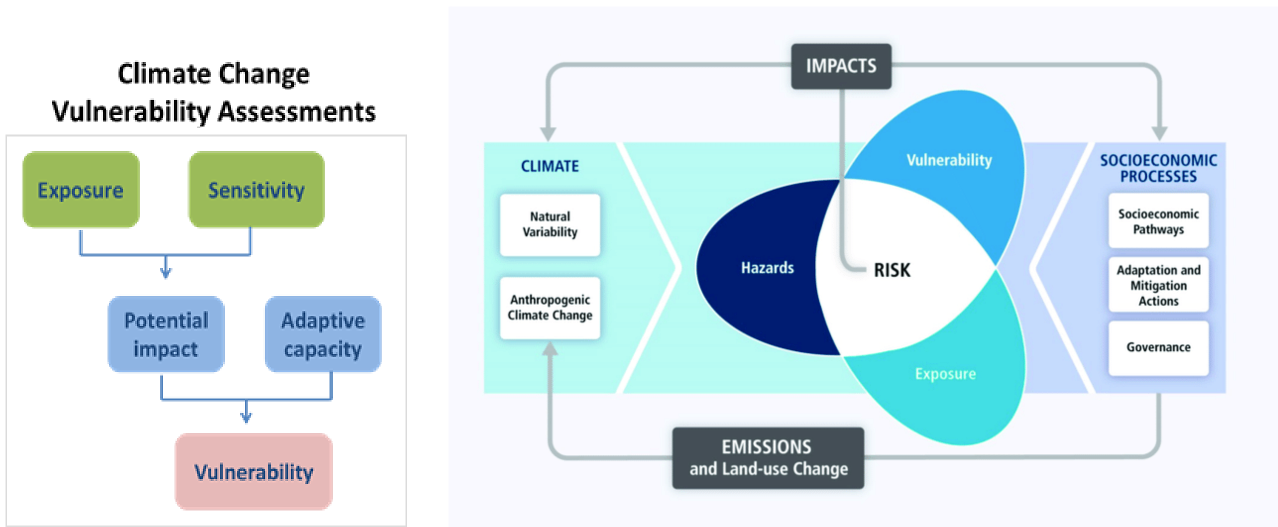

Figure 4.2 | Climate Change Impacts: Vulnerability and Resilience. (left) Relationship among the three major components of vulnerability: exposure, sensitivity, and adaptive capacity. (right) Schematic overview of the revised IPCC concept of risk, showing the interaction between vulnerability, exposure and hydro-meteorological events. Credits: (left) ***http://www.jamesford.ca/wp-content/uploads/2017/12/Inuit-Index_Arctic_Change_2017.pdf***. (right) adapted from IPCC Fifth Assessment Report, 2014.

natural systems. Examples of vulnerability determinants are the magnitude and the timing of impacts, their persistence or reversibility, their distribution and likelihood to occur. Another important vulnerability driver is the potential of the "vulnerable" system for adaptation, or the so-called ***adaptive capacity***. As said, developing countries are more vulnerable than developed ones: not only stronger impacts are expected in a developing country rather than in a developed one, but also lowered potential for adaptation. Adaptive capacity (or adaptation) is the other key element to fully understand vulnerability. It is defined broadly as the ability or potential of a system to successfully respond to variability and change[100] [4]. When talking about a climate system, adaptive capacity relates to the process of adjustment to expected climate change effects, aiming to moderate or avoid their harms and exploiting beneficial opportunities [5]. Adaptive capacity factors range from access to technologies and information, to the exploitation of knowledge skills, from the development of infrastructures to policies from governance and institutions. However, adaptive capacity represents only a potential to respond to climate change; it has an influence on vulnerability but does not state whether a region will be affected by climate change impacts.

- 4.1.3 – Resilience and related uncertainties

Another key concept in the Science of climate change impacts, is that of ***resilience***. If adaptive capacity deals with the ability of human systems to respond to climate change, resilience is the equivalent referred to natural systems: it represents their ability to return to a healthy state following a shocking change or a perturbation. Resilience can be defined for a socio-ecological system, both as its capacity to absorb shocks performing the same function after and without changing state, or as the ability to reorganize, change or evolve into more desirable configurations, improving the sustainability of the system leaving it better prepared to future changes [6] [7]. The resilience of a system depends on its so-called ***coping range,*** that is the amount of change a system can absorb without significantly shifting, as defined in the Climate Change Synthesis Report Glossary from the Intergovernmental Panel on Climate Change (IPCC). Adaptation acts with the aim of expanding the coping range, raising the threshold beyond which the system changes, enhancing its resilience as a result. Enhancing the climate system's resilience, means making that system less vulnerable to climate change impacts.

Once that the core concepts of vulnerability, resilience and adaptive capacity have been introduced, the focus can be shifted on the more tangible real impacts that are being experienced worldwide, keeping in mind that a degree of uncertainties is inherently present for some reasons:

- uncertainties rise on the way human system will respond. Even at the moment, in which the climate issue is becoming impossible to ignore, no great countermeasures seem to be taken or major debates to be pursued by the public opinion;

- uncertainties rise on the amplitude of the risks connected to consequences of global warming, if it is going to exceed certain thresholds. In other words, if the GMT rise exceeds the 3 °C, estimates certainness keep falling dramatically.

- natural and human systems are intrinsically highly complex.

A possible pathway to study climate change related impacts starts from emission scenarios, analyzes the carbon cycle response, then assign a global climate sensitivity, elaborates possible regional climate change scenarios and ultimately infers a range of possible impacts. Uncertainty grows as moving from the first steps towards the last ones [8]. Science will never be able to predict incontrovertibly and flawlessly the behavior of human and natural systems, but climate adaptation and mitigation are nevertheless essential.

[100] The concept of adaptive capacity applied to climate change has been borrowed from Sociology and Philosophy of Science in which it refers to changings undergoing to human and social systems.

- 4.2 - CLIMATE CHANGE IMPACTS: WHAT HAS HAPPENED AND WHAT IS HAPPENING

<u>Key points</u>

A variety of climate change impacts are currently being observed on natural systems. The terrestrial ones include extinction of many amphibian species, poleward migration of thousands of species, shifting timing and geographical zones of multiple natural events like flower blooming or bird's egg laying, changing crop yields and the abnormal growth of forests and invasive species. As for the coastal systems, coastal erosion and marshlands degradation are yet occurring. As regards the impacts on water, multiple stressors must be considered. Increasing temperatures are leading to coral reefs bleaching. The increasing concentration of carbon dioxide in the atmosphere is linked to higher acidity of the ocean. This affects strongly corals and the other marine creatures foundations of the food chains. Oceans circulation patterns are being affected as well by salinity and temperature changes. Fish migration and abundance are considered to have been substantially changed during the last decades. Being microcosms with proper characteristics, urban areas experienced and will be experiencing the toughest climate change impacts.

Evidences undeniably proof that ecosystems worldwide are already experiencing impacts. In some cases, these are only signs of major impacts that are to come in a near future, while in others they can bring entire communities to their knees, destroying their socio-economic backbone. In order to perceive the concept of climate-related impacts, it is crucial to think about the planet system as a whole. Does a bleached coral in Australia matter to a Sicilian farmer or a plumber in Berlin? Yes, it definitely does. The impacts in climate change exerts cascading influences that can start from a single process and then reverberate all around the globe.

- 4.2.1 – Impacts on Land

The broad Science that analyzes the ecosystems[101] knows that plants and animals live within particular climatic conditions in terms of ambient temperature, water availability, nutrients, etc. The success of one type of ecosystem (or species as well) over another, has leaded to their current distribution around the planet. For that reason, if climatic conditions change plants and animals will respond consequently. Furthermore, if these conditions go beyond the tolerance of a species, it may result:

- a shift to earlier or later in the season of annual natural events like mass migrations or blooming;
- species move to different locations, towards geographical site providing better climatic conditions (i.e. pole-ward);
- a changing in shape, reproduction or even genetic heritage, through the natural selection according to the Darwinian theory;
- if suitable conditions cannot be found, plant or animal species would become endangered or even extinct.

Multiple regions in the world have experienced these kinds of impacts, which were driven by climate change or through other mechanisms such as conversion to agriculture or human settlement[102]. Here it is a brief summa.

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[101] The term Ecosystem is defined by the Cambridge Dictionary as "all the living things in an area and the way they affect each other and the environment". Ecosystem's scale can range from very small to the entire biosphere.
[102] All these cases are comprised in the wider concept of Land Use Change (LUC) [10].

In North America and in Europe, leaves are unfolding progressively earlier in the spring in response to the higher temperatures recorded during the decade about to finish [11]. According to the NASA's *Arctic Boreal Vulnerability Experiment* (*ABoVE*) the tree line - or the boundary between habitable and inhabitable environments, circling for around 13,300 km landmasses of North America and Eurasia forming the longest ecological transition zone on Earth - is shifting to higher latitudes and elevations[103].

In Europe as in North America bird species seem to be deeply affected by the warming experienced. Egg-laying dates occur earlier in the season and several bird species no longer migrate out of Europe. These modifications in annual cycles of birds are caused by mismatches in food supply, snow cover and ambient temperature driven by climate change [12]. Significant northward shift of 329 species have been observed in the UK alone due to the extension of their livable ecosystems to northern regions that were previously cooler, as southern ones shrink with the temperature rise [13].

Extinction of amphibian species - which are considered to be particularly sensitive and vulnerable to climate change - have been recorded worldwide: the rise of temperature has led recently to the explosion of a fungus that has proved to be fatal for hundreds of amphibian species[104]. Important hallmarks of climate change impacts are the outbreak and the domination of plant or animal invasive species (e.g., in Southern Europe species of barnacles have overtaken their northern counterparts, reproducing more rapidly thanks to the warmer ambient conditions). The implications for biodiversity are rather serious; impacts of the biodiversity reduction reflect also on the terrestrial ecosystems that are directly bonded to humans.

Longer growing seasons, the fertilizing effect of rising CO_2 concentrations as well as precipitations changes, have led to an increase in vegetation growth over 25% to 50% during the period 1982-2009 in both the Northern Hemisphere and the tropics [14]. On the agriculture front, some crops like wheat, rice and maize in tropical and temperate regions are projected to be negatively affected by a local temperature increase of 2 °C (or more) above the late 20th century levels, while others will expand their range; for instance, hay in the United Kingdom and rice in the Philippines have gone down yet. This would pose large risks to food security, overall [5].

As seen in *Section 3.1.2*, the rising temperature leads to thermal expansion of oceans' water and the rapid melting of land-based ice: for these reasons, rising sea levels is becoming a serious concern. Sea levels rise, combined with coral bleaching and mangrove clearance is contributing to coastal erosion. The US East Coast is eroding in the 75% of its shoreline [15]. Beaches and shorelines are eroding in Fiji, Canada, UK, Australia and Southeast Asia as well. The result is that particularly sensitive habitats as the intratidial zones and tropical mangroves, are being strained between higher sea levels and uninhabitable inland geography. Altered tidial dynamics, sea level rise, together with human activity like land clearance for development is weakening wetlands and marshlands too. Both of them play fundamental roles in the ecosystem, including water purification, carbon storage and natural barrier provision against flooding. Degradation of marshlands has been observed in Louisiana after hurricanes Katrina and Rita [16] or on the Atlantic coast of New Jersey after the hurricane Sandy [17]. Transformations have been noted also on the Thames Estuary in the United Kingdom: due to change in wave energy and sea level rise, the Ocean overtakes wetlands on the coast with the so-called *coastal squeeze* phenomenon [18].

Coastal areas provide a classic example of high vulnerability system, because of the multiple influences by different impacts from human agents. For instance, dams prevent sediments from reaching deltas and consequently forming wetlands. The massive use of fertilizers undermines nutrients cycling within

103 In the Northern Hemisphere, climate is warming more rapidly than the global average. Both tundra and boreal forests are undergoing massive shifts [12].
104 This single chytrid fungus called *Batrachochytrium Dendrobatidis* has driven more than 200 amphibian extintions, representing a global threat to biodiversity [15].

these systems, causing mangroves to encroach on other wetlands. After that, storms, extreme weather events and higher sea levels act on coastlines, which are left more fragile by bleached coral. The paleoecological records show that ecosystems and biota of a planet undergoing to climate changes - comparable in magnitude with those projected for the ongoing century – result in large-scale shifts and extinctions. Many plant and animal species will not be able to adapt under the mid- and high-range rates of climate change (RCP4.5, RCP6.0 and RCP8.5 scenarios). Some low-lying areas in developing countries are expected to suffer more from coastal flooding and erosion, resulting in associated damage of several percentage point of GDP [5, p. 67].

- 4.2.2 – Impacts on water

Impacts that are relevant for the 75% of the planet are those involving marine ecosystems and freshwater. Oceans ecosystems are crucial for human society. As seen, oceans and seas are key elements for the climate system. On the one hand, they modulate the global environment through bio- and geo-chemical cycles and at the same time act as huge sinks of carbon and heat thanks to the large thermal capacity of water. On the other, they provide a home for many marine species which are not only fundamental in terms of biodiversity, but obviously also from a human socio-economic point of view[105]. Oceans create half the oxygen (O_2) we use to breathe or burn fossil fuels and provide some 17% of the world's population animal protein consumption through fishes.

Oceans ecosystems like mangroves and coral reefs provide fundamental natural barriers to coastlines against storms and tsunamis. The effect of climate change on the oceans is probably hiding in plain sight, but nevertheless it is undeniably ongoing. Oceans suffer from multiple coinciding impacts. Besides rising sea levels and acidification, other direct consequences of human activities put pressure on the oceans including overfishing, pollution (e.g., oil spills, microplastics, etc.) and the introduction of non-native species[106] that results in altering the balance of the ecosystem.

As the ocean's temperature rise, corals are one of the first creatures to be affected. Normally, corals live in symbiosis with algae that provide the 90% of coral's energy. Global warming is responsible for the expulsion of these algae by coral polyps: this is the so-called phenomenon of ***coral bleaching*** and starts occurring when temperature rises about 1 °C above-average for a period of two weeks. Most bleached corals starve after bleaching and do not recover. The period between 2014 and 2016 - considered to be the hottest ever recorded [19] - is responsible for the bleaching of 29% to 50% of corals on the Great Barrier Reef [20]. During the year 1998 - ranked ninth on the hottest ones record - the 16% of the world's corals died in a single event. Even if the role of climate change in coral bleaching is undeniable and proofed, it is still tough to disentangle the effects of climate change from other natural or anthropogenic-driven processes occurring in the Oceans. Pacific decadal oscillation and El Nino Southern Oscillation take a role in shifting ocean temperature on a yearly basis. Overfishing, pollution and even the atmospheric CO_2 concentration directly affect the life of corals too, making them one of the more complex ecosystems on Earth.

When thinking about fossil fuels combustion, the major concerning issue is the one involving the GHGs released in the atmosphere, but there is another way the carbon released can affect the planet: trough ***ocean acidification***. Actually, much of the carbon dioxide released in the atmosphere get ultimately absorbed by the planet's water sinks. The 30 to 40% of the atmospheric CO_2 from human activity dissolves into oceans, rivers, seas, lakes, etc.[107] Once there, reacts with water (H_2O) to form carbonic

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[105] About the 40% of World's population lives in coastal areas within 100 km of the coast. Human activity in those zones is highly affected by oceans and seas, which become the building blocks of their economy and society.
[106] "Non-native species" are those introduced to new areas artificially by humans [21].
[107] See *Section 2.6.2.4.*

acid (H_2CO_3). Then, hydrogen ions (H^+) and bicarbonate ions (HCO_3^-) are formed; consequently, the bicarbonate ions produce other hydrogen ions and carbonate ions (CO_3^{2-}). The higher the concentration of hydrogen ions, the more acidic the ocean gets. Ocean acidification has multiple impacts on marine ecosystems and creatures. It has been shown that this process reduces the ability of some plankton, reef-building corals and mollusks to produce their shells using calcium carbonate [21]. The scale of this phenomenon is nothing but huge, since these organisms are the foundation of the food chain and create habitats for other fundamental marine creatures as the coral reefs. Current estimates state that the acidity of oceans has risen by 30% since the Industrial Revolution dropping in terms of pH from 8.2 to 8.1 and it is expected to fall by another 0.3 to 0.4 by the end of the century [22].

Oceans not only are huge thermal and carbon sinks, but also act as heat conveyor belts with a constantly moving process. Deep-ocean circulation make approximately the same amount of thermal energy to move as the atmosphere does. The process is driven by temperature and salinity and for this reason it is also called *thermo-haline current*. The difference in density between salty cold ocean water and warmer fresh water from ice melting and rivers is the main driving force of the process. If the inflow from ice melting rises, the conveyor belt can slow down overtime [23]. Thermohaline currents are also forced by heat flows through convection. Climate models have shown that the warming associated to a quadrupling of CO_2 would cause an abrupt shutdown of the Atlantic Ocean Circulation (ACO)[108]. ACO is currently at weakest point in 1,600 years of recordings due to both warming and melting processes [24].

Marine beings and fishes must adapt to changing condition as well as animals on land do. Ocean temperature changes are not uniform. As freshwater ice melts and flows into the ocean, its salinity changes, causing plankton and other creatures that are the base of the food chain, to move out of their territory. Shifts in fish migration timings have been observed in lakes and rivers, occurring on average six days to six weeks earlier than they did both in East Africa and in Europe. These global marine species shifts coupled with some grade of biodiversity reduction will stress fisheries productivity especially at low latitudes, challenging the developing economies [5, p. 67]. The distribution and the abundance of many fishes and invertebrates are shifting poleward and towards deeper or cooler water. All these large and mainly irreversible shifts in distribution of species are projected to have severe implications for the planet's ecosystem.

Ongoing oxygen depletion is leading to a vertical expansion of the Oxygen Minimum Zone (OMZ)[109] - observed over the last 50 years - forcing the usable habitat for various fish species (e.g., billfishes, tunas, etc.) to shrink. This phenomenon may be associated with a 10-50% worldwide decline of pelagic predator [25].

As seen, climate change impact on oceans displays itself in multiple ways; many impacts are yet occurring simultaneously due to various drivers, from higher temperatures to higher water acidity and salinity. The wide range of factors intervening in climate change related impacts, makes however the role attribution to various phenomenon, rather complex.

- 4.2.3 - Impacts on urban centers

The trending up urbanization has brought more than half of the Planet's population into cities and the outstanding development going on in these areas has concentrated there services and goods. In addition -for the sake of logistical efficiency - energy systems, water and food supplies and finally transports have become centralized. These are the main source of vulnerability, that makes urban agglomerations places

[108] Atlantic Ocean Circulation (AOC) is the primary responsible for the pleasant balmy climate in Europe.
[109] OMZ is referred to a zone in seawater in which dissolved oxygen saturation is at its lowest level. It occurs at depth from 200 to 1500 meters in depth, when oxygen concentration falls from the canonic range of 4-6 mg/liter to below 2mg/liter [28].

particularly exposed to climate change impacts ranging from citizens' affected health, to economic losses from extreme events and the creation of environmental refugees. Vulnerabilities and impacts related to climate change in the urban context are maybe the ones that can commonly be grasped more.

Cities present a unique set of characteristics within which climate change impacts act, making them particularly vulnerable. The 54.7% of world population lives in urban areas [26] and the 68% is projected to live there by 2050 [27]. Cities house most economic activities and services, and they are consequently responsible for the larger share of GHG emissions. For this reason, a focus on climate change impacts on urban areas is essential.

The fact that world population living in urban areas overcame the one living in rural areas[110], may not be surprising for Europeans and North American citizen, but is nothing but a revolution in such zones as Africa, China, India, etc. Cities - especially the ones in developed country - are the most significant sources of GHG: they consume alone more than two-thirds of world's energy consumption and account roughly for the 75% of global GHG yearly emissions. Besides that, cities are also particularly vulnerable to climate change impacts. A key vulnerability is the extremely high population density causing potentially catastrophic loss of lives in case of extreme events (more serious than in sparsely populated rural areas). Also the cost of extreme events increases in urban areas, given the massive investment done in infrastructures and services in such zones. Moreover, cities are often relatively disconnected from the sources of food. This makes them more vulnerable also in case of food-system's disruptions. Other important element of cities' vulnerability is a "logistic" one. The increasingly centralized systems of energy provision and food or fresh water distribution, are more susceptible to large-scale malfunctions and temporary shut-downs that potentially can be deadly for more people, compared with the more resilient decentralized systems.

Cities have always presented unique challenges to human health. The effects of industrialization on citizens are known since the First Industrial Revolution. A rise in cancer, obesity and arthritis has been observed in men and women living even in the late 1700s' London [28]. These challenges and effects are only expected to be exacerbated by climate change in the decades to come. However, one of the major dangers for today's urban areas is certainly represented by extreme weather events. Heat waves are one of the plainest examples of extreme events. During the 2003 heat wave, over 70,000 people died in Western Europe (40,000 in France and Italy alone) [29]. Most of these were the more vulnerable part of the population, such as the elderly or the sick.

Besides the high density of population per square meter, another key element of cities vulnerability for is the so-called Urban Heat Island (UHI). According to the UHI phenomenon, the metropolitan area is generally warmer than its surroundings, due to multiple factors. The UHI effect in particular, is a result of concentrated dark paved surfaces covering the parts of the urban area and the waste heat from energy usage, transportation and all the other human activities taking place there. The effect is more marked at night than during the day. The temperature difference driven by the UHI effect is normally between 1 to 3 degrees Celsius with respect to the surrounding areas. This leads to an even intensified series of climate change impacts. By late-century the largest urban agglomerations will be exposed to temperature rises ranging on averages from 2.5 °C under the RCP2.6, to over 5 °C under the RCP8.5 [10]. It must be stressed that these are average values, meaning that peak rises can be even higher especially at higher latitudes cities.

Impacts of food and water diseases are instead particularly significant in developing countries. As temperature rises the incidence of such illnesses rises too, with a disproportional mortality (higher in

[110] This happened in 2008, according to 2009's *UN Population Program*.

urban areas). This is because infectious diseases tend to spread more easily in cities, due to the more frequent potential contact with carriers.

Not only food and water get affected by the impacts of climate change, but also the air we breathe. One of the main concerns for the public health nowadays is the air pollution, indeed. Right now, 9 out of 10 people worldwide breathe "polluted"[111] air according to World Health Organization (WHO). Around 7 million people die every year due to ambient (outdoor) or household (indoor) air pollution [30]. Exposure to harmful fine particles penetrating deeply into the lungs and eventually into cardiovascular system, can cause a wide range of diseases, including asthma, pneumonia and other chronic respiratory diseases, but also hearth diseases, stroke and lung cancer. The main sources of air pollution are without any doubt ones of anthropic origin. For instance, particulate matters come from an inefficient energy use - mainly coal-fired power plants – by households and industries, agricultural and transport sectors. The World Health Organization (WHO) recommends standard limitations on air quality. Thresholds on mean value concentrations are 20 μg/m^3 for PM_{10} and 10 μg/m^3 for $PM_{2.5}$. The highest today's air pollution levels are recorded in the Eastern Mediterranean Region and in South-East Asia (*Figure 3a*). In both these zones, the annual means exceed often more than 5 times the WHO limits. According to the Air Quality 2018 Report by the European Energy Agency (EEA), long-term exposure to particulate matters was responsible for 422,000 premature deaths in Europe during 2015. WHO recently stated that 1.8 billion children are breathing toxic air right now, storing up a public health bomb for the next generations.

Besides all these first-hand experienced human impacts, other ones are directly linked; billions of dollars of fixed investment are hosted in cities in the form of infrastructures that obviously cannot be removed in the face of an imminent extreme event. This is the cause of huge economic losses. For instance, the US has undergone 238 weather and climate disasters from 1980 to 2018, the overall costs of which exceeds $1.5 trillion [30]. The recordings show that these billion-dollars disaster events have been trending up during the last decade, with 2018 ranked fourth in terms of economic losses, just behind 2016, 2017 and the first one: 2011 [31]. The effect of climate change impacts associated to extreme events on cities infrastructures, facilities and services is clearly visible for hurricanes that often plague

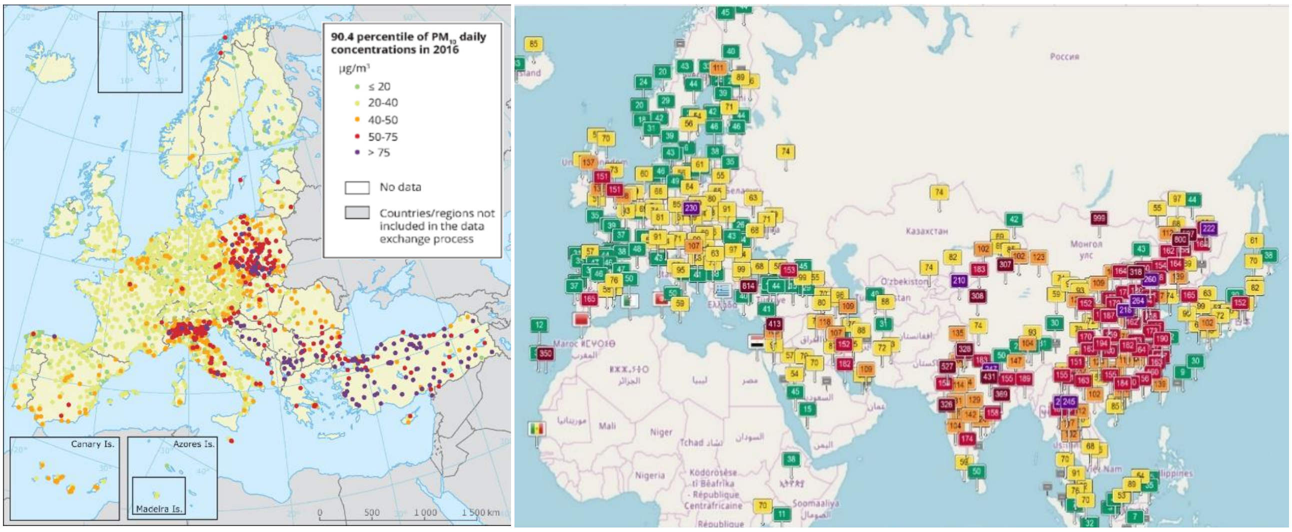

Figure 4.3 | Climate change impacts: vulnerability and resilience. (left) 90.4 percentile of PM_{10} daily mean concentrations in Europe in 2016. (b) People in Beijing with respiratory masks. The most affected group of people affected by air pollution are children. **Credits: (left) "Air Quality in Europe – 2018", EEA, 2018. (right) https://aqicn.org/map/world/**

[111] Air is considered "polluted" when the concentration of a harmful substance exceeds a certain threshold. Air pollution can be indoor or outdoor. A pollutant can be of natural or anthropogenic origin. Examples of the most important pollutants are carbon dioxide (CO_2), sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), Volatile Organic Compounds (VOCs), particulate matters (PM, distinguishing on the basis of the equivalent diameter of the particle: $PM_{2.5}$ for a 2.5μm diameter, PM_{10}, etc.), persistent free radicals, etc.

the United States. According to National Oceanic and Atmospheric Administration (NOAA), losses from Hurricane Harvey (2017) exceeded $125 billion[112], while Maria (2017) and Irma (2017) had total damages of $90 billion and $50 billion, respectively [32]. This proofs also that even cities in wealthier countries are vulnerable to climatic extremes.

The number of catastrophic events has been rising since 1980, reaching the outstanding number of 730 events recorded as relevant over the year 2017. The 600 events mark on a yearly basis has been exceeded only five times, all of which occurred in the ending decade *(Figure 4.4-left).* An increased trend in human and economic losses associated with weather-related events has been observed too since the late 80s, exceeding $340 billion in 2017 *(Figure 4.4-right)*. About 10,000 people were killed by 53 earthquakes, 255 windstorms, 345 floods and 77 climatological events (e.g., droughts, wildfires, etc.) Among the total fatalities due to natural disasters, roughly the two-third were in Asia, the 12% each in Africa and North America, and the 4% in Europe [33].

All the issues addressed may feed a ripple effect concerning the movement of people around the globe. The huge wave of the so-called environmental refugees is currently breaking down on Northern America and Europe, causing multiple implications under the socio-political point of view[113]. The worsening of climate change could see over 140 million people moving out of their countries borders by 2050 [34]. These are individuals whose livelihood has been lost due to droughts, earthquakes, food shortages and the conflicts brought on by those effects. This new form of refugees seeking the chance to live safely in countries that have experienced less the brunt of climate change, is expected to double when facing a warming of 4 °C, rather than a 3 °C one [35]. Even for this reason, developed countries should show a concern on these themes that does not seem to be showed at the moment. Developed countries however will be forced within a few years to address these tough questions regarding the ethics of denying livelihoods to those who lost theirs, as a result of GHG emissions from those same developed countries themselves in which the refugees are seeking asylum.

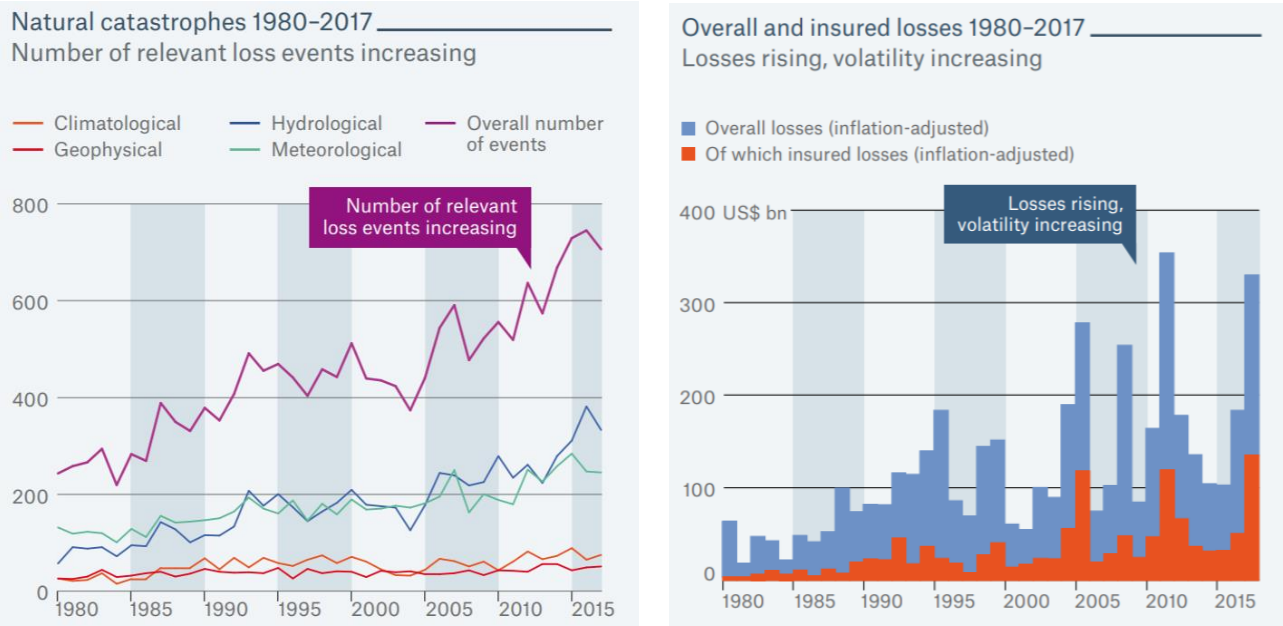

Figure 4.4 | Climate change impacts: an overview. The cities. (left) Overall number of relevant loss events during the period 1980-2017 (purple line). Climatological (orange line), Geophysical (red line), Hydrological (blue line), Meteorological (light green line) events are plotted on the same graph. (right) Overall losses (blue) vs insured losses (orange) during the period 1980-2017. **Credits: "TOPICS Geo Natural catastrophes 2017", Much RE, 2018.**

112 This ranked Harvey second, only to Hurricane Katrina (2005), the most destructive one in the 38-year period of record. Katrina smashed the cities of New Orleans killing more than 1800 people.
113 The human migration, that is driven by various factors, among which wars, persecutions and ultimately the climatic change is gaining a key role in the political agenda in the electoral campaigns all over the world.

- 4.3 - MITIGATION

Key Points

Climate change mitigation is besides adaptation, one of the two possible responses to the impacts of a changing climate. In contrast with adaptation which act once the impacts effect has occurred, mitigation deals with the causes, aiming to eradicate them. GHGs emissions and related concentrations are the main causes of climate change and consequently the issue on which mitigation should focus on. GHG reduction can be carried out according to two different approach: intensity-based targets (or "per unit of something emissions") and absolute targets (overall reductions). Carbon Capture and Storage (CCS) and Carbon Sequestration (CS) are other types of mitigation strategies, acting once carbon has been emitted, isolating and capturing it from the atmosphere, exploiting chemical or biological processes respectively. Finally, geoengineering is one of the newest mitigation strategies in which climate is deliberately manipulated mitigating the effect of climate change impacts. One of the core sets of mitigation strategies are those that tackle our demand for fossil fuels: the so-called demand-side mitigation strategies. Energy efficiency is the first major category of demand-side mitigation and the second one is energy conservation. While energy efficiency holds great promises since we may be able to maintain elements of the current lifestyle while consuming fewer resources, conservation addresses the important question of shifting our behavior making its goals more complex to achieve. The flip side of the mitigation coin is supply-side mitigation. The strategies underpinning supply-side mitigation are attempts to transform the current energy system in order to provide the goods and services we require in less carbon-intensive ways. The core component of supply-side mitigation is renewable energy. A focus of the most important renewable energy option with linked data is done. Renewable energy share in global market has been growing steadily during the last decade, but it is not enough.

Moving on from the exploration of the causes and the impacts of climate change, a step forward must be done towards the "pars costruens" of the issue, or the one dealing with the possible solutions. Time to take actions is now, as the Special Report on Global Warming of 1.5 °C (SR15) from the Intergovernmental Panel on Climate Change (IPCC) states that the possible solution space has narrowed during the ongoing decade and is going to shrink more as time goes by. When attempting to address climate change under the point of view of solutions, two basic aspects are crucial: Mitigation and Adaptation.

- 4.3.1 – The rationale of mitigation approaches. Targeting mitigation: emission, concentration and reduction targets

As seen so far, the Earth system and the human systems are inextricably linked: a constant mutual exchange (energy, matter, etc.) occurs between them. For instance, the way we choose to develop cities, grow food or consume energy, has a direct impact on the anthropogenic emission we put into the atmosphere and the level of climate change that is experienced as a result. Similarly, the places and the ways in which settlements are built, influences strongly the degree of vulnerability to the impacts of climate change on settlement themselves. In the following lines, a focus will be done on the mitigation of impacts.

Mitigation is a concept that deals with the causes, rather than the consequences of the climate change problem. The goal of mitigation is to take actions in order to prevent climate change before it starts, rather than facing the impacts once they have begun yet. Climate change mitigation has been the most important policy taken against climate change, since the first emerging evidences of human interference with the planet climatic balance started to be seen. The Intergovernmental Panel on Climate Change (IPCC) provides a definition of climate change mitigation as "a human intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs)"[41]. In other words, the efforts of mitigation divide in either reducing our yearly GHG net emission into the atmosphere and improving the ability of the Earth through ocean and forests to absorb carbon.

The combustion of fossil-fuels and the consequent decomposition of organic matter which has been storing carbon for thousands of years, are the primary human-caused sources of greenhouse gases emission. From the total amount of CO_2 gigatons emitted globally, the 42% was from energy processes (electricity and heat generation), over than 24% from transport, the 19% from industrial processes and the 8.4% from residential and commercial heating or cooling *(Figure 4.5-righ).* The rest comes from waste treatment and disposal, agriculture and other sources. In order to assess the multiple mitigation strategies facing the greenhouse gases issue, two concepts are crucial: ***atmospheric emissions and concentrations***[114]. The term "emission" relates to a flow of matter injected into the atmosphere. "Concentration" in contrast, refers to the quantity in atmosphere as a result of emission. CO_2 concentration represents the stock of carbon in atmosphere and it is measured in part per million (ppm).

The core of climate change mitigation solutions are the so-called ***reduction targets***. A greenhouse gas *emission target* refers to the emission reduction levels that States set out by a specified time. They are set both based on concentrations and emissions, depending on the quantities considered proper in order to have a stable climate and acceptable life conditions. In this context, two key methodologies have been developed. The first one involves the so-called ***intensity-based targets***. According to an intensity-based target, the governments subscribing it agree to reduce the amount of GHGs emitted per unit of something; an example of intensity-based target is the reduction of the amount of GHGs emitted per unit of Gross Domestic Product (GDP) or per capita. In this way, the total amount of GHGs emitted can go up though, if the size of the economy or the population respectively increases. The second type of GHGs reduction targets is based on the ***absolute targets***. This commits the subscribers to reducing the total amount of GHGs. This can apply both on atmospheric emission and concentration; an example of absolute target is the suggestion to keep globally the concentration of carbon dioxide to 350 ppm. Another example can be the commitment of the various nations in the context of Kyoto Protocol in terms of absolute emissions reduction (measured in tonnes) with respect to 1990 levels.

Controversies rose behind intensity-based targets. *(Figure 7-left)* shows the USA percentage deviations from a 1990 baseline in three different quantities: Gross Domestic Product (GDP), GHG emissions and GHG intensity (i.e., the amount of GHGs produced divided by its GDP). Despite a decline in GHG

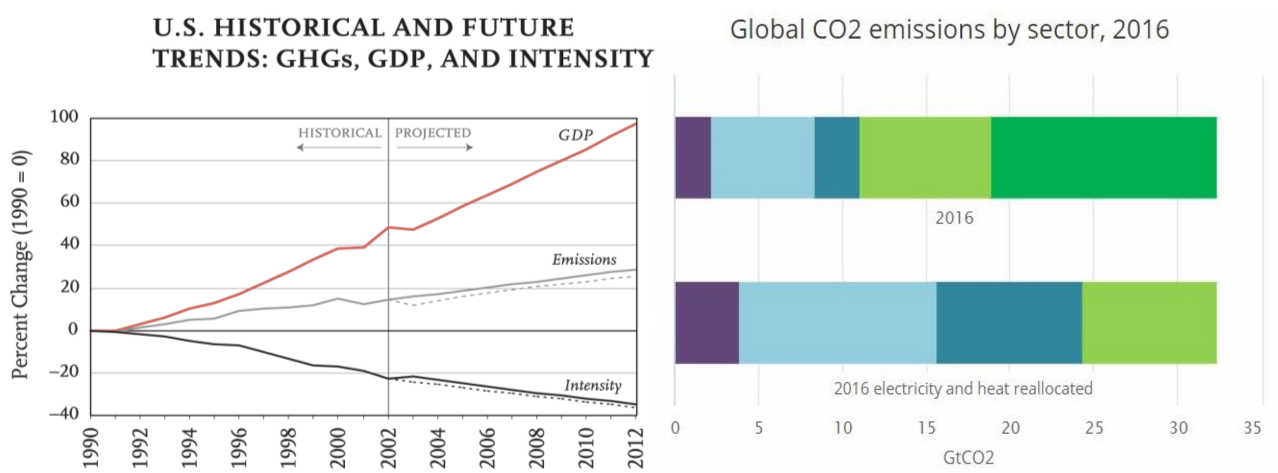

Figure 4.5 | Mitigation an overview (left) Percent changes in GDP (red line), GHGs emission (grey line) and GHG intensity (black line) for USA based on the World Resources Institute (WRI). Dashed lines represent the Bush administration target projections. (right) Global carbon dioxide emissions by sector in 2016. **Credits: (left) World Resources Institute (WRI) based on US government projections and Bush administration statements. (right)** https://www.iea.org/statistics/co2emissions/

intensity, GDP is still rising at such a rate as to make GHG intensity to decrease, even if the overall emissions are still rising. As a result, these intensity-based targets would not be expected to contribute as much as needed to the prevention of climate change impacts.

In addition to reducing the quantity of greenhouse gases emitted, the other approach is to enhance and empower the quantity that is taken up by the planet in order to mitigate climate. This is the core concept underpinning Carbon Capture and Storage (CCS) technologies. Fossil-fuels are still used to produce heat and electricity or to boost the transportation systems. Now with CCS, the carbon dioxide instead of being vented with the other exhausts from the combustion process into the atmosphere, it is captured with absorption or adsorption technologies and then stored. Crucial for this technology is the choice of the storage site. Suitable places can be for example deep geological formations after oil or natural gas has been extracted. Carbon is injected there; once filled, the site is packed and sealed. As a result, the carbon will never make it way into the atmosphere, nor influencing the climate again. The Carbon Capture and Storage (CCS) technologies are often referred to as non-biological processes, since they are carried out with chemical processes. Besides that, Carbon Sequestration (CS) is the CCS equivalent implementing biological processes. As CCS, CS means taking carbon out of the atmosphere after it has been produced. In contrast to CCS, CS involves the capacity of photosynthesizing plants to absorb carbon from the air (e.g., threes, crops, grasses, algae etc.)[115]. Both the CCS and the CS are mitigation strategies targeting concentrations rather than emissions.

Another important branch of possible mitigation strategy is the so-called *Geoengineering* or *Climate Engineering*. It is also one of the most controversial and has emerged only recently. Its proposal is to act deliberately on the Earth's climate, directly manipulating it with the aim to counteract the harmful effects of climate change. The scale of action of geoengineering is planetary rather than regional: its goal is to modify climate as a whole. Geoengineering refers both to actions considered as mitigation or adaptation ones. Fertilizing the oceans so that algae can grow and multiply, taking up more atmospheric CO_2 is an example of geoengineering acting from a mitigation point of view, while the injection of particles into the atmosphere in order to block part of the Sun's rays or creating artificial clouds as rain sources in case of severe droughts are ones from an adaptation point of view.

Since the combustion of fossil fuels is the main source of human-caused GHGs emissions, the fact that reducing global consumption of fossil fuels will lessen their impact on the climate, is almost trivial. Two pathways can be followed to accomplish this major goal: one is *demand-side mitigation* and the other is *supply-side mitigation*. Demand-side mitigation means changing both behaviors and technologies so that we use less fossil fuels; brief examples include increasing the efficiencies of the devices, managing the energy system with the aim of reducing its demand, assuming an eco-friendly attitude in everyday life, etc. Supply-side mitigation involves the use of completely new energy sources in order to decrease our reliance and dependence on fossil fuels; examples include the widespread use of renewables, the progressive phase-out of coal-fired power plants and the transition of the transport sector towards Electric Vehicles (EV). This section focuses on the first approach, or the demand-side mitigation.

- 4.3.2 - Mitigation: demand-side strategies

2017 and 2018 saw respectively a 2% and a 2.3% global energy demand rise, the two fastest growths in the ongoing decade that have been driven primarily by the word's economic growth and by changes

[115] See *Section 2.5.2.*

in consumer behavior. At this very moment the 81% of Total Primary Energy Supply (TPES) comes from fossil fuels [38].

The target to reduce a demand relying on this massive amount of fossil fuels can be attained in the first place through energy efficiency or conservation. Improving the energy efficiency means decreasing the amount of energy required to provide products, services or useful work and is one of the twin pillars of sustainable energy policy besides the use of renewable energy. The efficiency of the energy system tends to increase with the grade of development and the wealth of a country. Financial resources and higher level of education are drivers to build and expand energy-efficient technologies. However, along with economic and industrial growth come higher levels of GHGs emissions. In other words, richer areas such as North America or Europe use less energy per unit GDP (MJ/$) than those in South Asia or Sub-Saharan Africa thanks to the large size of the denominator rather than the small one of the numerator. The end result is nevertheless high levels of GHGs, driven by the higher GDPs and grade of productivity.

Technological development leading to increasing efficiencies and smarter ways to produce and consume energy is a key component in the context of the demand-side mitigation of climate change, but also our single attitude matters. Privately owned and operated vehicles are a core component of culture in many communities around the world; they tend to value the freedom, mobility and convenience of the way to move. This has pushed the unparalleled demand for cars that has been observed during the last years, starting from the 39.2 million of car saled in 1999 and reaching some 81.5 million sales during the 2018 [39]. The potential peak and then decline of conventional oil supply however as well as cities policy maker's decisions to ban diesel vehicles (e.g., Europe's cities including Rome by 2024, Madrid by 2020 and Oslo by 2019), have intensified the need for modes of personal transportation that makes better use of energy and creates alternatives to the increasingly expensive fuels.

These more energy-efficient options are actually one component of a multi-pronged approach to climate change mitigation that binds together the reduction of air pollution, the managing of GHG emissions and comfort and liveability of our cities. A lot of strategies can be implemented to make vehicles more fuel efficient, starting from the use of lighter materials for construction such as composites instead of heavy metals, improved aerodynamics which minimize the drag and new technologies such as plug-in hybrids or the Electric Vehicles (H/EV) which make use of cleaner electricity rather than the classic internal combustion engine consuming traditional fuel.

Even if the capacity of engine to transform fuel into work has generally increased over the last 30 years, this increase in efficiency has not turned necessarily into decreased fuel consumption, especially in developed countries. North Americans constructors for instance, have chosen to capitalize this increasing efficiency by building larger and more powerful vehicles thereby consuming as much or even more fuel in absolute terms than 30 years ago.

Energy efficiency can be addressed also in the context of buildings and private houses. New building standards show dramatic progress towards that direction; Key element ranges from the building location and surroundings, the types of materials used which must be eco-friendly and not allow the escape of heat, the smart placement of windows and light points and of course the devices that are used within that building such as heat pumps and geothermal energy to drive heating and cooling systems, solar and PV panels to provide hot domestic water and electricity. A high-performance building can halve its GHG emissions in contrast to a conventional one [40], which consume 70% more energy in the end [41].

The sector in which there is the main room for manoeuvre as regards energy efficiency however, is certainly Industry. Being responsible for around the 38% of global final energy use, the contribution of Industry to energy savings from improvements in energy efficiency is nearly 51% now. Light industry represents some 70% of potential energy savings in the Efficient World Scenario (EWS) outlined by IEA[116]. Iron and steel accounts for a 14% and chemicals & petrochemicals for the 10%. The global energy efficiency investment keeps rising and has reached the 231$ billion in 2016. Energy efficiency in the Buildings sector did the lion's share with over 133$ billion, while Transport and Industry account respectively for 61 and 37$ billion. Key technologies are electric motor-driven systems, electric heat pumps for heating and cooling and metals recycling [38].

In conclusion, the energy efficiency issue is both a matter of technologies as well as about decision making, political and cultural factors. Once new technologies have been created and developed, the second step is using and keep using them overtime. This means a deep human change in attitude, which does not seem in the current agenda. History and the Philosophy of Science[117] teach us that the human dimension on the technical change can influence strongly the technological innovation itself in multiple ways. On the one hand the perception of risk-taking and competitiveness of a certain technology and the priorities from companies and single individual as well, are key factors; on the other, political policies such as taxes or subsidies together with financial capacity underpin technical change from an economic point of view and provide a framework in which business can develop and be implemented with continuity.

Besides energy efficiency, the other corner stone of demand-side mitigation is energy conservation. Unlike the former, energy conservation deals with existing technologies or services, but in a different way. Energy conservation faces the same cultural and political dimension of behaviors both at a community and individual level that has been described in relation to energy efficiency. Examples of energy conservation are buying local food, minimize car travels, turning off electric devices when unused, etc.

All these options require shifts in our traditional patterns of attitude and even a rethinking of our core values. Moreover, the demand for alternative and less energy intensive ways of living, is heavily influenced by the way cities and environment are designed, the availability of these alternatives and finally the willingness to explore the potential of these alternatives and implement them in our everyday life. This can be often more complicated than replacing an obsolete technology (e.g., an inefficient car) with a more efficient one, performing exactly the same service. For this reason, the potential for conservation to contribute meaningfully to climate change mitigation has been a cause of significant debate.

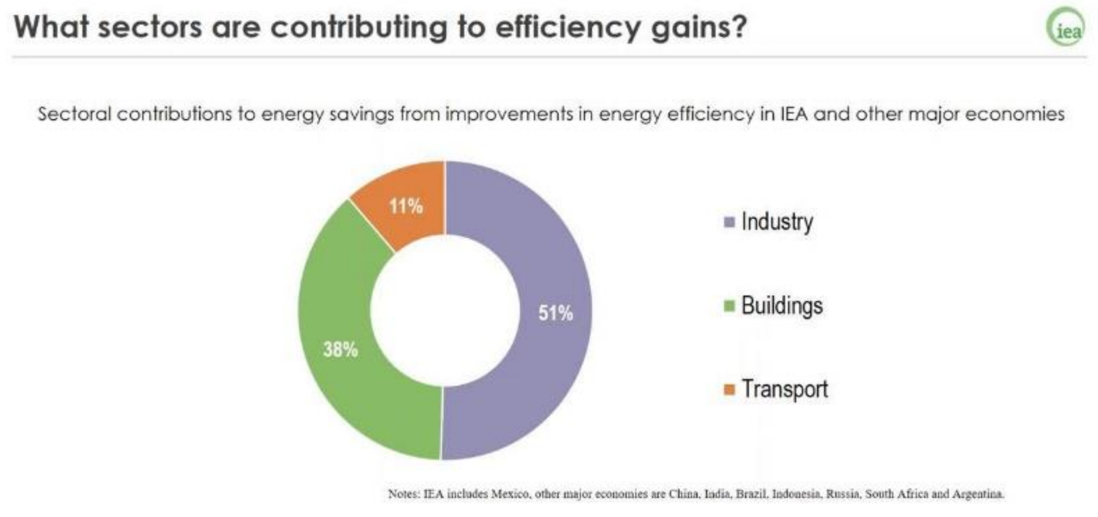

Figure 4.6 | Contributions to energy savings from improvements in energy efficiency by sector. Transport has made the smallest contribution due to variable policy and activity growth. **Credits: IEA's Market Report Series: Energy Efficiency 2018's Webinar**

[116] The EWS identifies the potential for industry to nearly double the production per unit of energy use in 2040, compared to current levels.

[117] From Karl Popper (1902-1994) with the Falsification Theory, to the "Cybernetics" with Heinz von Foerster (1911-2002), Humberto Maturana (1928) and Ilya Prigogine (1917-2003).

- 4.3.3 Mitigation: supply-side strategies

Over the last four decades the far-reaching implications of petroleum-based energy system has been plainly visible. Major marked disruptions in both 1973 and 1979 were triggered by frictions between the Organization of the Petroleum Exporting Countries (OPEC) and countries whose interests were deeply centered in maintaining a steady oil supply from the Middle East, like United States and others[118]. Oil embargo and the faltering supply resulting from military actions, led to shortages around the world and to an abrupt skyrocketing in prices that influenced economic security for the years following.

Escalating oil prices affect the production nowadays too, making possible the production of more costly and labor-intensive types of petroleum, the one defined ***unconventional*** but nevertheless feasible. The exploitation of these sources of petroleum such as the extremely dense bitumen rich sands (or bituminous sands) in Alberta, Venezuela, Kazakhstan, Russia, etc., previously thought to require too much resources for a too small yield, generated controversy over the environmental impact including the quantity of GHG emissions produced during the energy intensive process of oil sands mining. A quantity ranging from 280 ad 350 kWh of energy is needed to extract a barrel of bitumen and upgrade it to synthetic crude, leading to an Energy Returned on Energy Invested (EROEI) of 5-6, in contrast to conventional oil with EROEI often exceeding 20. For these reasons, one crucial issue to consider in the context of energy supply is the one related to geopolitical maneuverings made by countries in possession of energy sources in order to put pressure on the others, that are energy-dependent from them[119]. Given that, a proper energy supply mix should ideally look for affordability, security of supply, minimized dependency and minimal environmental impact.

- Focus 3 - The current energy system and projections by IEA

The current fossil-based energy system seen a spectacular increase in GHG emission from fossil fuels combustion in the last decades as seen in the previous chapter. By looking at the reports from the most influential world energy institutions, the International Energy Agency (IEA) expects it to increase even more by 2040 according to two scenarios out of three. The only one scenario contemplating a reduction in energy-related CO_2 emission is the **Sustainable Development Scenario** which "provides an integrated strategy to achieve the key energy-related elements of the United Nations Sustainable De velopment

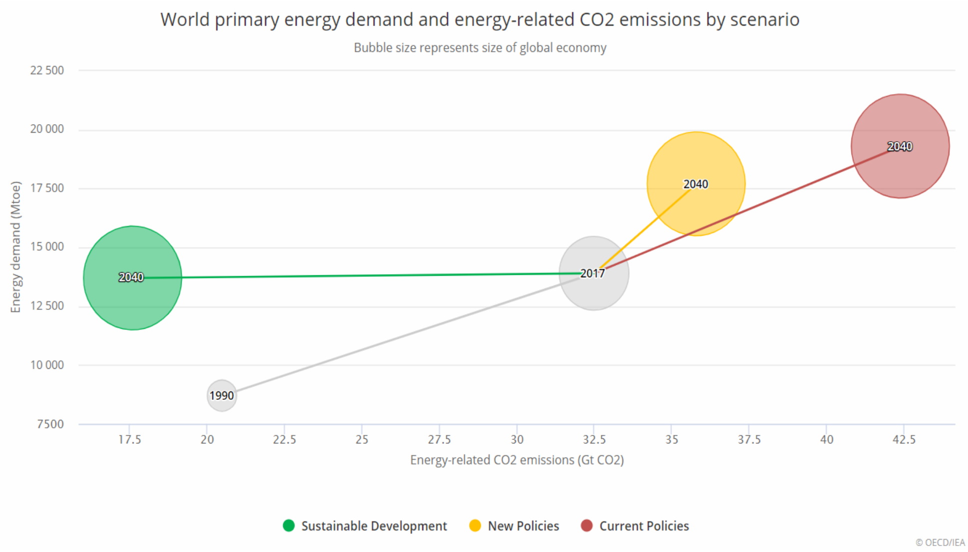

Figure 4.7 | Global energy related CO_2 emission in $GtCO_2$ are displayed on the x-axis and world energy demand in Mtoe are displayed on the y-axis for the three different scenarios identified by the IEA by 2040: Current Policies (red line), New Policies (yellow line) and Sustainable Development (green line). The World Energy Model has been used for these large-scale projections. **Credits: https://www.iea.org/weo2018/scenarios/**

[118] In October 1973, the members of the Organization of Arab Petroleum Exporting Countries (OAPEC), proclaimed an oil embargo targeted at nations that have supported Israel during the Yom Kippur War (1973) between Egypt and Israel (initially Canada, Japan, the Netherlands, the United Kingdom and the United States) [46].

[119] By looking to the historical background of the so-called "Energy Geopolitics", other key moments were the USSR (and then US) invasion of Afghanistan, the 2003 US and UK invasion of Iraq, the fall of Muammar Gaddafi's Libya, etc.

agenda" and includes all the major long-term objectives of the Paris Agreement, that were still not fully followed up during the COP24 in Katowice. The **Current Policies Scenario** take in consideration instead no change in policies from today, which would lead to strains on almost all aspects of energy security and an impressive rise in energy-related emission to about 42.5 $GtCO_2$ per year. The **New Policies Scenario**, accounts for improvements in energy efficiency and a proper management of sustainability and energy security, projects to reach the 36 $GtCO_2$ by 2040 [38]. This means that in absence of policies targeting this core issue that is the energy supply, emissions are undeniably expected to increase, even implementing some kind of "gentler" countermeasures.

These central concern about environmental sustainability, united with the geopolitical reliability and affordability of the fossil energy sources, raise the question of the sustainability of our current global energy system. If the global economy is fueled by a non-renewable resource that is less environmentally sustainable, that is becoming less affordable and less secure with each passing year, "investments in clean, green energy need to be scaled up globally"[120]. Renewable energy addresses the problem of GHG emissions at its source, rather than perpetuating the use of fossil fuels in smaller quantities or in a more efficient way. Fossil fuels are created by the natural decomposition of organic materials and the following weathering action on them, in a long-lasting timescale sometimes exceeding 650 million years [43]. Even if new supply of conventional and unconventional oil is continually being discovered though at a diminishing rate, the supply of fossil fuels does not replenish itself naturally at a rate that is consistent with a human timescale and economically useful. Renewables in contrast, draw upon virtually inexhaustible sources of energy such as the Sun, the wind, the core of the Earth, etc. In the following lines a brief focus on Renewables will be done.

- <u>Focus 4 - The unprecedented growth of renewables</u>

As known, the term ***traditional renewables*** generally refers to large-scale hydro and traditional biomass[121] combustion, both of which has significant environmental and social implications; for this reason, they are often not considered part of the new strategies that are being implemented by countries in the context of supply-side mitigation. So-called ***modern renewables*** instead - including solar, small scale hydro, tidial power, geothermal, wind and biofuels – form the core of the supply-side mitigation and have great economic, social and environmental potentials. Renewables provides about the 20% of Total Final Energy Consumption on the whole while fossil fuels supply the lion's share yet, with the remaining 80%. The renewables share currently divides up between traditional biomass burning122 (7.8%), nuclear (2.2%) and modern renewables (10.4%); the main contributors to the modern renewables share are solar, geothermal and hydropower together, followed by wind, PV, and biofuels for transportation ***(Figure 4.8-left)***. Rising oil prices, escalating geopolitical tensions, concerns about climate change and rapidly evolving technologies have driven significant growth in renewable energy capacity over the last decade [44].

In 2017 for the first time, renewables capacity additions of 178 GW accounted for more than two-thirds of global net electricity capacity growth. With 97 GW, solar photovoltaics (PV) saw the largest expansion, over the half of which occurred in People's Republic of China. The 2018 again saw two-thirds of global net electricity growth relying on RES. At the end of 2018, global renewable generation capacity amounted to 2,351 GW, with hydropower accounting for the largest share – 1,172 GW as stated by the Renewable Capacity Statistics 2019 by the International Renewable Energy Agency (IRENA).

[120] As the UN Secretary General António Guterres put it during the R20 Austrian World Summit.

[121] In contrast to fossil fuels, biomass such as forests, waste from farming or horticulture, etc., are considered renewables, but it must be considered that in many cases biomass consumption contributes to deforestation and unhealthy indoor air quality. "Renewable" is not always synonymous with "sustainable".

According to the International Energy Agency (IEA), renewable capacity is expected to grow by 46% in the near-term period (2019-2023) with around 1 TW of capacity added. PV account for more than a half of the expansion, followed by wind, hydropower and bioenergy. Wind capacity is projected to expand by 60% with 324 GW in the same period [45].

This impressive acceleration is driven by supportive government policies but also by technological and market improvements across most regions. Policy targets for renewable energy as regards the power sector which seek to increase the share of renewable energy supply in the interest of addressing climate change and the fossil fuel dependency, exist in 128 countries worldwide right now. A virtuous example of that is the European Union (EU) 20-20-20 package which sets a goal to bring the proportion of renewables in energy demand to 20% by 2025[123]. Technological advances and economies of scale have finally taken root, dramatically lowering the cost of both solar and wind energy. The implementation of renewables in the energy system on a grand scale brings multiple benefits; not only do they offer the potential to dramatically reduce carbon emissions and manage climate change, but they hold the promise of a diversified economy, that is not so closely tied to and affected by geopolitical instability, which is rather commonplace as seen previously.

Technologies such as solar cook stoves, replacing the combustion of coal and biomass can help to significantly improve indoor air quality in developing countries. One of the other renewables' major strength is that they can be implemented and ran locally, rather than transported at great cost and over vast distances, as fossil fuels often do. This positive effect of an improved local sustainability is tangible especially in developing countries. Electrification programs based on rural off-grid renewable energy are one of the most effective ways to give access to energy (mainly electricity) in remote areas of developing countries [46]. Finally, while the traditional energy system is a highly centralized one – based on large power stations with average outputs ranging from hundreds to thousands MW – a renewable-based one is modular and de-centralized, with the possibility to create self-sustaining district energy systems and to power individual family's homes through solar panels, wind microturbines or geothermal heat, not necessarily grid connected. This makes a renewable energy system considerably more resilient in the face of political instability, variation or depletion in resource flows, extreme weather events and all the other factors affecting vulnerability and resilience with respect of climate change impacts.

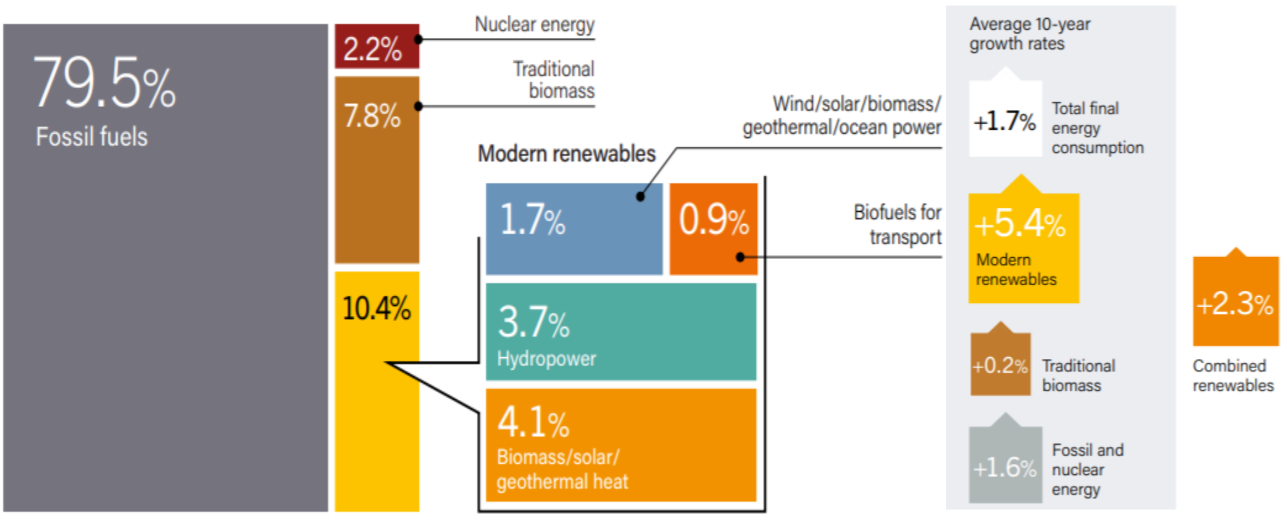

Figure 4.8 | Supply-side mitigation. (left) Estimated renewable share of Total Final Energy Consumption in 2016 (right) Growth in global renewable energy compared to Total Final Energy Consumption related to 2005-2015. **Credits: REN21. 2018. "Renewables 2018 Global Status Report" (Paris: REN21 Secretariat)**

[123] The 20-20-20 package includes also the 20% cut in GHGs missions from 1990 levels and a 20% improvement in energy efficiency.

However, renewable energy is not without challenges, as any other main energy- and climate-related theme at a global scale. Besides the main well-known drawbacks regarding its intermittency and consequent relative unreliability, some technologies such as large-scale hydro can lead to pretty extensive damages: for instance, the 48% of all river flow worldwide is moderately or highly fragmented by dams and altered as a result [47]. The transition towards a renewable-based energy system means moving away from the current system, in which considerable resources had been invested: the cost of this transition can often be quite high. This drawback is likely to be overcame partially with the falling of the electricity generation from renewables.

Considering the current prices, one kWh from onshore wind is now costing an average of $0.06, while solar PV is about 0.10$/kWh; the price for the two technologies has fallen respectively by 23% and 73% since 2010 and keeps falling. In comparison, the same kWh of electricity from fossil fuels ranges from $0.05 and $0.17 [48]. According to the International Renewable Energy Agency (IRENA), "all mainstream renewable energy technologies can be expected to provide average costs at the lower end of the fossil-fuel cost range" [49]. Furthermore, many renewable energy technologies are rather new; for this reason, companies, states and individuals have not had time to take advantage of economies of scale coming with the widespread production and application of these technologies. However, the main issue for many forms of renewable energy is the "historic" one: the non-steady possibility of access to energy that a fossil fuel ensures. The ways around this intermittency include the development of efficient energy storage systems with batteries or other devices. The capacity of storage systems will influence heavily the renewable's share in energy demand, not only during the peak hours. Seasonal storages are needed for instance, when more than 80% of the electricity demand is met by Renewable Energy Systems (RES) [50].

- Renewable: an overview on the latest

Now a focus on the single renewable sources and a state of art in terms of their penetration in the global energy system is required. All the data are taken from 2018 and 2019 Renewables Global Status Report by the International Renewable Energy Agency (IRENA).

- Hydropower

exploits the conversion of kinetic energy deriving from the falling or fast running water into electricity through turbines. There are two main type of hydropower production systems: dams and run of river. Hydro dams utilize the potential energy from the elevation of dammed water to generate electricity exploiting the gravitational force difference between the higher reservoir and the lower reservoir. From the lower reservoir, the water can be often stored and pumped to the higher for a release when electricity is in demand[124]. Run-of-river hydroelectricity (ROR) still uses turbines and generator but relies on natural flow rates of rivers, diverting a portion of water to turbines. The size of hydro plants ranges from *micro-hydro* with capacity <100 kW, *small-scale hydro* with capacity between 100 kW and 30 MW, to *large-scale hydro* with >30MW capacity. Hydro is considered "renewable" because water cycle is constantly renewed by the Sun; however, concerns especially about large-scale hydro rose. Damming a river in fact, has major impacts on the local environment, wildlife and even human life.[125] In addition, large quantities of cement used to build the plants make the hydro a not CO_2 free technology.

Hydropower represent the largest share of capacity installed among the renewable energy, mainly thanks to old plants as it has been growing slowly during the last decades. Global additions to hydropower capacity in 2017 were an estimated 19 GW, bringing the total to approximately 1,114 GW.

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[124] This is referred to as *pumped-storage* hydropower.

[125] Dams failure can be catastrophic, endangering the lives of those leaving downstream the dam.

China is steadily the leader in commissioning new hydropower capacity with the 40% of new installations in 2017, being the first country per capacity installed (28%) ahead of Brazil (9%) , Canada (7%) and the United States (7%) *(Figure 4.0-left).*

- <u>Tidal power</u>

TP is a form of hydropower deriving directly from the interactions between the Earth, the Moon and the Sun. The Earth's rotation on its axis and around the Sun drives the movement of the vast bodies of water on the Earth's surface. The energy coming from this movement can be captured in turbines basically in the same way as energy embodied in water pulled down slopes by gravity is captured in the traditional hydropower systems. The kinetic energy of moving water is used to power turbines that generate electricity, also in this case. This system is ecologically sustainable since produces zero GHG emissions. Proper sites for small-scale tidal power production can be found even in the most remote areas of the world. No real challenges are expected about the operation of the plants, as a predictably intermittent source of energy is exploited. Controversies relate to the environmental impacts of large-scale tidal power (the so-called *tidal barrage*) which includes dramatic changes in water turbidity and salinity and induced increased rates of fish mortality[126] . The intermittency and variability of tides creates further challenges for the storage of energy. Advances in turbine technology are making tidal power a more feasible renewable energy option, although a lot of efforts are required before it can provide a significant portion of global energy: of the 529 MW of operating ocean energy capacity at the end of 2017, the 90% was represented by only two big plants.

- <u>Solar Thermal</u>

Concentrating Solar thermal Power (CSP) makes use of mirror or lenses to concentrate the sunlight onto a small area. Electricity is then generated through a heat engine. CSP capacity grows at a pace of 100 MW/yr. The total capacity is around 4.9 GW, with China, South Africa and the Middle East as world leader countries.

As for solar thermal heating and cooling, it is a technology used for harnessing solar energy in order to generate thermal energy and has been serving millions of residential and commercial clients all around the world. Globally, 35 GW_{th} of capacity of both glazed (flat plate and vacuum tube technology) and unglazed collectors was newly commissioned this year, bringing the global capacity to an estimated 472 GW_{th}.

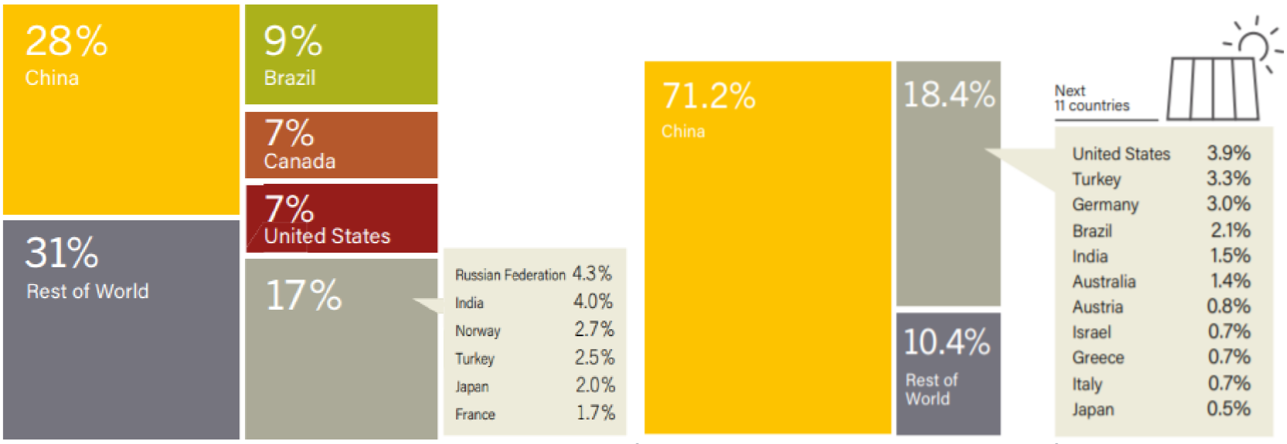

Figure 4.9 | <u>Supply-side mitigation. Renewable: the latest.</u> (left) Hydropower global capacity, shares of top 10 countries and rest of world in 2017. (right) Solar water heating collectors global capacity in operation. Shares of top 12 countries and rest of the world. Data for glazed and unglazed collectors. **Credits: REN21. 2018. "Renewables 2018 Global Status Report" (Paris: REN21 Secretariat).**

[126] Altering the characteristics of turbidity and salinity in the oceans means changing the conditions in which phytoplankton can grow, ultimately damaging the productivity of the ecosystem.

- Wind Energy

WE exploits the wind, formed by differences in pressure that result from the uneven heating of the planet surface by the Sun. Air moves away from areas of high-pressure (i.e., the colder portions of the Earth's surface) towards the warmer and low-pressure ones. The idea to capture the kinetic energy coming from that process in order to produce mechanical work is an ancient practice[127]. Only recently however have wind technologies evolved to efficiently capture the power of wind and convert it into electricity. The modern wind industry began around in the 1979 with the serial production of small wind turbines by Danish manufacturers.

Wind power owes its success to multiple facts. Firstly, it is almost clean with the only exception of the materials required to build the turbines (mainly glass and carbon fibers with additions of nano-polymers) and the other devices needed to work the plant. Wind power is also virtually inexhaustible, and it is equally available in remote or poorer areas as in the central and wealthier ones. Wind energy can be used both in a highly distributed energy system made by ***small-sized turbines of 1.5-3.5 m in diameter*** and ***1-10 kW electricity production*** or it can be implied in massive arrays of large-sized turbines reaching the ***height of 220 m, 164 m in diameter and 9.4 MW of rated capacity*** [51]. In the first case turbines are disconnected from the major power grid and supply single buildings or small communities. In the second one they are grouped together in plants called ***wind-farms***, which feed electricity into grid and power entire cities or industrial complexes. Challenges and controversies have been risen regarding one the one hand the ecological or visual impacts[128] and on the other the wind's rather unpredictable intermittency, not often coinciding with peaks in electricity demand

Cumulative global capacity of wind power is around 539 GW with a net yearly increase of 11% ***(Figure 4.10-left)***. China alone exceeds 235 GW. This year, Asia was the largest regional market for the ninth consecutive time, with nearly the 48% of global new capacity added, followed by Europe (over 30%) and North America (14%). The vast majority of the wind turbine manufacturer market is dominated by a few big Companies like Vestas (Denmark), Siemens Gamesa (Spain), Goldwind (China), General Electric (USA), etc. ***(Figure 4.10-right).***

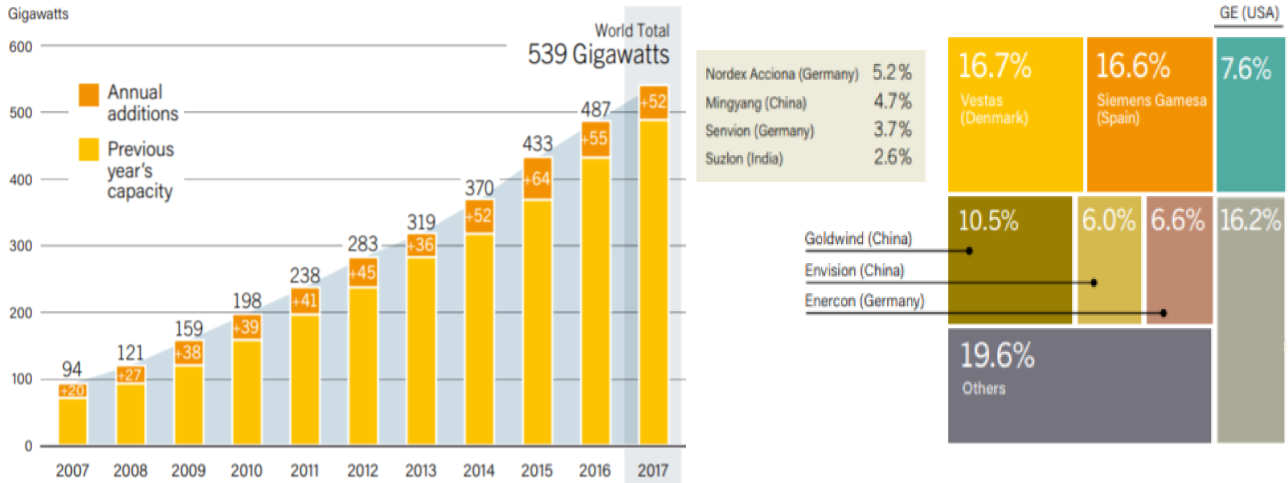

Figure 4.11 | Supply-side mitigation. Renewable: the latest. (left) Wind power global capacity and annual additions during the period 2007-2017. (right) Market shares of top 10 wind turbine manufacturers. Credits: REN21. 2018. "Renewables 2018 Global Status Report" (Paris: REN21 Secretariat).

[127] The Greek windwheel is the first known instance of using wind to power a machine and dates back to the first century A.D [56]. Wind has then been used for millennia to crush cereals, for transportation, etc.

[128] Birds in ecologically sensitive zones such as flyways or breeding grounds can be threated by the motion of wind turbines blades; visual impact on the landscape and noise pollution are other cause of rejection of this technology by some communities.

- <u>Solar Power</u>

SP provide electricity from sunlight directly through solar panels used to collect and transform solar radiation into power with Solar Photovoltaics (PV). Solar power like wind power is intermittent, but predictably. Tiny percentages of the annual potential of solar energy available on the Earth that ranges from 1,575 to 49,837 EJ [52], can meet several times the world energy consumption, that was 13730 Mtoe (or 574,84 EJ) in 2017 [50]. The challenge of this technology is to capture and efficiently store it. As wind, solar power is a virtually inexhaustible source of energy, is equally available in both poorer areas and in the highly developed countries' cities. Moreover, solar cells provide a direct conversion of energy from light to electricity through the so-called ***photovoltaic effect***. For this reason, there is no need of post-processing it beyond the solar cell output, differently from fossil fuels which need to go through an extensive mining and refining process instead. Another strength of solar power is the modularity: power plants can be shaped with various size adding and removing solar panels (or modules), matching the context for which they are built.

Challenges of solar power regard the manufacturing systems of solar cells[129], which are quite complex and energy demanding. Harsh chemicals and heavy metals used in some of these processes are a reason for concern too. Solar photovoltaics (PV) has been the fastest-growing source of new energy added worldwide since 2016. In 2017 the world added more capacity from solar PV than from any other type of technology. At least 98 GW_{dc} were installed on- and off-grid reaching a cumulative total of approximately 402 GW following an exponential trend ***(Figure 4.12-left).*** China with the nearly 53.1 GW added in 2017 (more than the one added worldwide in 2015) is indisputably the solar PV market leader accounting for the 54% of it. For the first time in 2017 solar PV was the leading source of new power capacity added in South Asia. For the second consecutive year, solar PV represented the country's leading source of new generating capacity also for the United States of America accounting for the 10.8% of new capacity added, and remaining the second largest market player, ahead of India (9.3%) and Japan (7.1%) ***(Figure 12-right).*** Boosted by the competitiveness of the market, the global weighted average Levelized Cost Of Energy (LCOE) of large-scale solar PV plants was 100 $/MWh, with a 73% decrease from 2010 levels. According to Bloomberg New Energy Finance the global LCOE for onshore wind is now at 55 $/MWh, the equivalent for sol ar PV without tracking system is 70 $/MWh, while according to the US Energy Information Administration (EIA) the LCOE for Advanced Combined Cycle electricity ranges from 44 to 77 $/MWh. In other words, in many locations, solar PV is competing head-to-head with fossil fuels, often doing so without financial support. Improvements in efficiency are being developed, often exceeding 20% in laboratory for perovskite-silicon solar cells.

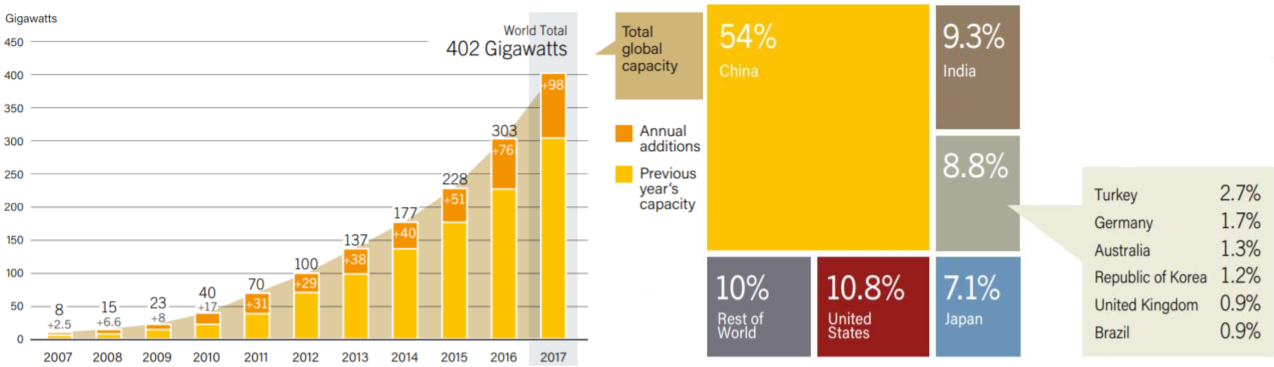

Figure 4.12 | <u>Supply-side mitigation. Renewable: the latest.</u> (left) Solar PV global capacity and annual additions during the period 2007-2017. (right) Solar PV global capacity additions, shares of the top 10 countries and the rest of world in 2017. **Credits: REN21. 2018. "Renewables 2018 Global Status Report" (Paris: REN21 Secretariat).**

129 Solar cells are mainly made up by semiconductor materials like polysilicon, monocrystalline silicon and amorphous silicon covering the large part of the market or Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS) and others, relevant for utility-scale markets of stand-alone power systems.

- Bioenergy

Bioenergy is the exploitation of organic matter to yield heat. Bioenergy is the oldest known use of renewable energy, being prevalent since the earliest human civilizations. It continues to provide energy for nearly the 13% of the global final energy demand, being the largest among the renewable contributors. *Biomass* is considered renewable because there is no net increase in carbon dioxide or GHGs in the atmosphere when burned. In other words, the same amount that it releases through combustion is taken up by plants when growing back.

Biofuels in contrast, represent a more recent effort to transform vegetable fats, plants waste from agriculture and industrial processes or fermented sugar products into highly efficient sources of fuel. The modest growth of biofuels has been driven by the skyrocketing fuel prices and concerns about climate change. Biofuels are created through a series of cyclical chemical processes. Solar energy and carbon dioxide are used by plants to create carbon-based cellulose: their major structural component. In biofuels industry, carbon is harvested and processed to strip the cellulose out of the plant. Cellulose is then broken down into sugars by enzymes. Microbes feed on these sugars, causing them to ferment producing ethanol (C_2H_5OH). Ethanol is a relatively clean burning fuel, which can be used both as a gasoline additive or to replace it entirely.

Biodiesel is another form of biofuel created by processing fats or oils with methanol (CH_3OH) or ethanol and can be used in any car engine that normally consumes traditional diesel. Other examples of biofuels are biogas, a byproduct of landfills and organic matter decomposition and syngas, a mixture of hydrogen (H_2), carbon monoxide (CO) and often carbon dioxide (CO_2) in smaller quantities. Syngas is a reaction intermediate for the creation of synthetic natural gas (SNG) through the reactions of steam reforming, dry reforming and other partial oxidations. The major benefits of the exploitation of bioenergy include that - as said previously - no net carbon emission is created. The byproducts of biofuel creation are relatively non-toxic and do not create problems associated with spills and leakages. Biofuels can be integrated seamlessly with our current energy system.

Challenges and controversies regard the fact that traditional burning of biomass creates dangerous levels of particulate matter especially in indoor air, creating serious implications for human health. Other big challenges relate to the "food or fuel debate"[130], the quantity of water required to produce the feedstock that will supply the biofu el production process and similarly, the fact that ecologically sensitive lands are being cleared of plant matter to feed biofuels production leading to ecosystem impacts[131].

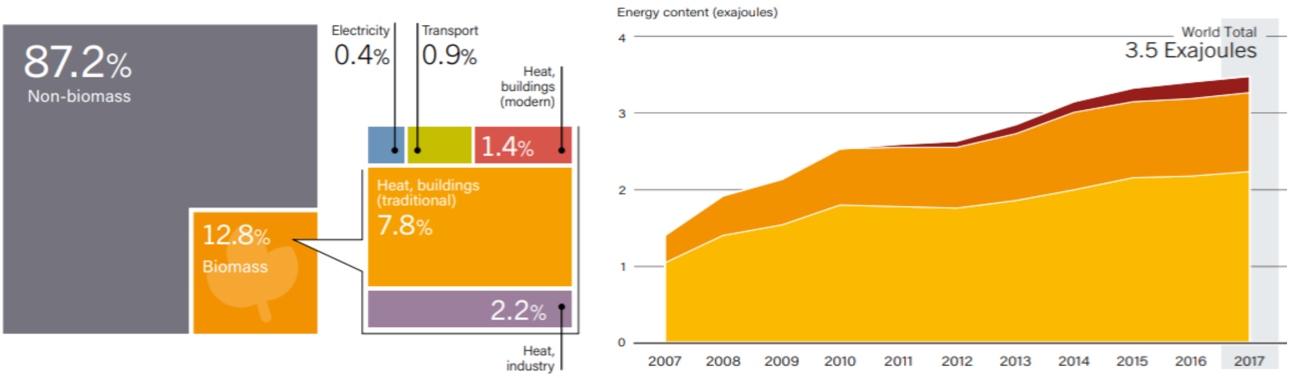

Figure 4.14 | Supply-side mitigation. Renewable: the latest. (left) Overall shares of bioenergy in total final energy consumption in 2016. (right) Global trends in Hydrotreated Vegetable Oil (HVO)/Hydrotreated Esters and Fatty Acids (HEFA) in red, biodiesel or Fatty Acid Methyl Esters (FAME) in orange and Ethanol in yellow. *Credits: REN21. 2018. "Renewables 2018 Global Status Report" (Paris: REN21 Secretariat).*

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130 In some countrie s the spreading of biofuels use is such that plant matter and areas that could be used as food crops for humans is being diverted to the biofuel production.

131 For a deep focus on the relationships between biofuels production and deforestation see "*A global analysis of deforestation due to biofuel development*", Yan Gao, Margaret Skutsch, Omar Masera, Pablo Pacheco, 2011.

Finally, the overall sustainability of biofuel production system is controversial as long as is based on a reliance on fossil fuels for heat and power. Despite the critics, biofuels are mainly viewed as a proper transitional solution in order to have a renewable source able to fuel the current fleet of vehicles and industrial systems while other renewables become cheaper and more efficient.

Bioenergy contributed to the 12.8% of the total final energy consumption in 2016. The 7.8% is represented by space heating use in building, which reached 314 GW_{th} global installed heat capacity *(Figure 4.13-left).* Europe is the largest consumer of modern bio-heat by region, followed by North America and Asia. Bioelectricity (electricity generation from bioenergy) increased 7% between 2016 and 2017, reaching 122 GWel installed globally. Biofuels production is rising slowly, exceeding 143 billion liters in 2017. It is also very concentrated geographically with more than 80% taking place in the United States, Brazil and the EU combined. An estimated 65% of biofuels production in energy terms comes from ethanol, the 29% from biodiesel Fatty Acid Methyl Esters (FAME) and the 6% from Hydrotreated Vegetable Oil (HVO)/Hydrotreated Esters and Fatty Acids (HEFA) *(Figure 4.13-right).*

- Geothermal energy

Geothermal exploits the energy that results from radioactive decay processes continually taking place at the Earth's core and from the energy that the planet's crust absorbs from the Sun. Geothermal energy has been used for thousands of years to provide heat; now is more commonly used to generate electricity. Geothermal energy is a viable source of renewable energy because it is widely available, environmentally sustainable, requires no fuel to be produced and the heat extracted through geothermal systems is only a tiny part in comparison to that available at the planet's core. Geothermal energy is also highly scalable: it can be used to provide heat and/or electricity to individual buildings or entire cities as well and it can feed directly into the existing electricity grid. The challenges associated to this kind of energy concern the relatively high capital cost especially for large-scale geothermal installations, cutting off the poorer communities together with the fact that long-term withdrawals in a single location may exhaust the local capacity if not carefully monitored. Drilling the soil to seat the geothermal system can lead to alteration of the morphology of lands or aquifers and even trigger mad-made earthquakes[132]. 0.7 GW of new geothermal capacity was added in 2017, bringing the total to an estimated 12.8 GW. The countries with the largest capacity installed are the United States the Philippines, Indonesia and Turkey.

- Electric Vehicles (EVS)

According to the Germany's nonprofit Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW), the world's car electric vehicles fleet reached 5.6 million. China is steadily the

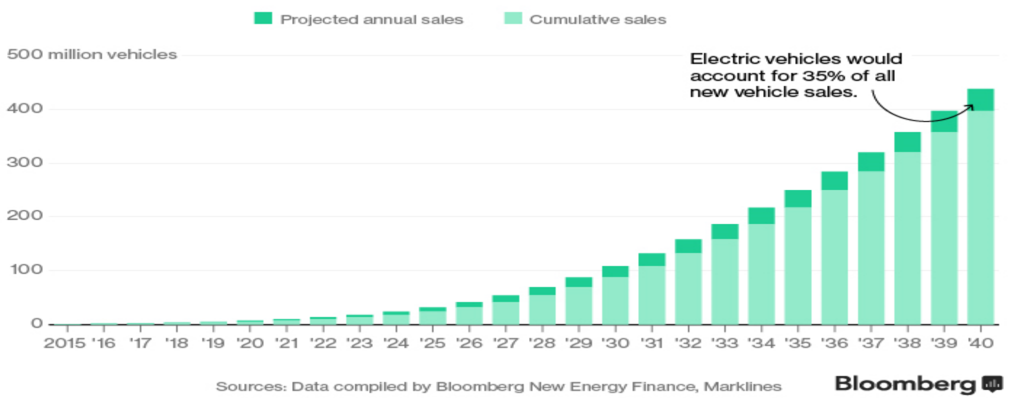

Figure 4.15 | The rise of electric cars from 2015 to 2040. By 2022 EV will cost the same as their Internal Combustion Engine (ICE) counterparts. That is the exact point of liftoff for sales. **Credits:** *https://about.bnef.com/electric-vehicle-outlook/*

[132] Examples of induced seismicity caused by geothermal energy projects are the 2006's earthquake in Basel (magnitude 3.4) and the 2013's one near St. Gallen (magnitude 3.5) [59].

largest market. In the 2018 EV Outlook, Bloomberg New Energy Finance projects an exponential growth to come *(Figure 4.15).*

- ## 4.3.4 - Mitigation: Carbon Capture and Storage (CCS) and Carbon Sequestration (CS)

There is a further set of mitigation strategies that does not neatly fit into the previously seen demand- and supply-side mitigation categories. Carbon dioxide not only can be emitted at lower rates by means of reducing the energy demand or through an ecological transition in energy supply, but also can be taken up from atmosphere once that it has been emitted. Non-biological Carbon Capture and Storage (CCS) is a process by which CO_2 is captured through chemical reactions and then stored with multiple methods including the injection in geological sites or deep oceans or the transformation of carbon into mineral carbonate form. Biological Carbon Capture and Storage or Carbon sequestration (CS) utilizes the capacity of plants to absorb carbon and bind it into their tissues. Afforestation and reforestation are the two strategies making use of this capacity.

- ### 4.3.4.1 - Overview

The core concepts of climate change mitigation are mostly about an increasing efficiency during all kinds of energy process, an energetic market transition from fossil towards cleaner fuels and renewable sources and finally a complete cultural change relating the way we transport, produce, deliver and ultimately use energy. Actually there is another option at our disposal in the context of climate change mitigation: Carbon Capture and Storage (CCS) and Carbon Sequestration (CS).
As discussed up here, there is a certain variety of strategies that can be used to address the issue of rising levels of GHGs in the atmosphere and help mitigating climate change. Carbon Capture and Storage (CCS) is one of them, although it does not fall into the previous supply- or demand-mitigation categories. Despite its great potential, it remains one of the less common mitigation strategies. CCS removes carbon either before or after the combustion, both exploiting biological or non-biological mechanisms. Carbon Sequestration (CS) refers to the capacity of some biological organisms like plants to extract atmospheric CO_2, store and then use it to build cellular structures for their tissues. Being widely considered to have a significant potential for mitigation, the CCS cannot solve the climate issue single-handedly: it is rather a part of a mitigative actions portfolio which is diversified. CCS is now rather supposed to act as a bridge from the current fossil-fuel based energy system, to a lower carbon future. This "assisting" role of CCS with respect to a more complex ecological transition, is feasible because of its relatively easy applicability to our current energy system.

CCS implementation on existing fossil-fuel plants - especially coal – can lead to 80%-90% cuts in carbon emissions [53]. Those dramatic reductions become cost-effective only when a significant price is attached to carbon. A coal plant with a CCS system costs nearly two-thirds more than an equivalent one without CCS that produces the same amount of electricity [54]. In *(Figure 4.16)* is clearly visible that

Metric	Unit	Ultrasupercritical Coal	Ultrasupercritical Coal with 90% CCS	Onshore Wind	Solar PV
Overnight Capital Cost	$/MW	3,636,000	5,569,000	1,690,000	1,373,690
Fixed O&M Cost	$/MW-year	42,100	80,530	39,700	21,800
Variable O&M Cost	$/MWh	4.60	9.51	0	0
Fuel Price	$/MMBtu	2.20	2.20	0	0
Heat Rate	btu/kWh	8,800	11,650	0	0
Capacity Factor	%	0.85	0.85	0.40	0.25
CO2 Transport & Storage	$/MWh	0	9.13	0	0
Levelized Cost	**$/MWh**	**$92.46**	**$151.34**	**$58.36**	**$71.12**

Figure 4.16 | Levelized generation costs of coal, coal with CCS, onshore wind and solar PV plants at the moment. Credits: https://www.forbes.com/sites/energyinnovation/2017/05/03/carbon-capture-and-storage-an-expensive-option-for-reducing-u-s-co2-emissions/#2049ea506482

as a source of low-carbon power, CCS implemented in a coal plant cannot compete economically with solar PV and wind in terms of Levelized Cost of Energy (LCOE). Bringing CCS costs in line with the two major renewables, would require approximately a $80/MWh subsidy according to the latest estimates [54].

- ### 4.3.4.2 - CCS

CCS consists of a three-steps process. First the carbon dioxide is collected from air or plant's flue gases making the use of various technologies (e.g., adsorption, absorption, scrubbing, etc.), then it is transported from the source to the storage. Finally, it is sealed and eventually buried so that it cannot reach the atmosphere. One of the greatest issues for CCS technologies is the choice for the storage sites. The most commonly used option for captured carbon is storing it in geological formations such as coal beds with low commercial values, deep saline aquifers or exploited oil and gas reservoirs. In none of these cases the CO_2 is injected in empty caverns, but rather confined into porous sediments or liquids. Another storage option is to inject CO_2 deep into the ocean, where it would remain insulated for centuries. Over millennia, carbon would eventually be exchanged with the atmosphere, resulting as if it were directly injected into the atmosphere but with a longer timescale. Ecological near-terms impacts linked to this solution include the acidification of the ocean in the vicinity of the injection site, causing potentially dramatic ecosystem changes. As seen previously, ocean acidification is an ongoing process contributing to coral reef mortality that would had better not to be exacerbated. A third way to store carbon dioxide after being captured is the transformation from gaseous CO_2 into stable mineral carbonates through reactions with metal oxides[133].

Geological storage remains the most promising technology among the above mentioned, given that often pipelines are already in place to transport and store carbon in depleted oil and gas reservoirs while dangers to flora and fauna make ocean injection ecologically risky. Mineral carbonation technology is not yet ready for application as it requires massive input of energy. Other controversies surround non-biological CCS, such as the risk of sudden release from underground reservoirs of the highly concentrated CO_2 (even if it is rather unlikely), or the fact that it is far from being the ultimate solution, but at best a bridge from a high-carbon system to a low carbon one.

- ### 4.3.4.3 - CS

Besides non-biological CCS, there is another way of removing carbon dioxide from the atmosphere and the Planet does it all on its own. Extracting atmospheric CO_2 and binding it in the living tissue of photosynthesizing organisms is the so-called Carbon Sequestration (CS), often referred as Biological Carbon Capture and Storage.

Two core strategies can be used to increase the amount of carbon that a piece of land sequesters. The first is called ***afforestation*** that is planting threes on land that has never had threes on it (or at least not in recent memory). This results in a net increase in the amount of carbon uptake from that piece of land. The other strategy, the ***reforestation,*** replaces forests that were recently removed. Other ways to improve biological carbon sequestration are the use of soil amendments and no-till agriculture. Biological CCS has weaknesses too. On the one hand forests are not permanent in the sense that if a fire occurs, the combustion of the living matter releases the carbon dioxide bound in the plant tissues back into the atmosphere. On the other hand, wood from forests can be used for fuel by humans who often clear lands for agriculture or other activities. For this reason, a key problem with CS as a mitigation

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[133] Mineral carbonates storage is not yet commercially viable because it is a rather energy intensive process. A powerplant with mineral carbonation requires on average 60 to 180% more energy to work than a typical plant without mineral carbonation [62].

strategy is one of permanence. In addition, this method of mitigation carries considerable uncertainty and calculation errors associated with reliable estimates on the amount of carbon that will be taken up by a given area of threes. For these reasons, biological CS (as non-biological CCS), cannot be considered as the most effective long-term mitigation strategy available.

- 4.4 - ADAPTATION

Key points

Besides mitigation strategies, adaptation is required to face the multiple impacts of a changing climate. There are both biophysical and human dimensions of the adaptation. In order to develop a successful adaptation strategy for a certain place or community is crucial to consider the underlying drivers of their related vulnerability and the technical or ecological tools available there to deal with the impacts. Specific strategies exist, ranging from preservation of ecosystems, support for developing countries and poorer areas, smarter planning of cities' infrastructure and ultimately literacy initiatives about climate change process and mechanisms. A quick look at the so-called ecosystem-based approach adaptation is then taken.

- 4.4.1 – Overview

In the first Section of this Chapter, the range of observed and predicted impacts of climate change have been discussed; then the second outlines the strategies developed to reduce GHG and help to mitigate climate change. However, some degree of climate change is inevitable, even if we suddenly take our global emissions to zero tomorrow[134]. This means that we must prepare and protect communities and planet ecosystems from the impacts of climate change that are yet occurring or that are expected to occur soon. This is the domain of adaptation.

In order to discuss the core concepts of climate change adaptation, the definitions of "Vulnerability", "Adaptive Capacity" and "Resilience" must be refreshed. ***Vulnerability*** to climate change impacts represents the convergence of exposure and sensitivity to impacts; ***adaptive capacity*** indicates the ability or potential of a system - including its technological and financial resources and human or social capital as well - to successfully respond to climate variability and changes; finally, ***resilience*** refers to the severity of the impact the system can undergo, without being fundamentally altered[135]. Adaptation is a set of responses that help to reduce vulnerability and enhance resilience at the same time through a management of the risks associated with climate change impacts. Adaptation experts are often specialized on risk perception/analysis, disaster management, urban planning and ecology.

One of the first common distinction between adaptation and mitigation concerns their level of operation: adaptation is essentially local in focus, while mitigation is rather global[136]. Adaptation is best implemented if it is integrated into already existing programs, like city planning, development aid or ecological conservation measures. An important distinction based on the timing of the adaptation actions differentiate between responsive or ***reactive adaptation*** and anticipatory or ***proactive adaptation.*** On the one hand, adaptation can be viewed as reactive either ***in stimulus*** or ***in form***. "In stimulus" means in response to observed changes (e.g., if a community experiences water shortage, it can develop irrigation systems that address the problem). "In form" refers instead to actions that do not prevent the impact from occurring but help to recover after the occurrence. Insurance is a good example of reactive

[134] See *Section 3.3.5.*
[135] See *Section 4.1.*
[136] The benefits of erecting a flood protection system (which is a typical adaptation action), only protects those people in the nearby floodplain. Emission reduction (which is a typical mitigation action) implemented in any location, affect the global climate equally instead.

in form adaptation as it helps compensate victims of climate change impacts but does not protect them physically. Reactive adaptation is informed by direct experience rather than forecasts. For this reason, resources can be targeted to precise strategies, with lower uncertainties. Reactive adaptation is rather familiar to humans as we have been doing it for thousands of years. There are many examples of climate adaptation throughout history: irrigation, water management and crop diversification for instance, have been common reactive adaptation strategies in agrarian societies since the development of agriculture[137]. More recently other reactive adaptation strategies like disaster risk management have been developed to face the increasingly frequent extreme events, helping communities to recover from and prepare for them as well. On the other hand, proactive adaptation relies on future estimates or forecasts. As proactive adaptation's driving force is the prediction or expectation of events that have not been experienced yet, it can be seen as the ultimate goal of the climate change research and practice community. Depending on forecasts and estimates, proactive adaptation faces also the related uncertainties: infrastructures, services and cities planning must depend on accurate information about the extent, timing and distribution of the impacts. Proactive adaptation is the frontier of climate change responses and requires significant advances in the science underpinning models and scenarios.

Even if it is true that adaptation is a familiar concept to humans, as we have been adapting to the environment we live for hundreds of years, it is now clear that anthropogenic climate change is pushing humanity outside of its well-trained capacity to adapt. Not only droughts and heat waves are more extreme in many places than ever seen in the past, but newer impacts like rising sea levels and increased unpredictability of extreme events are being experienced more and more frequently. Besides these challenges, there is the fact that massive infrastructure and huge cities have often been built in vulnerable zones, without taking in consideration the linked risks. All this considered, it must be highlighted that the ability to proactively adapt to climate change is constrained primarily by the knowledge of the phenomenon of climate change as well as the political wish to take precautionary actions and the public's perception of the risk.

- 4.4.2 – Adaptation strategies

As discussed deeply in *Section 4.1,* multiple impacts of a changing climate are clearly visible yet. Higher temperatures, unpredictable and more intense precipitations, more frequent extreme events, etc., are pushing ecosystems into new territory. Generally speaking, ecosystems are shifting to higher latitudes leaving behind areas that are no more favorable. This brings a couple of significant repercussions. First, the more fragile species whose habitat exists o an edge such as the top of a mountain or a coastline (the so-called *edge species*), can be pushed into extinction. Secondly, the human dimension of these shifting processes must be taken into account. At the moment, we depend on a particular mix of crops and cultivations and we are consequently vulnerable to the upheaval in the market that would inevitably follow if these cultures begin to fail. In some areas, warming may benefit those types of crops that are typically grown there, but if the higher temperature exceeds a crop's optimum temperature, yields will decline.

On the whole, the increasing temperatures are likely to have a negative effect on the global yields of wheat, rice and maize. In particular, each degree Celsius increase in Global Mean Surface Temperature (GMST) is estimated to reduce average global yields of wheat by 6%, rice by 3.2% and maize by 7.4% [54]. The regions involved in these yields' cuts, might support typical hot climate crops like pecans, olives and even avocadoes within the end of century. This means a transition in economies and a stress supply of some foods over others. So, how to adapt is the crucial question. Part of the answer is to anticipate

[137] By 5000 B.C., Sumerians had developed large-scale intensive cultivation of land and organized irrigation. Cultivations of barley in Egypt, Mesopotamia and Iran were grown even in areas where the natural rainfall was insufficient to support the crop.

the ways climate will change and start to grow crops that are amenable to that change. The same goes more broadly to ecosystems. This branch of adaptation requires to preserve the habitats of vulnerable species by creating protected area in response to habitat fragmentation and even in some cases, supporting the shifts of ecosystems into new territories. This is the first huge category of adaptation: responding to stresses from climate change to which ecosystems are subjected to.

The second broad adaptation category deals with the underlying drivers of vulnerability. As discussed yet, communities and individuals are much more vulnerable to climate change if they are situated in poorer, less educated or unhealthy areas and the ones lacking access to services like sanitation as well. The task in these zones is to cultivate community-based proactive adaptation, including literacy programs, a smarter management of food and water provision and agricultural adaptation like crop rotation or new ways of irrigation. Right here a clear responsibility for wealthier nations exists too. As the majority of GHG emissions have historically come from the industrialized West[138], while most of the impacts are suffered by people in the global South, the wealthier nations have a responsibility and a moral duty to support development in the regions that are and will be most deeply affected by climate change. This has led to the creation of the Official Development Assistance (ODA) - an indicator to detect the international aid flow, used since 1969 - from the Organization for Economic Co-operation and Development (OECD) and multiple humanitarian programs. Scientific literature however has conclusively shown that literacy, nutrition, education and security of livelihoods are the most important components of resilience to future climate change impacts [56].

The third broad category of climate change adaptation responses pertains directly to projected impacts. As exploring future climate and social scenarios is getting more and more accurate, a better idea of the actions that are required to protect the humanity against potentially catastrophic events are gained. For instance, smart city planning can provide a distributed energy generation system, a secure food supply and protected vital infrastructures. Technological improvements including better insulated buildings, reflective roads and walls, built-in cooling system (not air-conditioning), etc., will be fundamental in this context. Administrative solutions that can be put into place as well. Possible examples are efficient weather warning systems, policies encouraging tree planting and designed emergency plans to address heat waves or the extreme events especially on the most vulnerable individuals. Other examples are supports for refugees that can be "created" by climate change, flood defenses and a widespread vaccines stockpiling.

Finally, in the context of adaptation as in any other climate or energy related issue, there is the personal behavioral dimension. Solutions for individual adaptation strategies range from maintaining a proper body hydration to changing our work hours, wearing less formal clothing, etc.
A key part of climate change adaptation (and climate change in general, as any other issue) is simply understanding more about it. Greater certainty in models and scenarios is needed as well as a better understanding about how human systems will respond to the predicted changes. The science and social science of climate change must continue to improve in order to support actively the adaptation to climate change. An example of this continued learning and improvement is what is called the *Participatory Scenario Development*. Models and scenarios about the future have always been about science and scientists. The point is that the complexity of human behaviors and governance is one of the biggest question marks within all the climate change aspects. This means that Science needs more voices at the table. Nowadays, some of the most valuable scenarios of emissions and impacts comes from a participatory process allowing the sharing of traditional knowledge about ecosystems changes

[138] The US alone accounting for the 28.8% of the total global cumulative emissions between 1850 and 2007 and other European countries in the top 10 like Germany (6.9%), the UK (5.8%) and France (2.44%) [55].

and permitting different groups of people to voice their views about what can be desirable for a possible future.

One of the greatest challenges of climate change adaptation is to feed the outcomes of these scenario processes into decision making, giving them a practical implementation. A flexible mindset from policy makers is required in order to shift decisions once new information emerges. In other words, we need to adaptively manage our communities to account for shifting values and habits, priorities and information.

- 4.4.3 – Ecosystem-based approaches

A relatively new approach to climate change adaptation (and mitigation as well) is the *Ecosystem-Based* management, or *Environmental Management* approach. This aims at delivering on multiple priorities simultaneously, rather than just one. It means for instance, using living systems like forests or wetlands instead of the traditional "grey" infrastructures. A practical example is using a series of salt marshes to capture and purify stormwater, rather than burdening the sewage system, rising floods. Another example is the use of oyster reefs to protects coastlines from wave action or storms rather than simply building higher walls. The use of "green" instead of "grey" infrastructures, when feasible, can have several benefits. One of the most important is that multiple objectives are achieved at the same time, from sinking carbon, to protecting against floods and purifying water. Sustainability is not only about the reduction of emissions or protecting mankind against the impacts of climate change, but rather creating communities that are healthy and resilient.

As ecosystem-based approaches are economically speaking "new territory", the financial costs associated can be higher in the short-term period. Other challenges relate to their complexity and management; ecosystem-based approach is an unfamiliar technology and therefore it needs the collaboration between different experts and wide variety of stakeholders to be designed and engineered.

- 4.4.3.1 – Two examples: Malmoe and the Maldives

An example of ecosystem-based approaches implementation as a part of a broader community transition towards sustainability is a neighborhood of Augustenborg in the city of Malmoe (Sweden). Augustenborg was plagued by floods from overflowing stormwater systems and was also facing socio-economic decline. The residential area launched the project called "*Ekostaden Augustenborg*" (Ecocity Augustenborg) since 1998 which made the use of a sustainable urban drainage system based on wetlands that is currently doing the its job, managing stormwater while also sinking carbon, preserving habitats for birds and amphibian species and providing beautiful landscapes for residents. The project aimed to enable residents to take a leading role in during the design and implementation of the plan. The environmental impact has decreased and Augustenborg has become an attractive and multicultural neighborhood as a result [56].

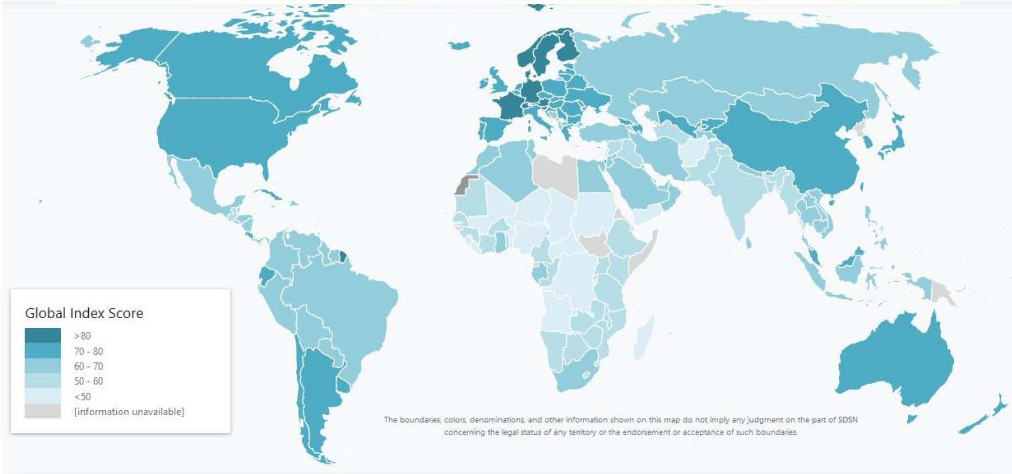
Another example of this kind of adaptation is happening in the Maldives. Being the planet's lowest lying country, the nation made of 192 islands in the Indian Ocean, the Maldives hosts 448,000 people [57]. Many of these are exposed to the threat of rising sea levels and wave actions. In response to these risks and also to the tremendous damages that resulted from the 2004 tsunami, the Government begun building safe islands that are the products of dredging sand from the Ocean floor and have a larger buffer zones between settlements and the Ocean. Besides that, renewable energy, waste management and coral reefs preservation are also part of the Maldives plan.

CHAPTER 5 – SEVEN DIFFERENT SCENARIOS FOR THE FUTURE

Current commitments contained in the Nationally Determined Contributions (NDCs)[139] are inadequate to bridge the climate system to a below 2 °C warming at the end of the 2100. Technically it is still possible to ensure it below 1.5 °C, but if NDCs ambitions are not strongly adjusted by 2030, exceeding the 1.5 °C goal will be virtually certain. Unprecedented mitigation and adaptation actions must be taken by all nations now. Total annual GHG emissions including all the sources reached a record high in 2017 exceeding the 50 GtCO2eq (53.5)[140]. In order to meet the goal of limiting global warming to 2 °C or 1.5 °C respectively, global GHG emissions in 2030 need to be 25% and 55% lower than 2017, according to the Intergovernmental Panel on Climate Change (IPCC) that has put it down black and white with unprecedented confidence. Actions, behaviors, new perception about climate change and new way of tackling it are required. The UN have gathered them in the so-called Sustainable Development Goals (SDGs) that are part of the Resolution 70/1 of the United Nations General Assembly, the 2030 Agenda. A sketch of the 17 SDGs is provided after this paragraph, as well as a World atlas showing countries that are closest to meeting the SDGs and those farthest in 2018.

In this context it becomes crucial to understand better the future that awaits us, in a practical and scientific way, by delving into the various interrelations governing all the climate system and change aspects. This is done by the assessment of a set of scenarios starting from several hypothesis and boundary conditions (from socio-economic to climatic and thermodynamic ones) worked out using Java Climate Model (JCM), an open-source software developed by climate scientist Ben Matthews, Université Catholique de Louvain, Centre de Recherche sur la Terre et le Climat. The ratio with which scenarios are modeled is exactly the same (obviously due proportions) as the one with whom the United Nations Framework Convention on Climate Change (UNFCCC) or the International Energy Agency (IEA) elaborate their Reports (e.g., respectively the Assessment Reports (ARs) and the World Energy Outlooks (WEOs)).

[139] NDCs are the reductions in GHG emissions that all countries that signed the UNFCCC were asked to publish at the 2013 United Nations Climate Change Conference held in Warsaw, Poland, in November 2013.
[140] In 2016 they were 49.3 Gt-eq [2].



- 5.1 – Types of scenarios elaborated

The first three scenarios are the ***normative scenarios***. A normative scenario starts from the present situations and tries to answer to the question "***How can a specified target be reached?***". In other words, knowing where we want to go, what has to be done between now and a future point in order to reach that objective? The objective here is the stabilization of a pivotal climate parameter[141]: the analysis is intended to steady the climate parameter by adjusting the others. The parameter to be stabilized in the following normative scenarios presented will be the Global Mean Temperature (GMT). The time horizon considered in the analysis spreads from now to the year 2100. This is exactly what the most updated scientific literature available tries to do and the rationale underpinning the IPCC's scenarios. The three Stabilization scenario that will be discussed are ST1.5, ST2.0 and ST3.0, where "ST" stands for Stabilization and 1.5, 2.0 and 3.0 for the entity of the increase in GMT at the end of 2100.

The second pack of scenarios are three so called ***predictive scenarios***. They answer to the question "***What will happen?***". Starting from what we know about the present and the past, what is the more probable situation in the future? Obviously, given the impossibility to estimate uniquely one single future for a system this complex as the climate one is, three different scenarios are modeled, leading to rather widely differing outcomes depending on the weight of some anthropogenic climatic driving force.

The first two Predictive scenarios are ***Current Policies Scenarios***. This is the kind of scenario that is often referred to as "Business as usual" in all the Reports from IEA, IPCC, UNEP, IRENA and so on. Here in particular, two Current Policies scenario (acronym CP) are analyzed. CP1 considers a rather fossil-fuel based development of the energy system, while CP2 accounts for a more balanced one, with renewables starting to get momentum right now[142]. The third Predictive scenario is the ***New Policies Scenario*** (NPS).

[141] These scenarios are often referred as "Stabilization Scenarios".

[142] The current renewables growth rates are implied in CP2, but Renewables weight in the future energy system is stressed even more with respect to the present situation.

NPS is quite similar to the 2018 WEO homologous one and implies basically its energy demand growth and pathways concepts. NPS accounts for all the climate policies that have taken place right now, and all the ones that have been announced by institutions, especially after COP 21. This is a quite optimistic approach, but somehow significant in the outputs, as will be seen.

The last scenario taken into consideration for this analysis is an **exploratory** scenario. This type of scenario considers the present situation and aims to answer to the question "*What might happen?*" given different hypothesis and pathways leading to different possible futures. In particular here the *Sustainable Development Scenario (SDS)* - in line with what the last two (2017 and 2018) WEOs do - models the most preferable future we can expect, in which accelerated energy transition put the world on track to meet several Paris Agreement goals, clean air and water, social equity and welfare access to developing economies.

So, let us start digging into the subject.

- 5.2 – Stabilization Scenarios (ST)

The following three scenarios will be similar in the hypothesis and in the outcomes to the ones that the International Panel on Climate Change (IPCC) proposes in its Reports. The most important point that comes out from their development and must be remarked is the substantial unlikeliness of the two scenarios projecting a GMST warming smaller than 2.0 °C. In particular, it is physically correct to say that the below 1.5 °C GMST warming is yet feasible, but considering the climatic inertia, the unprecedented magnitude of the counteractions that would be required to meet the goal and most importantly, the fundamental unwillingness by Institutions and Government to pursue them, it does seem to be practically unachievable.

- ST1.5

Scenario ST1.5 takes into account the most ambitious goal in the context of the Paris Agreement: a stabilization of the global mean temperature to 1.5 °C above the pre-industrialization levels. By looking at the temperature curve, it is clearly visible the magnitude of change that our current climate system would undergo to meet the 1.5 °C commitment: the rising trend that we are currently experiencing would be abruptly interrupted. In order to have a stabilization at 1.5 °C by 2100, the current trend must be reversed within nearly 10 years, reaching 1.45 °C by 2030 and not declining until 2100 *(Figure 5.1-a)*.

The idea of the unlikeliness of ST1.5, is dramatically visible with the CO_2eq emission curve *(Figure 5.1-b).* ST1.5 projects a GHG emissions peak in 2019-2020. This means that in order to have a chance to keep the GMT rise down the 1.5 °C, the GHGs emissions must peak today and start a rapid decline tomorrow. This is something that we have to understand and get in our head. However, the most interesting point is the entity of that peak: 53-54 GtCO_2eq per year, that is slightly over the 2018 value. As said, after that peak a dramatic decrease is needed to meet the 1.5 °C goal. The entity of this decrease in GHGs emission is yet physically feasible if extremely unlikely. This is clear even only by looking at the shape of the emission curve that is quite forced and unexpected.

A similar behavior follows the GHG emission from the energy sector curve *(Figure 5.1-c),* reaching a peak (9.6-9.7) GtCO_2 per year and then declining abruptly, following a similar pathway as the total GHGs emission curve does.

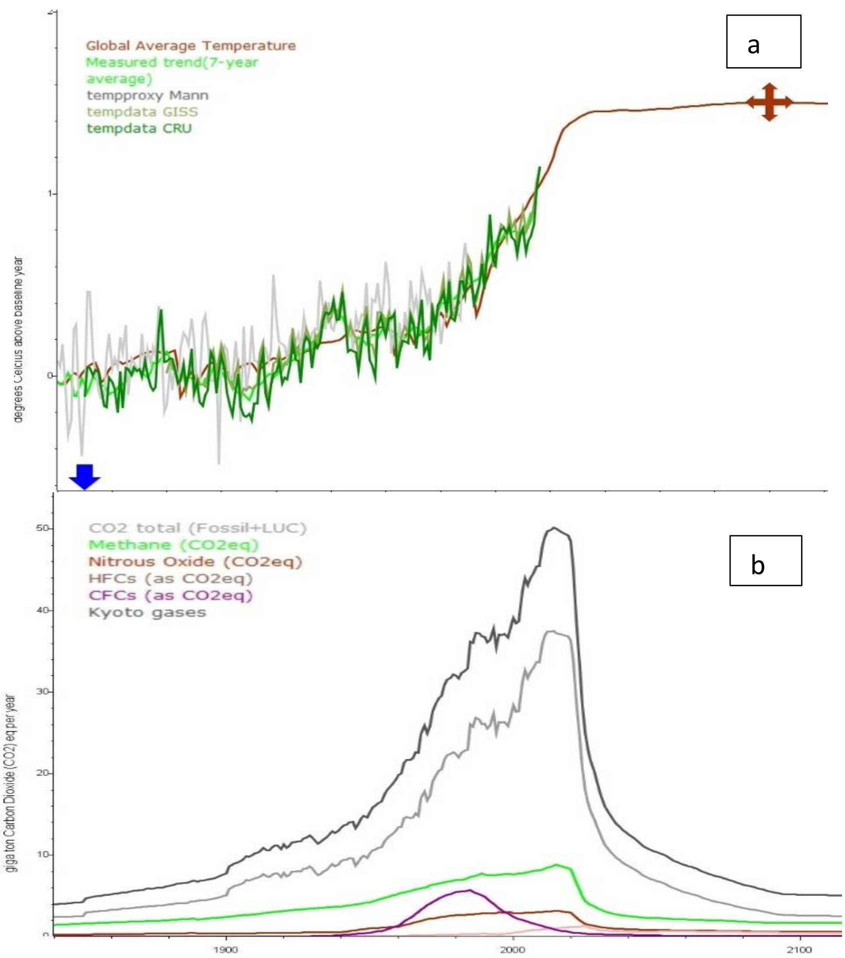
Regarding the atmospheric concentrations, the one that is most significant to the analysis is obviously the CO_2 one *(Figure 5.1-d solid black line).* ST1.5 estimates for it a peak during the period 2022-2024 with values around 414-415 ppm, not so far from the current levels (409.23 in Jan 2019, 410.03 in Feb

2019, 413.09 in Mar 2019). By 2100 CO_2 concentration would fall off to approximately 403 ppm. Even by looking at the trend of the curve, it is quite clear that ST1.5 picture a future that almost certainly we are not going to experience, given the well discussed theme of the huge inertia to which climate system (and natural ones generally speaking) are subject.

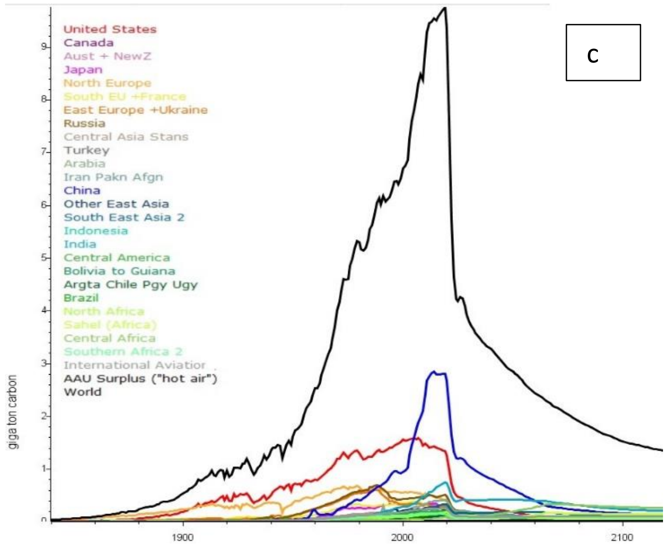
As it comes to the Radiative Forcing (RF), the trend is basically the one seen for the emission curves but shifted afterwards a little bit. The peak is placed approximately in the period 2023-2025, reaching 2.85-2.95 W/m^2 *(Figure 5.1-e).*

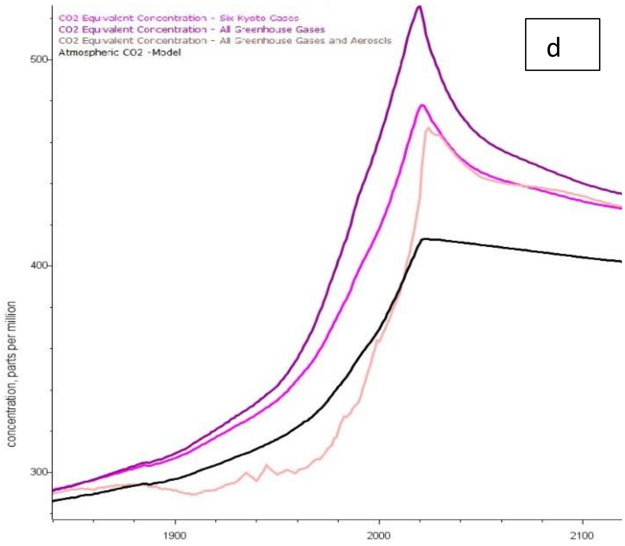
Sea level rise would be rather modest[143] and would reach 440 mm by 2100 but without peaking (increasing trend after 2100).

Finally, for the ST1.5 the horizon at 2030 seems to be rather unlikely with values of 14.74 $GtCO_2eq$ in total global GHG emitted, 3.79 $GtCO_2$ from the energy sector, RF of 2.78 W/m^2, 260-2.270 mm of sea level rise. In other words, the path bridging us to only guarantee a 1.5 °C warming at the end of the century is technically possible, but it would require peaking global GHG emission as we speak, at this very moment. According to Global Carbon Project, CO_2 emissions have resumed increasing after a plateau during the period 2014-2016, with a +1.6% rise in 2017 and a +2.7% in 2018 [1]: no peak signs seems to be at the horizon. This conveys the insight of what is the magnitude of efforts that humanity must put into the climatic issue. In conclusion, ST1.5 is a purely informative scenario and gives the idea of how far we are away from the safest world possible (but not so safe in absolute terms), the one which provides for a 1.5 °C warming by 2100, given the current climatic and anthropogenic boundary conditions.



[143] If this word associated to a huge Earth system modification as sea rise is, does make sense.





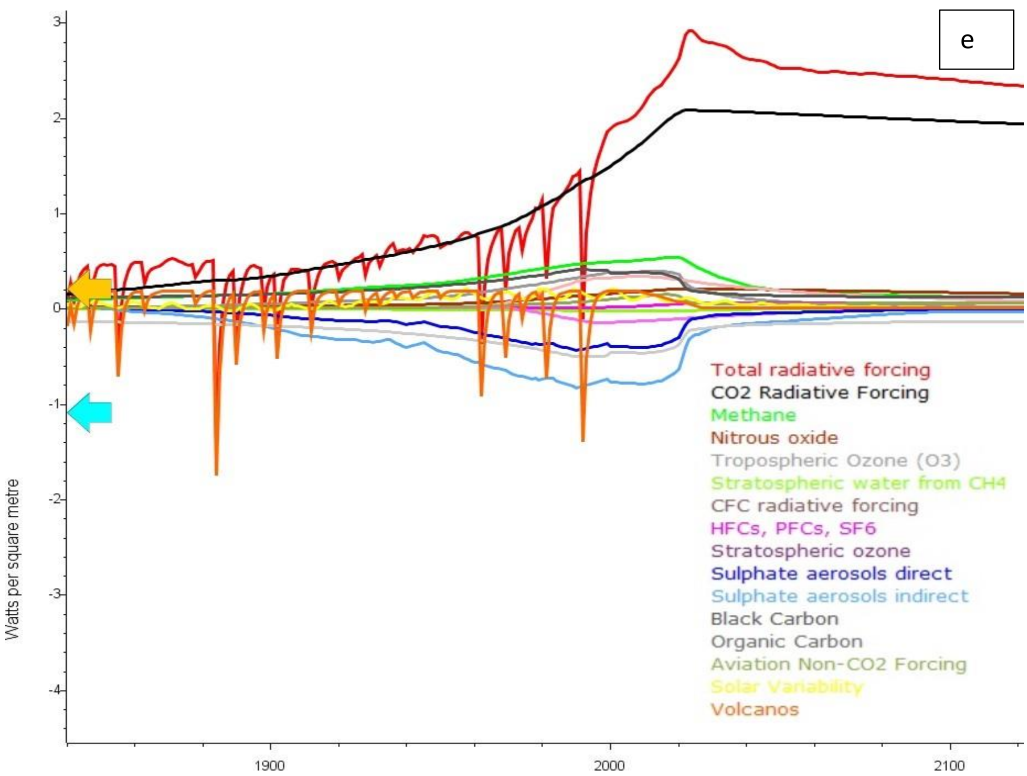


Figure 5.1 | Seven different scenarios for the future: ST1.5 (a) Global Mean Surface Temperature (GMST) trend referred to 1850 as baseline year. (b) Global GHGs emissions measured in gigatons equivalent CO_2 per year. (c) Global CO_2 emissions from the energy sector by country measured in gigatons of carbon per year. (d) CO_2 and other GHGs concentrations in atmosphere measured in ppm. (e) Radiative Forcing (RF) trend from the major drivers – mainly CO_2, methane, nitrous oxide, ozone, water vapor, CFC, HFC, PFC, SF6.

- ST2.0

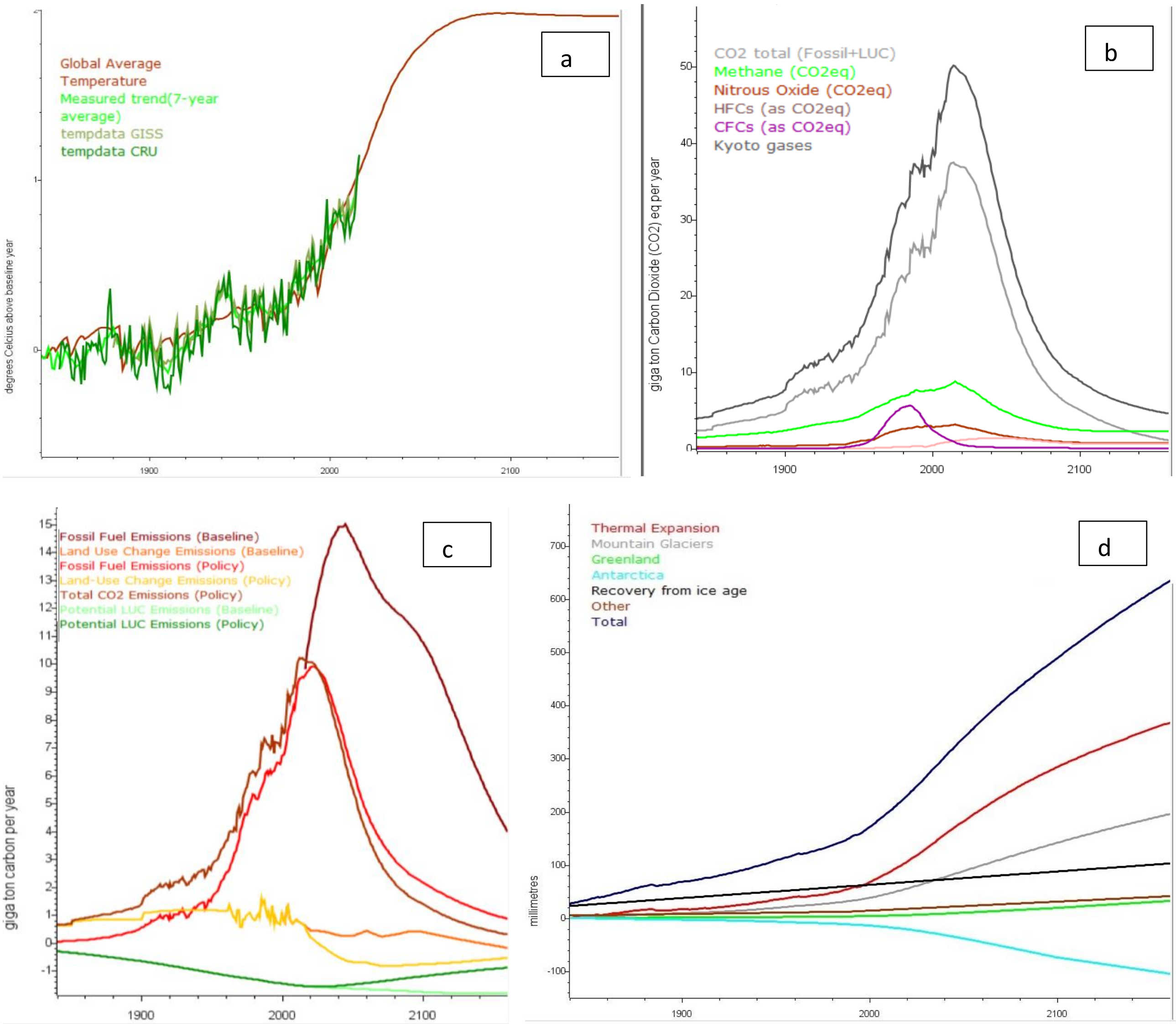
According to scenario ST2.0, the difference between the mean temperature projected and the one measured in the baseline year (which is 1850) approaches the equilibrium approximately in 2100, after the abrupt increase that we are experiencing, reaching the 2.0 °C *(Figure 5.2-a, brown solid line).*

It is interesting first of all to delve into the radiative forcing parameter (RF) *(Figure 5.2-).* In order to stabilize a 2 °C warming of global mean temperature it is needed to peak the radiative forcing at values into the range [3.34 -3.35] W/m^2. The peak is projected to occur between 2050 and 2060. This fact is crucial to convey concretely the concept of climatic inertia that has been discussed in the previous Sections: in order to peak and stabilize temperature to a certain value (that is more likely than the ST1.5 one) until 2100, the RF must peak from 40 to 50 years before. This is a quite significant result, because it does mean that if the RF rise one year with respect to the previous, the probability that the GMST will stabilize within 40 or 50 years gets smaller and smaller.

Coming to the more tangible GHG emissions *(Figure 5.1-b),* ST2.0 projects this "precursor-acting" behavior to be even more marked. For the 2 °C scenario, the peak in global annual emission of equivalent carbon dioxide is expected in nearly a year by now (2020) reaching the 53-54 $GtCO_2eq$, a value close to the one that we are currently emitting, as for ST1.5.

Concerning sea level rise *(Figure 5.1-d),* as it deals with the most important contributor of climatic inertia, all the curves accounting for the rise coming from thermal expansion of water (red solid), ice melting (solid black), etc. show an increasing trend. In other words, while radiative forcing and GHG emissions peak and then start to decline before 2100, sea level rise keeps on increasing even after. The rise in ocean and sea level will reach approximately 500 mm by 2100, according to this scenario.

It is important to highlight that considering the global total equivalent carbon dioxide emission plot, measured and projected data until 2019 show an exponentially increasing curve. As for the ST1.5, it is rather obvious that reversing such a trend, given the massive driving forces underpinning it, is quite difficult and fairly unlikely even for a less ambitious goal as the 2.0 °C ones is. The rates and even the possibility of this decrease seem to be definitely not on the agenda at the moment, making also the goal of limiting global warming to 2 °C before 2100 technically possible, but basically and practically almost impossible.



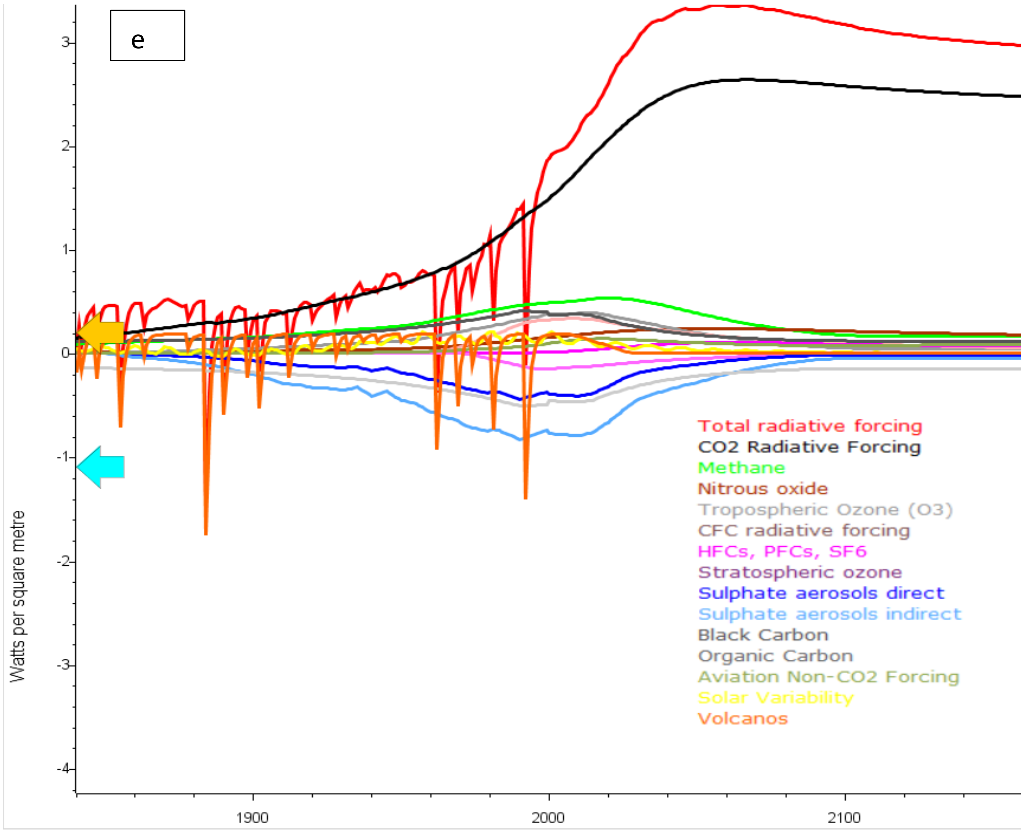


Figure 5.2 | Seven different scenarios for the future: ST2.0 (a) Global Mean Surface Temperature (GMST) trend referred to 1850 as baseline year. (b) Global GHGs emissions measured in gigatons equivalent CO_2 per year. (c) Global CO_2 emissions from the energy sector by country measured in gigatons of carbon per year. (d) Sea level rise and various contributions. (e) Radiative Forcing (RF) trend from the major drivers – mainly CO_2, methane, nitrous oxide, ozone, water vapor, CFC, HFC, PFC, SF6.

- ST3.0

ST3 is the last stabilization scenario considered by this analysis. It considers the maximum difference between global mean temperature projected and the one of the baseline years as 3.0 °C. Time horizon stretches until 2100 again. As illustrated below, this is the most plausible between the stabilization scenarios.

In *(Figure 5.3-a)* is shown the temperature trend. As opposed to ST1.5 and ST2.0, ST3.0 projects a peak-and-decline behavior, reaching the 3.0 °C peak by end of century. Temperature difference by 2030 will be 1.4-1.5 °C with respect to pre-industrial levels.

Coming to the global total equivalent carbon dioxide emission curve *(Figure 5.2-b),* a lot of significant outcomes come out. After ST1.5 and ST2.0, again a quite clear peak-and-decline behavior can be noted as regards the GHG emissions (solid black line) in $GtCO_2eq$ and the CO_2 share alone as well (solid grey line).

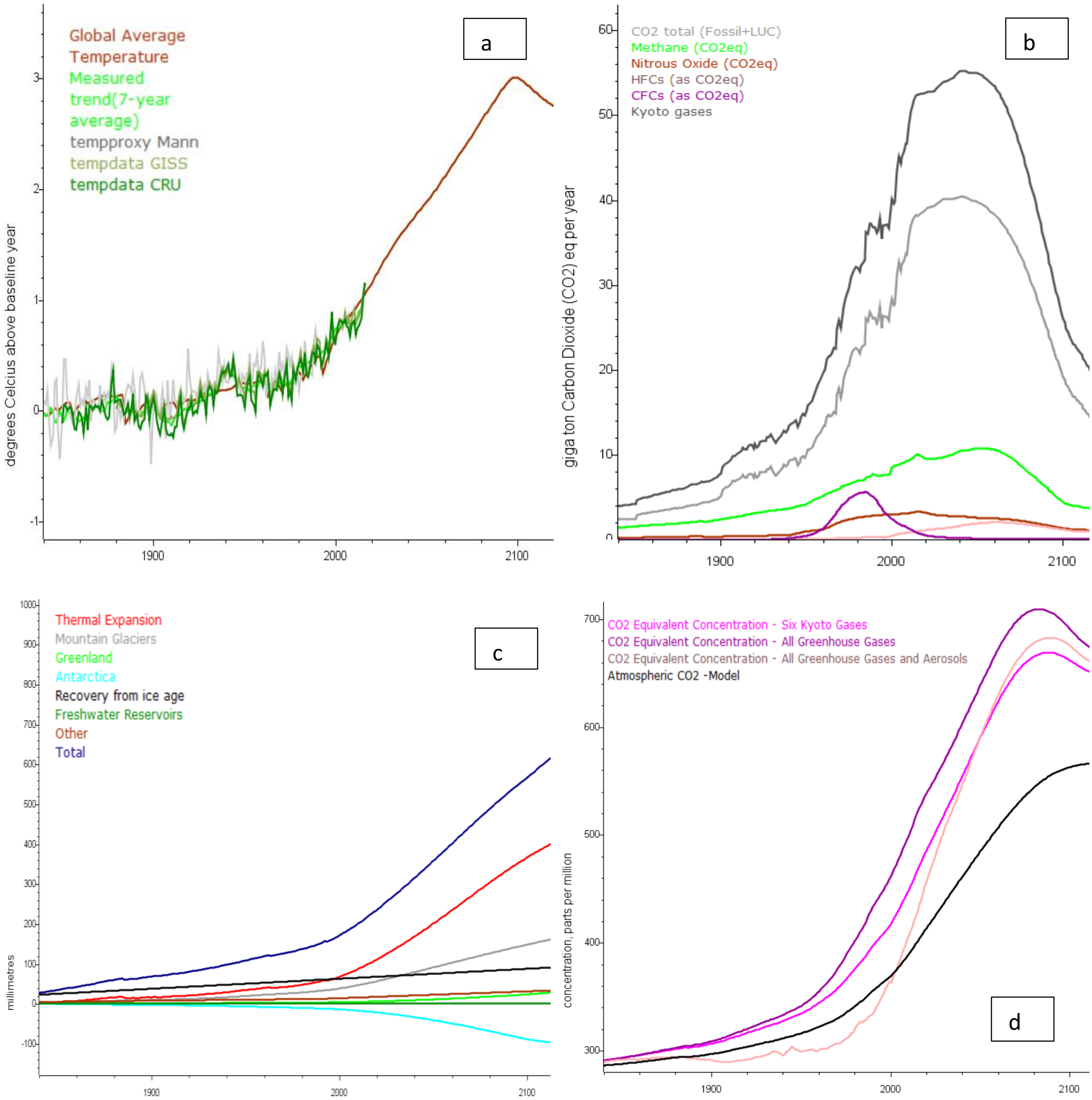
ST3.0 seems to project a more likely GHG emission trend, following something like a parabolic pathway, with a vertex (the emission peak) that is smoother with respect to the two previous scenarios spreading out on a period of more than 40 years (2019-2063). The peak reaches the 55.13 $GtCO_2eq$ by 2040. This evolution is far more consistent on the one hand with the climatic inertia and on the other with the current values and rates of economic growth and anthropogenic impacts.

A peak-and-decline trend is shown also by the RF curves. Total RF *(Figure 5.3-c solid red line)* is projected to reach 4.8-4.9 W/m^2 between 2087 and 2092 and then start declining slightly thereafter.

Moving to sea level rise, the curve show the usual increasing trend, approaching the 560-570 mm rise by 2100 *(Figure 5.2-d).*

As far as atmospheric concentrations are concerned, the CO_2 curve *(Figure 5.2-e black solid line)* estimates to reach 562 ppm by 2100, with the peak yet to come. Atmospheric carbon dioxide for ST3 will be 432-433 ppm in 2030 and 454-455 in 2040.

In the end, the ST3.0 scenario seems to be more consistent and geophysical feasible than the two previous ones, especially considering the CO_2.eq curve that has a far less sharp peak with respect to ST1.5 and ST2.0. It has to be pointed out, however that even for this scenario that is not so ambitious at all as it provides for the significant increase in global mean temperature of +3 °C, we are currently not on track. Unprecedented mitigation actions would be required also in order to meet ST3.0 goals. The magnitude of these actions is of course smaller than that of ST1.5 and ST2.0.



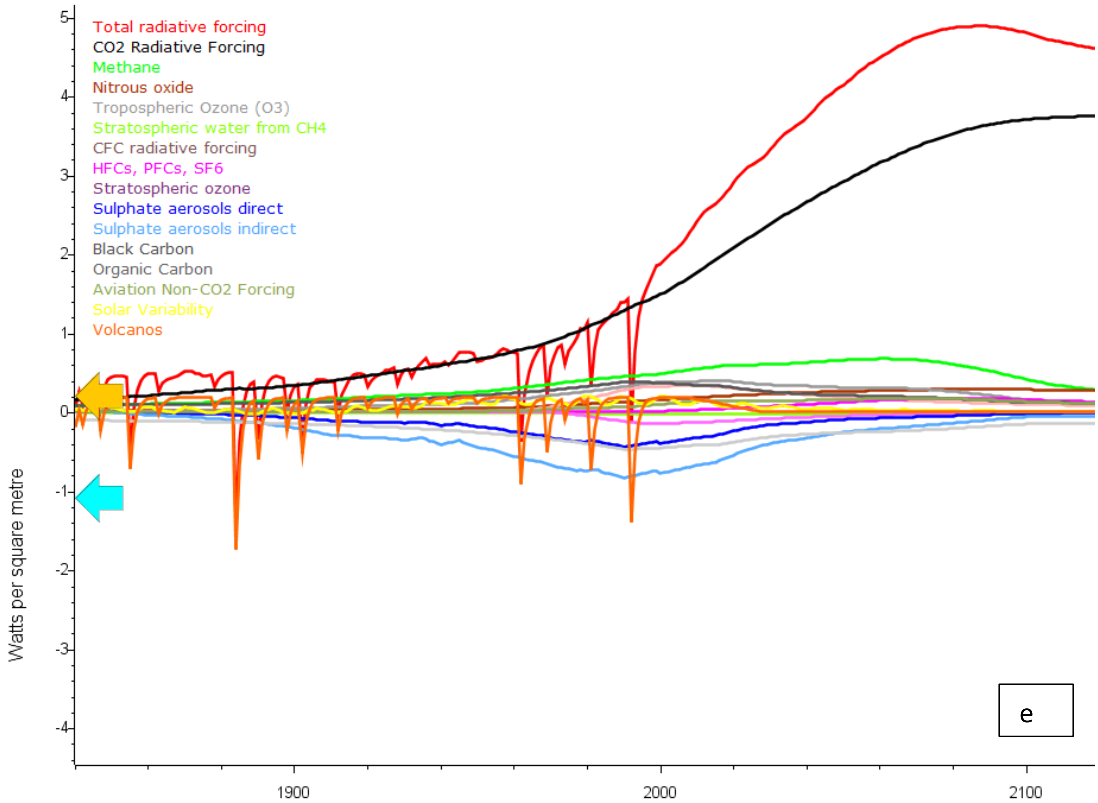


Figure 5.3 | Seven different scenarios for the future: ST3.0 (a) Global Mean Surface Temperature (GMST) trend referred to 1850 as baseline year. (b) Global GHGs emissions measured in gigatons equivalent CO_2 per year. (c) Radiative Forcing (RF) trend from the major drivers – mainly CO_2, methane, nitrous oxide, ozone, water vapor, CFC, HFC, PFC, SF6. (d) Sea level rise and various contributions. (e) CO_2 and other GHGs concentrations in atmosphere measured in ppm.

- 5.4 – "Future is" scenarios

As discussed previously, here a different approach is followed. Rather than considering the stabilization of a certain climate parameter such as the Global Mean Surface Temperature (GMST) by a certain year (2100), a group of different futures is covered with ranges of possibilities, given current values of all the climatic parameters that are implied. This methodology, as said, is the one followed by the International Panel of Climate Change (IPCC) and the International Energy Agency (IEA) in their Reports (World Energy Outlooks, Assessment Reports, etc.).

This task does not aim to forecast the future in a precise manner, but rather provides a way of exploring different possible futures, following different pathways. The most significant point of this kid of analysis is to track the various drivers that could bring to these pathways and analyzing the interactions that arise across the several elements of climate, energy and human systems.

- 5.4.1 - Current Policies Scenarios (CPs)

For the Current Policies Scenarios (CPs) the baseline case is assessed. The International Energy Agency (IEA) has developed one sound CP scenario that keeps updated in every years' WEO. The rationale of the CPs assumes that future development trends follow those of the past and no changes in policies will take place. The akin for the CPs in the Intergovernmental Panel on Climate Change (IPCC)'s Reports is represented by the so-called "business-as-usual" scenarios. To give a reference on the basis of the scenarios analyzed in Chapter 4, the CPs lead to outcomes that can be placed between the RCP6.0 and RCP8.5.

- CP1

As said, the CPs assume no change in policies from today is expected. However, from the point we are, multiple parameters can be adjusted to outline possible future developments taking into account that they will be adherent to the recent past ones. The peculiar aspect of CP1 is that the development of the energy system will be yet fossil-fuel relying. This is a relevant aspect in order to attribute in a practical way, the crucial weight of the energy system on climate change. As discussed in previous sections, the energy sector is the major contributor to anthropogenic climate change, but how much it is worth this field on the various climate parameter, how does that reflect in terms of Global Mean Surface Temperature (GMST), Radiative Forcing (RF) or Greenhouse Gases (GHGs) emission change?

As will be seen, a rapid development of our society, based on a yet fossil-relying energy system is going to lead to increasing strains on almost all aspects of climate and energy security. In addition to this, major rises in CO_2 emissions are expected, especially (and obviously) energy-related ones. The current medium World's GDP growth rate is considered (3.74% according to World Bank in 2019).

This CP1 pathway bring us to a warming on GMST of about 4.023 °C by 2100 *(Figure 5.3-a)*. No peak is shown, meaning that the temperature increase would extend overtime after 2100. CP1 projects to reach and overcome 1.5 °C (1.568 °C) warming - the Paris Agreement's goal - by 2030, within 10 years. This outcome in particular is practically overlapping to the latest estimates by the International Energy Agency (IEA), Intergovernmental Panel on Climate Change (IPCC), International Renewable Energy Agency (IRENA) and others.

In terms of emission per source, the predominance of fossil fuel one is clear in *(Figure 5.3-b)* with a nearly overlapping behavior of the Total Fossil-Fuel Emissions (red solid line) and the Total CO_2 Emission one (brown solid curve). It must be highlighted that results are in gigatonnes of Carbon. The peak is reached at the end of the century, making clear the disruptive effects of delayed actions of mitigation and adaptation, with respect to the sudden start of the climate change countermeasures.

The weight of a delayed counteraction towards climate change effects and the lack of policies linked, is clearly visible also by looking to the total carbon dioxide emission curve *(Figure 5.3-c).* In this case too, the trend is exponentially increasing until midcentury, starting from the current values of 53-54 $GtCO_{2}$-eq and continuing with more likely ones for the years to come with respect to the STs, crossing the 68 $GtCO_2$-eq by 2030 and touching the remarkable 75 $GtonCO_2$-eq by 2040. CP1 projects the peak in global carbon emission to occur approximately by 2100, exceeding downright the 87.0 $GtonCO_2$-eq. This means that given the current rates of economic growth, climate drivers and climate related policies the World will increasingly continue to emit carbon dioxide in the atmosphere until the end of the century.

This situation is even more manifestly portrayed in *(Figure 5.3-d).* The atmospheric CO_2 concentration curve is self-explaining; the curve (black solid) starts from the today's 410-411 ppm[144], reaches 444-445 ppm by 2030, rises to 481 ppm by 2040 and exceeds the impressive value of 736 ppm by the end of the century, showing no sign of inversion. This is quite obvious as, by looking again to the emission curve *(Figure 5.3-c),* the peak occurs only by 2100. Concentrations are consequent to emission and therefore suffer from a "carry-over effect", being their change linked to the concentration ones, but postponed.

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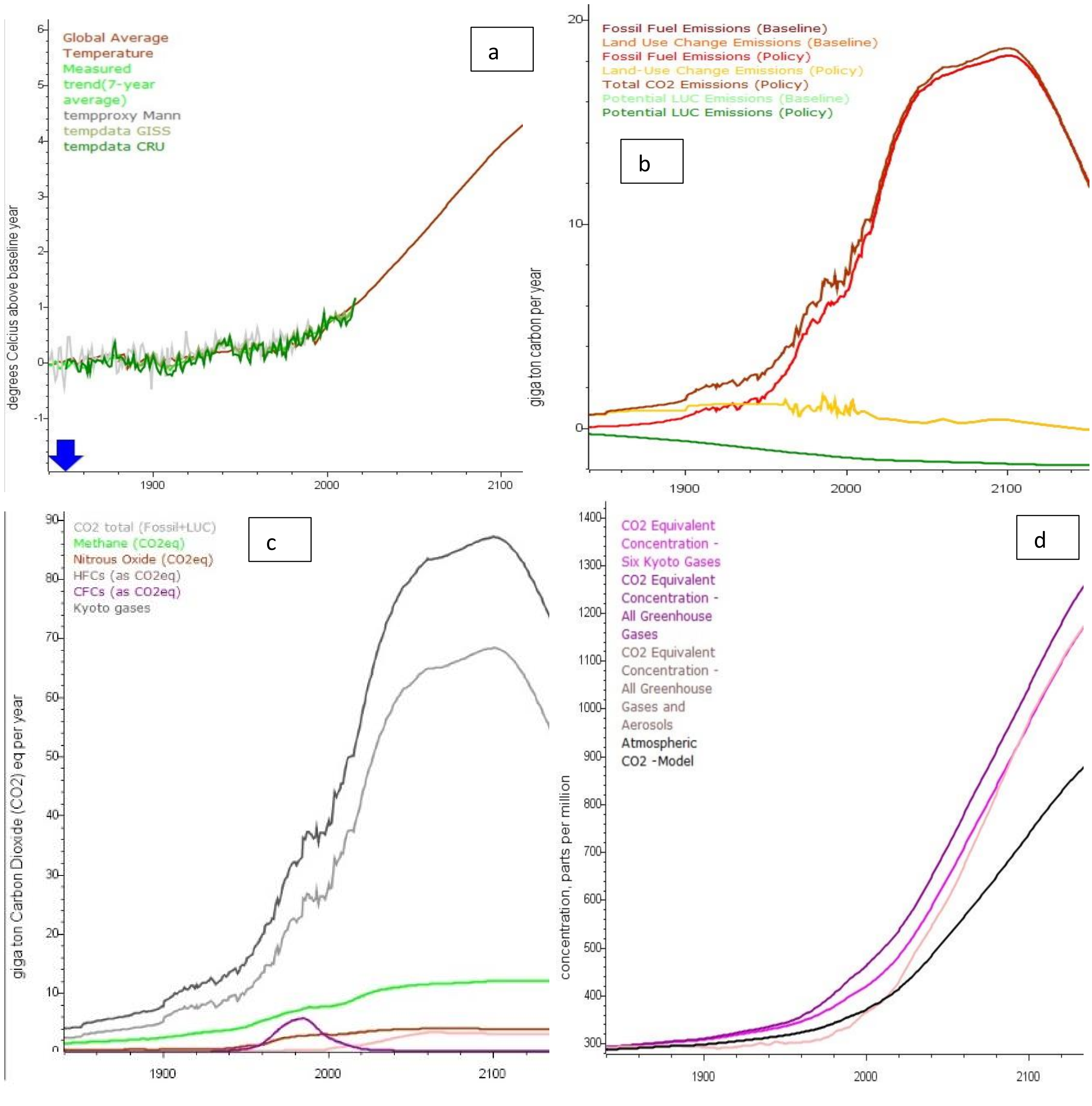
[144] 410-411 ppm is the yearly average for 2018-2019. It is important to compare the same periods' measurements for different years in order for the atmospheric carbon dioxide trend estimates to be reliable. The periodic yearly fluctuation due to the Carbon Cycle has to be taken into account.

Coming to the Radiative Forcing (RF), a similar reasoning holds true. CP1 estimates the RF to be about 2.4 W/m^2 by 2030, rising to 2.93 W/m^2 by the end of 2040, increasing with high rate and reaching the 5.94 W/m^2 by 2100, approaching a modest reduction, only in growth rate terms, after the end of the century *(Figure 5.3-e)*.

As far as sea level rise is concerned, CP1 expects a 266 mm rise by 2030, 307.5 mm by 2040 and another rather impressive value: 611.7 mm by 2100 *(Figure 5.3-f).*

This set of data and projections depicts a quite catastrophic future. The CP1 world will be hotter, unhealthier and finally the more difficult to live in for our sons and grandsons, but also for a lot of us. As a matter of fact, the alarming data starts to come out within ten years. In other words, carrying on with the current paces in terms of energy demand and economic growth, but most importantly persisting with the current attitude towards the climate change issue (meaning basically no attitude) will result in a virtually inhabitable planet.

The magnitude of the consequences that this kind of climate parameters will have on human beings is absolutely unknown at the moment.



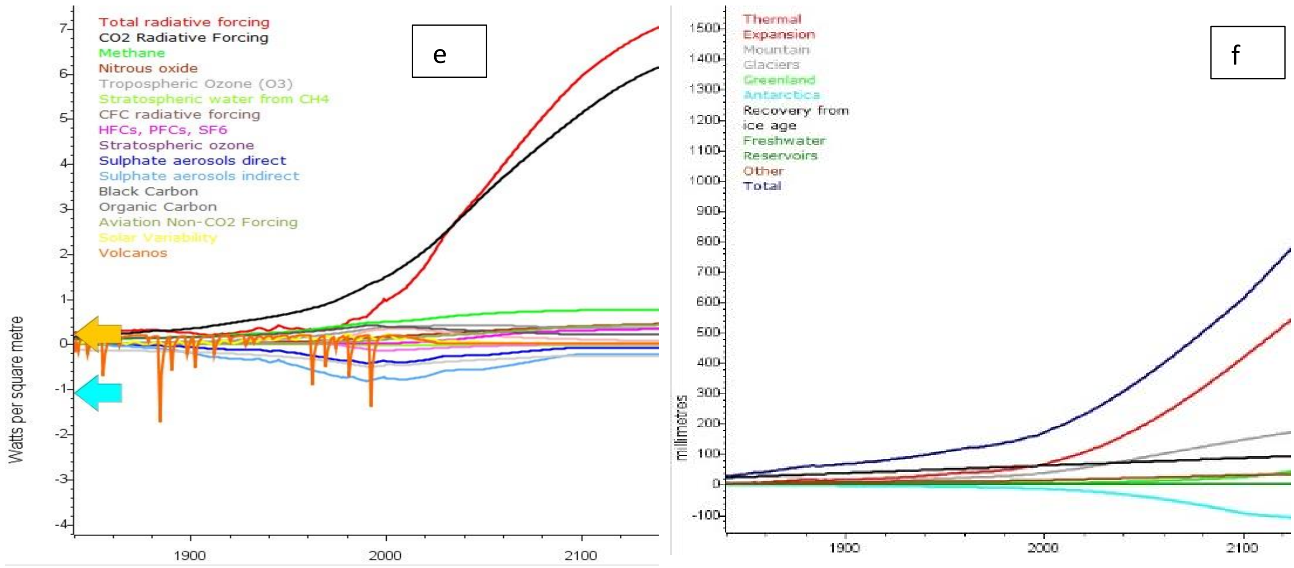


Figure 5.3 | Seven different scenarios for the future: CP1 (a) Global Mean Surface Temperature (GMST) trend referred to 1850 as baseline year. (b) Global CO_2 emissions from the energy sector by country measured in gigatons of carbon per year. (c) Global GHGs emissions measured in gigatons equivalent CO_2 per year. (d) CO_2 and other GHGs concentrations in atmosphere measured in ppm. (e) Radiative Forcing (RF) trend from the major drivers – mainly CO_2, methane, nitrous oxide, ozone, water vapor, CFC, HFC, PFC, SF6. (f) Sea level rise and various contributions

- CP2

The second scenario considered is similar to the previous one with some important notes. CP2 considers the current situation of the world energy system and the current levels of Land Use Change (LUC) as well. As for the socio-economic aspects, as for CP1 the present rates of growth are taken as a baseline and are projected in the future using the estimates by World Economic Forum (WEF), International Monetary Fund (IMF), United Nations (UN) and others available at the moment. Current social behaviors and attitude towards the climate issue are accounted.

The decisive assumption on which CP2 is based is that the energy system development from now on, will not be dominated by fossil fuels, but rather will be balanced between all energy sources as moving towards 2100. The climate policies implemented with CP2, are the few that are being implemented right now; no other policies are considered.

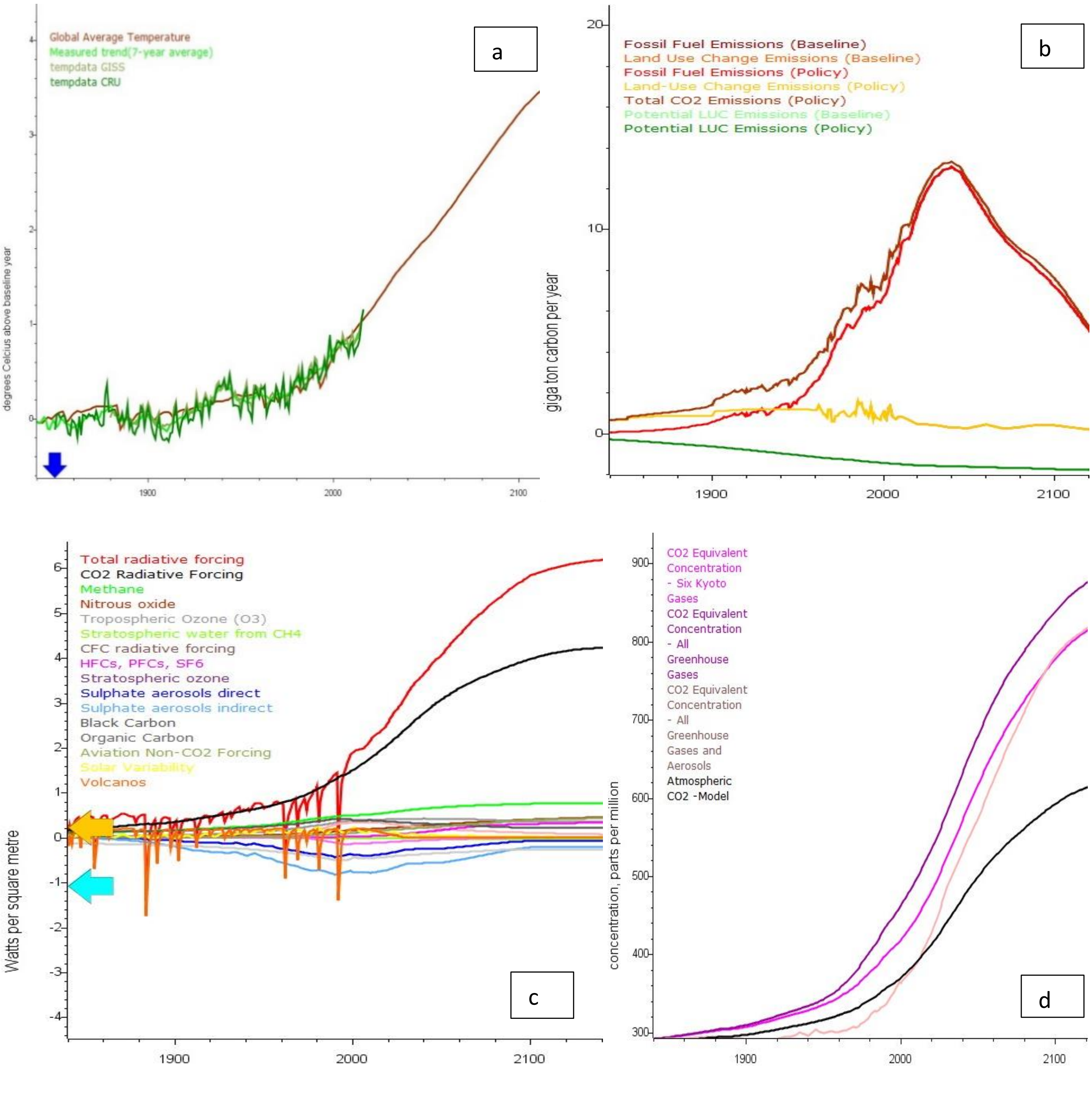
Before analyzing the model's outputs, it is important to emphasize again the fact that this scenario considers a balanced developing of the word sources of energy, with the weight of renewables that gets momentum further and further in the years to come, coming to share equally with the three fossil fuels sources the split of Total Primary Energy Supply (TPES) within a few years. This means that right now we are not even close to be on track for this. This is also the main difference with CP1 (huge, as will be seen).

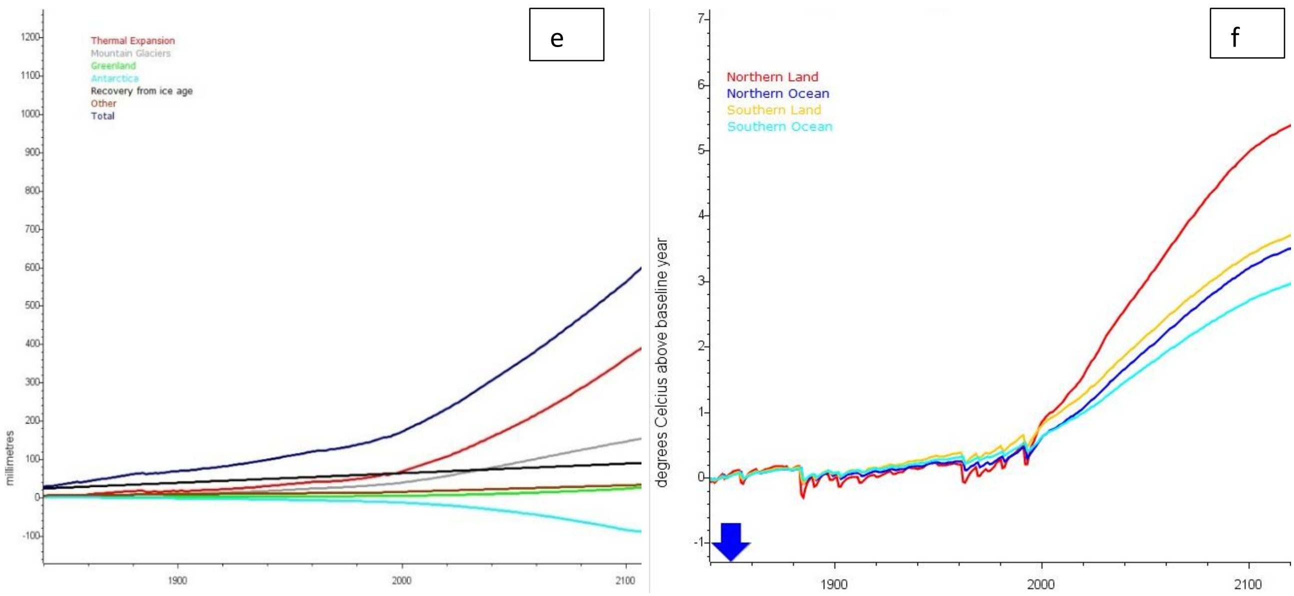
CP2 estimates for global average temperature a warming with respect to the baseline year of 3.2 °C-3.3 °C by the end of 2100 *(Figure 5.4-a).* This means on the one hand that the Paris Agreement goal to limit the warming well below the 1.5 °C is disintegrated, but on the other that there is a difference with CP1 pretty remarkable of 0.8-0.9 °C on GMST by 2100. This is a rather impressive outcome and means that a relatively slight difference in the development of the energy sector, can make the climate parameters (not only the GMST, as follows) to diverge very much one from another.

Turning to the Radiative Forcing (RF), CP2 projects a peak for total RF of 6.0 W/m^2, with the CO_2 term at 4.15 W/m^2 *(Figure 5.4-b).* Here again, no major volcanoes eruption is considered to occur.

As for the GHG emissions *(Figure 5.4-c)*, CP1 projects to reach a peak as early as the middle of the 21st century (around 2045 or 2046). The peak, expressed in equivalent carbon dioxide is approximately 73.14 $GtCO_{2}$-eq, more than 75% of which is made up by carbon dioxide alone (55-56 $GtCO_2$). After this peak, CP1 projects a decline in CO_2 emission. This decline is the product of that shift to a more balanced energy system, relying less on fossil fuels and more on renewables, which sees the CO_2 emission down to approximately the current levels (54-55 $GtCO_{2}$-eq) by the end of 2100.

CP2 is a good representation of what can happen in a likely future in which no further actions and strategies are taken into account to face the climate issue, but the energy system - which is the major responsible for it - follows a rather balanced development, not fossil-fuel based. Such a development is anything particularly difficult to achieve, but at the same time it does not seem to be feasible given the current Governments' mindsets. However, CP2 conveys us a sound certainty: if we carry on the current policies, at the current rate of growth, but even changing in a modest way our energy system relying more on renewables and less on fossils, we would be not absolutely on track for the ambitious Paris Agreement goal. On the other hand, the picture portrayed by CP2 is surely better than the CP1's one, with values of GHGs emission, carbon dioxide concentrations, sea level rise and finally warming on GMT that are better without any doubt.





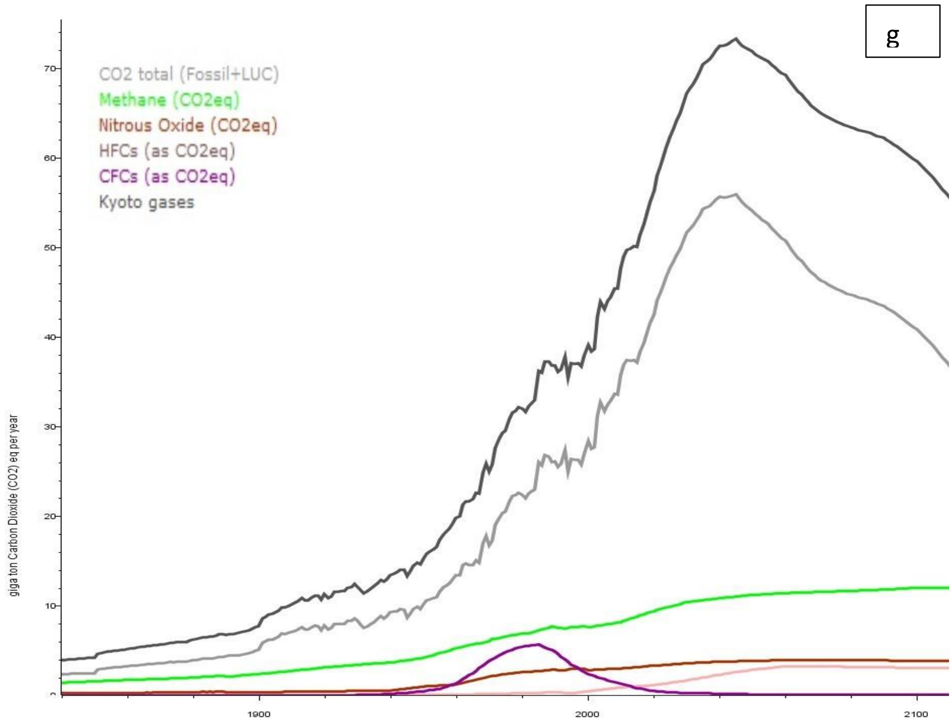


Figure 5.4 | Seven different scenarios for the future: CP2 (a) Global Mean Surface Temperature (GMST) trend referred to 1850 as baseline year. (b) Global CO_2 emissions by sector measured in gigatons of carbon per year. (c) Radiative Forcing (RF) trend from the major drivers – mainly CO_2, methane, nitrous oxide, ozone, water vapor, CFC, HFC, PFC, SF6. (d)) CO_2 and other GHGs concentrations in atmosphere measured in ppm. (e) Sea level rise and various contributions. (f) GMST change by world area. (g) Global GHGs emissions measured in gigatons equivalent CO_2 per year.

- ## 5.4.2 – New Policies Scenario (NPS) and Sustainable Development Scenario (SDS)

As said, both the Current Policies Scenarios does not seem to be enough to keep the GMST warming well below 2 °C or even 1.5 °C. This is a quite certain fact. No doubts about it. Besides the CPs, two more scenarios are analyzed in order to find some strategies that can bring us someway to a future that matches the Paris Agreement Goals. These two scenarios are quite similar in terms of boundary conditions and initial hypothesis as the ones that the International Energy Agency (IEA) has developed and deeply engineered in the last years' WEOs. In practice the NPS takes into account the current situations but considers also the various announcements of strategies that are not yet pursued, like the Paris Agreement pledges from all the 195 countries that has ratified it. In other words, the NPS is a "realistic-optimistic" scenario, providing for a future that is based on the one hand on the soundness of the current conditions and on the other relies on the willingness to pursue all the actions that have been announced. As for the Sustainable Development Scenario (SDS), as the IEA's one does, tries to outline a cleaner and more inclusive energy and environmental future. The projections provided by the SDS account for revolutionary transformations in the energy sector over relatively short time period. The main point of the SDS is to achieve three different policy goals together: climate stabilization, cleaner air and universal access to modern energy. The importance of a future SDS-lookalike is clear thinking to the nearly 1 billion people lacking electricity, the 2.7 billion without access to clean cooking facilities, the 2.5 million premature deaths per year due to poor indoor air quality and 4.6 million due to poor outdoor air quality.

So, let us try to figure the NPS and the SDS out and see the outcomes.

- NPS

As said, the New Policies Scenario (NPS) tries to picture the future towards which we are heading with policies that are currently in place at the moment. The main crucial difference with the CPs scenarios is that policies and targets that have been only announced by governments and institutions are considered to be put in place. The NPS here follows the same rationale of the WEO's one. According to the NPS global energy demand is projected to grow by more than a quarter from the current levels by 2040. A rapid economic and population growth is foreseen, with 1.7 billion people more by the same date, mostly located in developing economies urban areas. For the NPS, a more detailed focus on the energy system development is provided.

The largest change in global energy demand by source for NPS comes from Renewables, with the addition from the current situation of 483 Mtoe by advanced economies and twice that quantity (1.107 Mtoe) from developing ones. Developing economies are the driving force of the energy system development from here to the 2040 with a change in Primary Energy Demand of around 1.200 Mtoe in Natural Gas with respect to the modest about 130 Mtoe coming from the advanced economies. As regards the global demand in Oil for the NPS, it is projected to grow by 744 Mtoe in developing economies with the major shares covered by Passenger cars and Petrochemicals. Advanced economies on the contrary are expected their total Oil demand to fall by 454 Mtoe from here to 2040. Coal is the less growing source as global primary energy demand is concerned, with a rise in advanced economies of 415 Mtoe and a net decrease in advanced economies of nearly 355 Mtoe by 2040. In 2000, Europe and North America alone, covered more than 40% of global energy demand, while developing economies in Asia accounted for around the 20%. By 2040 the situation is completely reversed. Low-carbon technologies led by renewables and underpinned by NG will account for more than 80% of the increase in global demand.

Delving into the result of the NPS estimates, comes out that even if it includes the policies that tries to satisfy the COP 21 pledges that are currently in force or have been announced and are planned to be, the NPS projects a temperature rise that is not in-line with the Paris Agreement goals of around 2.75 °C by 2100 *(Figure 5.5-a).*

The emission curve for NPS shows a typical peak-and-decline behavior, that is quite comparable to ST3.0. *(Figure 5.5-b)*. NPS projects the flat part of the peak to occur in a few years (the period 2019-2022) reaching 53-54 $GtCO_2$-eq by 2020. This means that with NPS the emission decline would need to start as we speak. This emission decline would be faster than in CP2 and of approximately the same magnitude of ST3.0. The reason is that ST3.0 considers a stabilization at 3 °C by the end of 2100, NPS gets there with a lower value (2.75 °C). The main technical difference between the two scenarios and the cause of the apparently slight deviation in warming temperature at 2100, is the extent of the emission peak. ST3.0 global GHGs emission curve has a peak that is distributed in more than 40 years, while the NPS's here is a rather sharp one. This means that under the current not so promising circumstances (climatically speaking), action is needed, but also that the timing with whom action is pursued is crucial to succeed in the struggle against climate change. The more we stagnate at carbon dioxide emission peak values, the less likely will be to stay below certain levels of GMST rise. Here, for the NPS, the decline after the peak of GHGs emission curve brings to 46.63 $GtCO_{2}$-eq by 2030 and 42.09 $GtCO_{2}$-eq by 2040.

Coming to the carbon dioxide emissions per sector *(Figure 5.5-c)*, once again the relatively narrow plateau of the emission peak is quite clear during the period 2016-2031, reaching the highest value (10.223 $GtCO_2$) in 2020. The NPS world would see the CO_2 emissions to 10.18 $GtCO_2$ in 2030, with the start of the decline, coming to 9.67 $GtCO_2$ in 2040 and 5.17 $GtCO_2$ by 2100.

As far as atmospheric CO_2 concentration, the curve *(Figure 5.5-d)* shows a shy sign of (future) peak after 2100 but it has to be pointed out that concerning time periods that are consistent with human life, the trend is strongly increasing. NPS projects atmospheric CO_2 concentration to reach 434-435 ppm in 2030 and 455-456 ppm in 2040. By 2100 the concentration will be between 531-532 ppm.

Coming to Radiative Forcing (RF), the NPS expects a RF far lower than both CP1 and CP2 and also ST3.0 *(Figure 5.5-e)*. However, the shape of the trend followed by the curve is quite similar to the ST3.0 one, even if different in terms of real numbers. While RF in ST3.0 peaks before the end-of century (approximately around 2090) at 4.9-5 W/m^2, the NPS's RF do not show any peak-and-decline behavior[145]. Specifically, for the NPS by 2030 the RF will be around 3.31 W/m^2 and 3.57 W/m^2 by 2040. By the end of the century RF is estimated to be 4.4-4.5 W/m^2, approximately 0.5 W/m^2 less than the 3.0 °C stabilization scenario.

Regarding sea level rise *(Figure 5.5-f)*, the NPS projects an elevation of about 276-277 mm by 2030, 312-313 mm by 2040 and 541-542 mm by 2100.

The global picture that comes out of NPS is a rather fair one, especially comparing it with CP1 and CP2. Both of the latter indeed show emission, concentration and RF curves that are worse than the NPS ones. This is reflected in the global mean temperature warming at 2100 that is around 4.0 °C for CP1, 3.2-3.3 °C for CP2 and 2.7-2.8 °C for NPS. This means that at the moment, the joining of a more balanced energy system development and less fossil-relying on the one hand together with the full implementation of all the policies that have been announced by Institutions and Government it is worth from 0.6 °C to 1.3 °C in terms of GSMT rise. This is a quite remarkable result.

It has to be highlighted that even though the NPS depicts a future that is far better than the CP1 and CP2 ones, it comes out in the end with a GSMT that is not absolutely in line with the Paris Agreement goals.

In conclusion:

- the NPS is without any doubt the most desirable scenario as matters stand;
- the rate of emission decline – that is crucial to meet that 2.7-2.8 °C warming at 2100 - is reasonable and technically feasible, but absolutely not likely if government and institutions announcements will remain so.

In other words, there is no chance to stay even below 3 °C under the current circumstances, with the climate policies that are in place at the moment as the sole ones. Under the NPS energy demand is projected to grow by more than 25% to 2040; it would require a $2 trillion per year investment in new energy supply. In other words, the energy transition required in order to be in line with the NPS would be the most disruptive that the energy system has ever saw.

[145] The RF peak for NPS is projected around 2140.

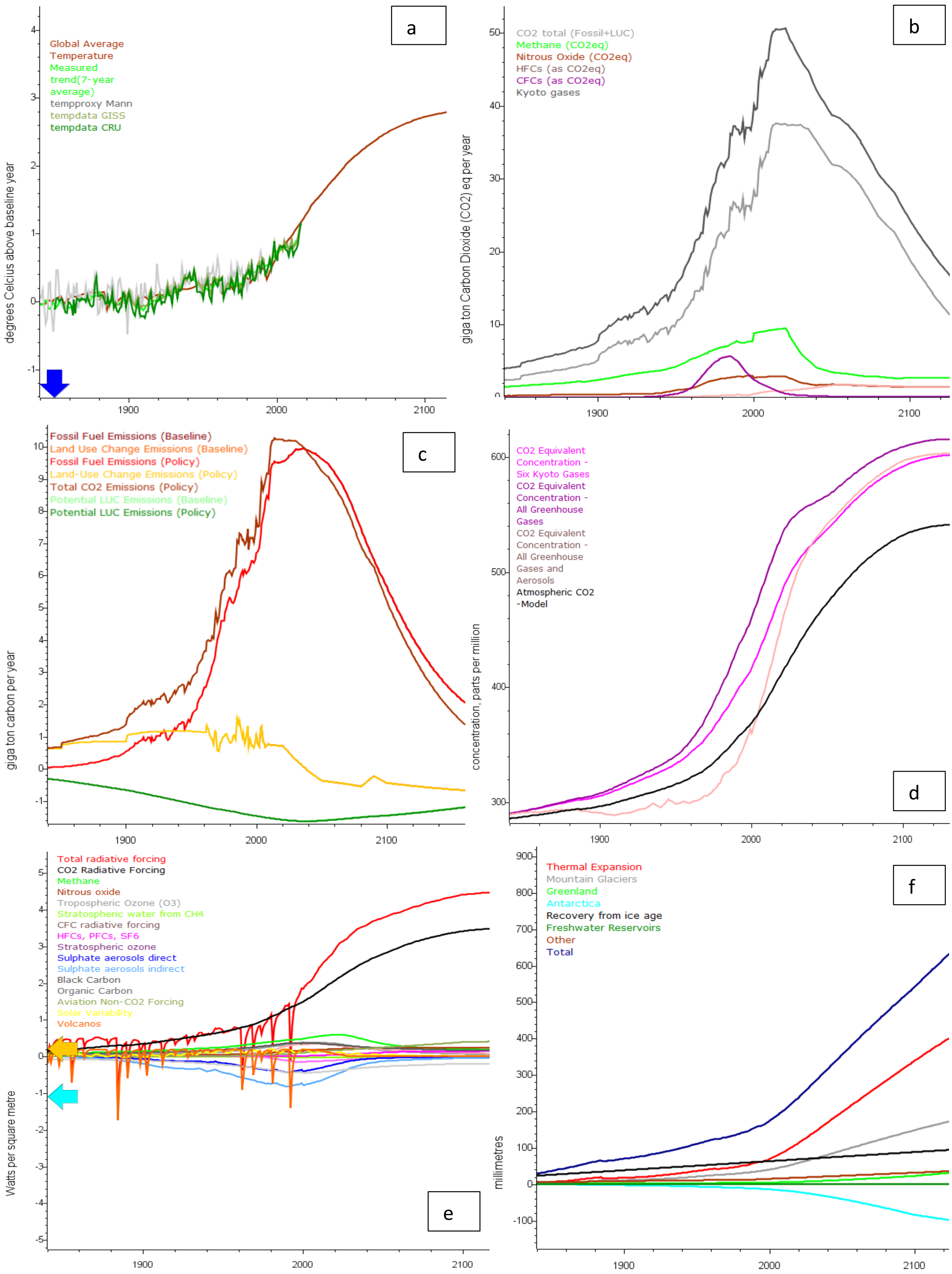


Figure 5.5 | Seven different scenarios for the future: NPS (a) Global Mean Surface Temperature (GMST) trend referred to 1850 as baseline year. (b) Global GHGs emissions measured in gigatons equivalent CO_2 per year. (c) Global CO_2 emissions by sector measured in gigatons of carbon per year. (d) CO_2 and other GHGs concentrations in atmosphere measured in ppm. (e) Radiative Forcing (RF) trend from the major drivers – mainly CO_2, methane, nitrous oxide, ozone, water vapor, CFC, HFC, PFC, SF6. (f) Sea level rise and various contributions.

- SDS

As previously said, the world is not even close to be on track to meet the main commitments of the Sustainable Development Goals (SDGs) agreed by 193 countries in Paris during the 2015 COP 21. The unlikeliness of a world experiencing a rise in GSMT by 2100 of 1.5 °C and 2.0 °C as well has been well displayed in scenarios ST1.5 and ST2.0.

The current levels of economic and demographic growth as well as the present climatic and energy-related parameters will lead us to futures that are described in CP1 and CP2. A different pathway is finally assessed in NPS, where not only the yet-in-place pledges from the COP 21 are considered, but even the ones that have been only announced. All these different scenarios - which start from different hypothesis on the multiple parameters of interest, account for different ways the future can evolve and give rather diverse outcomes in terms of CO_2 concentrations, RF and all the other climatic benchmarks starting with Global Mean Surface Temperature (GMST) – are variously far away from reaching the Paris goal of limiting global warming to "*well below 2 °C, or 1.5 °C if it possible*".

For this reason, a new approach must be thought. A new way of perceiving the climate issue, as the energy system development, as the socio-economic growth. This revolutionary change is described by the Sustainable Development Scenario (SDS), in line with what the IEA has been doing since the 2017's World Energy Outlook (WEO). The SDS analyzed here, tries to outline a future utterly modified thanks to major transformation of the global energy system, supported by an unprecedented turning in behaviors from the humanity, which implies literacy, information and a new strong perception about the climatic issues.

The future depicted by the Sustainable Development Scenario (SDS) offers a new perspective in order to achieve the Paris goals and show how can the world evolve trying to fix at least some of the damages done until now. As it will be seen, the outcome of this SDS will lead to a temperature rise of 1.7-1.8 °C by 2100 taking our sons and us back on track to a healthier, safer and livable planet.

It is significant to highlight that the SDS is ontologically different from the three Stabilization Scenarios ST1.5, ST2.0 and ST3.0 even if they lead to quite similar outcomes, as will be discussed. The main focus of the three Stabilization Scenarios ST1.5, ST2.0 and ST3.0 in fact, is on the stabilization of GMST at the end of the century at different values. The pathway followed in order to get to those values is analyzed in the single scenarios. The Sustainable Development Scenario (SDS) instead, starts considering the UN Sustainable Development Goals (SDGs) and works back to outline what would be needed to fulfil these goals. Technically, the SDS starts from a group of desired outcomes (not only the GSMT stabilization) and identifies what would be necessary to deliver them.

Crucial to reach these outcomes is to peak early the CO_2 emissions and rapidly decline. This is the focus of the SDS, in line with the Paris Agreement, with the IPCC's Special Report 15 (SR15) and with the Global Environment Outlook 6 (GEO6) by the United Nations Environment Program (UNEP). The SDS offers a pathway through which develop differently from what humanity has done until now. Climate stabilization, cleaner air and water, universal access to energy, electrification and reduced energy security risks are key elements for a sustainable development.

The SDS provided by the International Energy Agency (IEA) projects that air pollution is reduced significantly by 2040, leading to 1.6 million fewer premature deaths globally. Access to clean cooking will contribute for another 1.5 million reduction by the same period. Low-carbon sources double their share in the energy mix to 40% by 2040, coal demand is projected to decline and oil consumption to peak soon thereafter. Power generation is almost decarbonized relying massively on renewables (60%), nuclear power (15%) and a contribution also from CCS (6%). All economically viable paths to improve efficiency are followed keeping the overall demand in 2040 at today's level.

Coming to the various outcomes analysis, let us start with the GMST, as usual *(Figure 5.6-a)*. The SDS projects a trend for the GMST that is quite different from the NPS and also from CP1 and CP2. According to these last three scenarios, the peak in GMST is estimated to be quite remote in time, occurring nearly by 2100 or even further. On the contrary, the SDS peak occurs on nearly ten-years period (2055-2064) and approximately by 2059, reaching a rise with respect to the pre-industrial levels of 1.81 °C. After this plateau, the GMST start to decline, approaching by 2100 about 1.65 °C.

By looking to the atmospheric GHGs emission curve *(Figure 5.6-b)*, it can be noted that the peak occurs between 2018 and 2019, approaching obviously the current values[146]. The SDS projects the carbon dioxide emission from fossil fuel burning and Land Use Change (LUC) to peak by 2019-2020 reaching the 37.2-37.3 $GtCO_2$ per year and reach the net zero by 2070 fully in line with the estimates by IEA and IPCC: According to this scheme, global GHGs emission in terms of CO_{2}-eq will touch the 1.6 $GtCO_2$-eq by 2100.

As for the RF (Figure 5.6-c), the SDS projects a peak-and-decline trend with a quite rounded and flattish peak placed between 2037 and 2055, with the absolute maximum occurring by 2045 reaching 3.2-3.3 W/m^2. The RF is projected to decline to 2.56 W/m^2 by 2100.

Once again, looking to the concentration curve *(Figure 5.6-c),* another peak-and-decline behavior is expected, with the peak period extending between 2047 and 2053. The vertex reaches the 449.61 ppm by 2050. The atmospheric carbon dioxide is projected to exceed the 431 ppm yet by 2030 and the 445-446 ppm by 2040. The value by 2100 is settling to 422-423 ppm, rapidly declining. These results are quite relevant thinking about the cause-effect that GHGs emission exerts on the concentrations. As seen in *(Figure 5.6-b),* the peak of the GHGs global emissions is projected by 2018-2019 to happen in according to the SDS. Given that, *(Figure 5.6-c)* inform us that the peak in concentrations is shifted by more than 20 years. The reason for that phenomenon is the climatic inertia, but what most important is that even if we begin suddenly to put in place all the mitigation actions available at the moment in order to decrease the global anthropogenic emissions, the effects of these countermeasures would start to be experienced only more than twenty years later.

Switching to the sea level rise *(Figure 5.6-d),* the SDS projects a progressively increasing behavior. No sign of decline even after 2100. Going deeper, a net rise of 268-269 mm by 2030 is estimated, which become 305-306 mm by 2040, reaching 468-470 mm by the end of 2100.

In conclusion, the SDS does seem to be significantly different from the other scenarios for many reasons, the most important of is that it is the only one (except obviously from the ST1.5) not projecting an increase in GMST exceeding 2.0 °C, with the rather small possibility of staying around the 1.5 °C. It must be highlighted also the peak-and-decline trend of the GMST. This is quite a remarkable fact, in the sense that in all the other scenarios the GMST do not show any sign of a U-turn in the trend (no decrease is provided in any of the STs, CPs or in the NPS). Why this? This quite obviously has to do with the magnitude of the counteractions considered by this very scenario and most important, in the timing with which these counteractions are put in place. In other words, only the size of the policies that must be put in place together with their timeliness can someway prevent the planet form major disruptions, that are very likely with current levels of economic growth and the actual development of the global energy system. Here are briefly listed some of the unprecedented actions that both the Sustainable

[146] These values are constraints for the model. The interesting projections concern both time and entity of the decline in Greenhouse Gases emissions.

Development Scenario (SDS) and the New Policies Scenario (NPS) consider in their analysis, primarily regarding the energy and transport system.

For instance, as regards Wind and solar PV energy generation together, the SDS estimates 14.1 thousand TWh by 2040, while the NPS only 8.5 thousand TWh. In both cases it will be disruptive change from the today's 1.5 thousand TWh. The same goes for the electric car fleet; the transition towards a healthier future seems to be only possible with a massive change in transportation behaviors. From the today's 9.2 million electric cars currently on the streets, the NPS estimates a total 304.4 million by 2040, while the SDS projects 933.3 million for the same period.

It is clear that all the numbers coming both from the SDS and the NPS are something hard even to imagine at the moment.

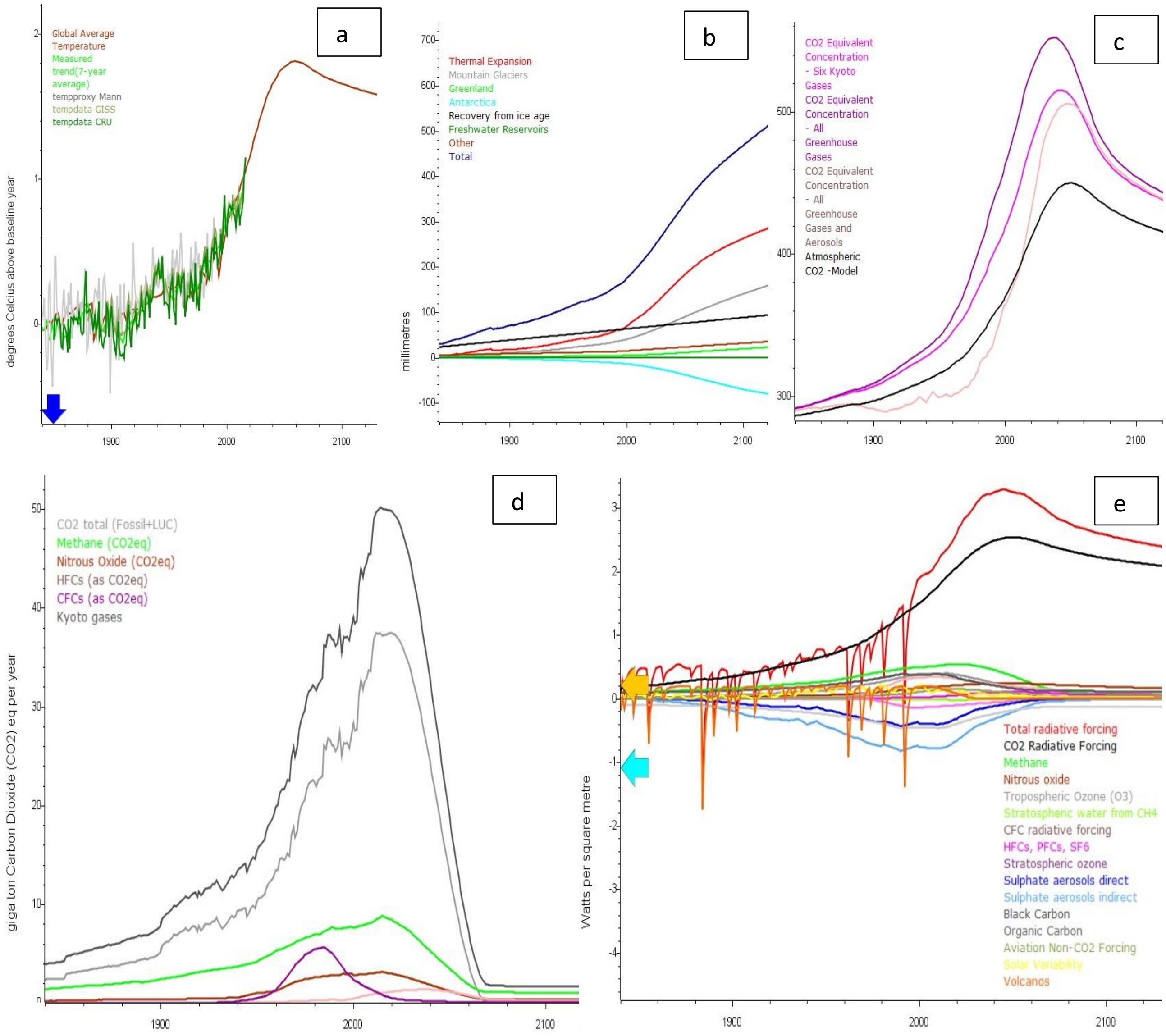


Figure 5.6 | Seven different scenarios for the future: SDS (a) Global Mean Surface Temperature (GMST) trend referred to 1850 as baseline year. (b) Sea level rise and various contributions. (c) CO_2 and other GHGs concentrations in atmosphere measured in ppm. (d) Global GHGs emissions measured in gigatons equivalent CO_2 per year. (e) Radiative Forcing (RF) trend from the major drivers – mainly CO_2, methane, nitrous oxide, ozone, water vapor, CFC, HFC, PFC, SF6.

CHAPTER 6 – CONCLUSIONS

It is not necessarily needed to know about the Paris Agreement, the United Nations Framework Convention on Climate Change, the International Energy Agency or the Intergovernmental Panel on Climate Change to understand that right now we are definitely not on track to meet the COP 21 goals and therefore to meet the need to live on a livable Planet. Climate Change impacts are in the sight of all. There is a quite likely possibility that in just a few years the humanity will face unprecedented and potentially disruptive changes. We do not know what future life will be within such an environment. We know on the contrary how can we try to reverse this tendency, but as a matter of fact every moment we even think about that, we are losing time.

Science has been outstandingly right on climate, but the "Short twentieth century"[147] totem of consumerism is yet showing its strength. This is gradually depicting a reality that looks like the myth of Cassandra, one of the princesses of Troy. According to the Myth, Cassandra was blessed with the gift of foreseeing the future, but no one believed her. Cassandra foresaw the destruction of Troy by the Greeks if the Trojan had brought the horse in the city. No one in Troy believed her, with the known results. So, when things will get worse and worse – and they will for sure – for thousands of scientists that have tried to warn humanity about this huge challenge will be nothing left but the rightness, but it will not be a great pleasure.

So, being honest about it, one of the main reasons why governments have delayed so much to put climate policies in place has a lot to do with resistance that certain groups have carried on. A limited number of industries knew everything about climate change since decades ago but did not want really anything to change. This has been and currently is the problem. To give an idea, the six world's "Big Oils" - British Petroleum, Shell, Exxon, Total, Eni and Chevron – have spent $1 billion since the Paris Agreement on a pro-fossil narrative alongside climate lobbying, according to the 2019 survey by Influence Maps [2]. It is quite easy to grasp that the ones who have to lose the most by acting on climate change were (and currently are) fossil fuels companies. Many of those industries have been deliberately confusing the messages by Science with massive campaign for decades[148]. Few doubts that these doubt seeds have made clean-energy transition slower and more difficult.

Scientific evidences are unquestionable. Given the current socioeconomic, energy and demographic conditions seems extremely unlikely not to exceed the 1.5-2.0 °C increase in GMT by 2100. Science has never been clearer than now. Climate change is no more ignorable. Nations, Governments, Institutions, Companies and most important, we as individuals have a great responsibility. Trying to overturn this trend is vital. The attitude we will show towards climate change in the next few years will affect life on the Planet for the next many generations.

[147] As the British historian Eric Hobsbawn labelled the twentieth century.

[148] This dynamic is the same one that has been undertook by the big tobacco industries some years ago.

BIBLIOGRAPHY

[1] N. Zhou, «Australia heatwave: overnight minimum of 35.9C in Noona sets new record,» *The Guardian ,* 2019.

[2] O. Milman, «'Coal is on the way out': study finds fossil fuel now pricier than solar or wind,» *The Guardian ,* 2019.

[3] N. E. S. R. Laboratory, Carbon Dioxide, 2013.

[4] UNESCO, «World Water Resources: A New Appraisal and Assessment for the 21st Century,» 1998.

[5] UNESCO, «World Water Resources: A New Appraisal and Assessment for the 21st Century (,» 1998.

[6] J. K. H. Phillips, «Guide to the Sun,» *Cambridge University Press,* 1995.

[7] J. T. F. a. J. K. Kevin E. Trenberth, «Earth's Global Energy Budget,» *American Meteorological Society,* 2009.

[8] F. Qiang, «Radiation (Solar),» *Encyclopedia of atmospheric sciences,* 2003.

[9] A. R. A. S. H. Daniel P. Shepardson, in *Teaching and Learning about Climate Change: A Framework for Educators*, 2017.

[10] S. H. Sarah Burch, Understanding Climate Change: Science, Policy and Practice, 2014.

[11] R. K. a. G. Hegerl, The Equilibrium Sensitivity of the Earth's Temperature to Radiation Changes.

[12] A. Ford, Modeling the environment, 2009, p. cap: 9.

[13] J. A. Coakley, «Reflectance and albedo, surface,» *Encyclopedia of the Atmosphere,* 2003.

[14] J. PERLIN, «https://psmag.com/environment/keeping-cool-with-the-albedo-effect-3837,» 2009. [Online].

[15] W. Z. e. al., «Monitoring land surface albedo and vegetation dynamics using high spatial and temporal resolution synthetic time series from Landsat and the MODIS BRDF/NBAR/albedo product,» *International Journal of Applied Earth Observation and Geoinformation,* 2017.

[16] «https://scied.ucar.edu/longcontent/water-cycle,» 2011. [Online].

[17] K. Bellomo, A. Clement, T. Mauritsen, G. Rädel e B. Stevens, «Simulating the Role of Subtropical Stratocumulus Clouds in Driving Pacific Climate Variability,» *Journal of Climate,* 2014.

[18] T. Stocker e e. al., «Physical climate processes and feedbacks,» 2001.

[19] H. W. C., «Aerosol Technology,» 1999.

[20] D. L. Hartmann, Global Physical Climatology, 1994.

[21] J. H. a. L. Nazarenko, «Soot Climate Forcing via Snow and Ice Albedos,» *Proceedings of the National Academy,* 2004.

[22] S. S. S. e. al., «Contribution of Working Group I to the Fourth Assessment Report of the IPCC,» 2007.

[23] I. P. O. C. Change, Climate Change 2007: Working Group I: The Physical Science Basis, 2007.

[24] J. Z. e. al., Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present, 2001.

[25] U. N. O. N. A. Office, Explanatory Supplement to the Astronomical Almanac, 1992.

[26] J. G. Williams, Contributions to the Earth's obliquity rate, precession, and nutation, 1994.

[27] NASA, «https://earthobservatory.nasa.gov,» [Online]. Available: https://earthobservatory.nasa.gov/Features/Milankovitch/milankovitch_2.php.

[28] J. L. e. al., «Orbital, precessional, and insolation quantities for the Earth from -20Myr to +10Myr,» *Astronomy and Astrophysics,* 1992.

[29] E. c. members, «Eight glacial cycles from an Antarctic ice core,» *Nature,* p. 429.

[30] W. G. I, «Intergovernmental Panel on Climate Change Fourth Assessment Report. Chapter 1: Historical overview of climate change science,» 2007.

[31] W. G. I. T. P. S. Basis, «IPCC Fourth Assessment Report: Climate Change 2007,» 2007.

[32] «https://www.epa.gov/ghgemissions/understanding-global-warming-potentials,» 2018. [Online].

[33] «https://earthobservatory.nasa.gov/Features/CarbonCycle,» 2011. [Online].

[34] R. Holmes, The Age Of Wonder, 2008.

[35] U. D. o. E. O. o. Science, «Carbon Cycling and Biosequestration: Report from the March 2008 Workshop,» 2008.

[36] D. Archer, THE GLOBAL CARBON CYCLE, 2010.

[37] T. U. o. N. Hampshire, «http://globecarboncycle.unh.edu/CarbonPoolsFluxes.shtml,» 2008. [Online].

[38] W. G. I. T. P. S. Basis, «IPCC Fourth Assessment Report: Climate Change 2007,» 2007.

[39] C. C. 2. W. G. I. T. P. S. Basis, «IPCC Fourth Assessment Report: Climate Change 2007,» 2007.

[40] C. D. K. T. P. W. R. B. Bacastow, «Seasonal amplitude increase in atmospheric CO2 concentration at Mauna Loa, Hawaii, 1959–1982,» *Journal of Geophysical Research: Atmospheres.*

[41] W. G. I, «IPCC Fourth Assessment Report: Climate Change 2007,» 2007.

[42] IPCC, «Climate Change 2014: Synthesis Report,» 2014.

[43] P. Friedlingstein, «Emissions de CO2 et objectifs climatiques».

[44] S. e. al., «The Oceanic Sink for Anthropogenic CO2,» *Science,* 2004.

[45] CDIAC, «Global Carbon Project,» 2014.

[46] W. F. Ruddiman, «The Anthropogenic Greenhouse Era Began Thousands of Years Ago,» *Climatic Change,* 2003.

[47] methanelevels.org, «https://www.methanelevels.org/,» 2019. [Online].

[48] J. Cartwright, «How does carbon fertilization affect crop yield?,» *Environmental Research Letters,* 2016.

[49] R. D. Field, «Human amplification of drought-induced biomass burning in Indonesia since 1960,» *Nature.*

[50] IPCC, «2014».

[51] O. A. Anisimov, «Potential feedback of thawing permafrost,» *ENVIRONMENTAL RESEARCH LETTERS,* 2007.

[52] R. A. F. e. al., «Impact of Anthropogenic CO2 on the CaCO3 System in the Oceans,» *Science,* 2004.

[53] D. A. e. al., «Dynamics of fossil fuel CO2 neutralization by marine CaCO3,» *Global Biogeochemical Cycles,* 1998.

[54] G. Colburn, «The time scale of the silicate weathering negative,» *Global Biogeochemical Cycles,* 2015.

[55] W. e. al., «Astronomical calibration of the Paleocene time,» *Palaeogeography, Palaeoclimatology, Palaeoecology,* 2007.

[56] J. P. Kennett, «Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Paleocene,» *Nature,* 1991.

[57] G. D. S. F.-M. B. W. C. J. F. J. H. D. K. J.-F. L. D. L. B. M. T. N. A. R. G. Myhre, «2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis.,» 2013.

[58] V. Ramaswamy, «Radiative forcing by well-mixed greenhouse gases: Estimates from climate models in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4),» *Journal of Geophysical Research: Atmospheres,* 2006.

[59] IPCC, «Climate Change 2014: Synthesis Report,» 2014.

[60] NOAA, «Global Temperature Anomalies,» 2018.

[61] L. D. a. R. Lindsey, «www.climate.gov,» 2018. [Online]. Available: https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content.

[62] IPCC, «Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,» 2015.

[63] J. K. Willis, «ocean.si.edu,» 2018. [Online]. Available: https://ocean.si.edu/through-time/ancient-seas/sea-level-rise.

[64] J. Y. D. D. G. M. N. P. v. d. L. X. D. K. M. a. C. J. Houghton, «Climate change 2001: The scientific basis,» *Cambridge University Press,* 2006.

[65] «https://www.skepticalscience.com/do-we-know-when-the-arctic-will-be-sea-ice-free.html,» 2012. [Online].

[66] T. W. R. Estilow, «The Climate Data Guide: Snow Cover Extent (Northern Hemisphere) Climate Data Record,» *Climate Data Guide,* 2018.

[67] N. O. a. A. Administration, «https://www.co2.earth/,» 2019. [Online].

[68] S. I. o. O. (SIO), «ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_annmean_mlo.txt,» 2018. [Online].

[69] T. D. Q. G.-K. P. L. A. S. A. N. B. F.-M. B. J. C. U. C. S. E. P. F. P. F. N. Stocker, « Technical Summary. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental,» 2013.

[70] P. e. al., 2012.

[71] E. E. Agency, «https://www.eea.europa.eu/data-and-maps/daviz/atmospheric-concentration-of-carbon-dioxide-3#tab-based-on-external-data,» 2018. [Online].

[72] R. R.HeimJr., «An overview of weather and climate extremes – Products and trends,» *Weather and Climate Extremes,* 2015.

[73] G. J. M. B. A. P. B. S. C. W. C. P. C. F. D. S. E. V. E. C. F. P. G. E. G. C. Flato, «2013: Evaluation of Climate Models. In: Climate Change 2013: The Physical Science Basis.,» 2013.

[74] C. Brief, «https://www.carbonbrief.org/qa-how-do-climate-models-work,» 2018. [Online].

[75] «http://mason.gmu.edu,» 2012. [Online]. Available: http://mason.gmu.edu/~rehrlich/chapter_6.pdf.

[76] «https://atmos.washington.edu,» 2001. [Online]. Available: https://atmos.washington.edu/2002Q4/211/notes_greenhouse.html.

[77] Z. Hausfather, «www.carbonbrief.org,» 2018. [Online]. Available: https://www.carbonbrief.org/qa-how-do-climate-models-work.

[78] P. Williams, «https://www.carbonbrief.org/qa-how-do-climate-models-work,» 2018. [Online].

[79] «https://www.carbonbrief.org/qa-how-do-climate-models-work,» 2018. [Online].

[80] «https://climatedataguide.ucar.edu/,» 2018. [Online]. Available: https://climatedataguide.ucar.edu/climate-model-evaluation/cmip-climate-model-intercomparison-project-overview.

[81] I. F. A. L. D. R. S. L. R. R. G. R. a. P. S. J. Hansen, «Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model,» *Journal of Geophysical Research,,* p. 9341, 1988.

[82] I. F. A. L. D. R. S. L. R. R. G. R. a. P. S. J. Hansen, «Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model,» *Journal of Geophysical Research,* 1988.

[83] N. G. I. f. S. Studies, «GISTEMP Team, 2018: GISS Surface Temperature Analysis (GISTEMP),» GISTEMP Team, 2018: GISS Surface Temperature Analysis (GISTEMP), 2018/11/16. [Online]. Available: data.giss.nasa.gov/gistemp/.

[84] K. C. R. G. Way, «Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends,» *Quarterly Journal of the Royal Meteorological Society,* 2013.

[85] Z. HAUSFATHER, «www.carbonbrief.org,» 2017. [Online]. Available: https://www.carbonbrief.org/analysis-how-well-have-climate-models-projected-global-warming.

[86] C. o. W. G. I. t. t. F. A. R. o. t. I. P. o. C. Change, «IPCC, 2007: Climate Change 2007: The Physical Science Basis,» 2007.

[87] M. M. H. W. M. T. S. M. S. Julienne Stroeve, «Arctic sea ice decline: Faster than forecast,» *Geophysical Research Letters,* 2007.

[88] 2. IPCC Technical Summary, «Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies».

[89] J. E. M. K. K. R. A. T. K. H. G. C. H. T. K. V. K. J.-F. L. T. M. M. M. N. N. S. J. S. S. K. R. Detlef P. van Vuuren, «The representative concentration pathways: an overview,» *Climatic Change,* 2011.

[90] K. M. Y. H. Toshihiko Masui, «An Emission Pathway for Stabilization at 6Wm-2 Radiative Forcing,» *Climatic Change,* 2011.

[91] S. R. V. K. C. C. V. C. G. F. G. K. N. N. P. R. Keywan Riahi, «RCP 8.5—A scenario of comparatively high greenhouse gas emissions,» 2011.

[92] D. P. v. V. e. al., «The representative concentration pathways: an overview,» *Climatic Change ,* 2011.

[93] I. W. G. I, Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013, p. 1067.

[94] T. D. Q. G.-K. P. L. A. S. A. N. B. F.-M. B. J. C. U. C. S. E. P. F. P. F. N. Stocker, «Technical Summary. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental,» 2014.

[95] M. R. K. J. A. J.-L. D. T. F. P. F. X. G. W. G. T. J. G. K. M. S. C. T. A. Collins, «Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,» 2013.

[96] IPCC, « Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental,» 2013.

[97] O. C. J. P. P. v. d. L. a. C. H. M.L. Parry, «IPCC, 2007: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,» Eds. Cambridge University Press, Cambridge, Cambridge, 2007.

[98] M.-L. H. a. M. W. David Eckstein, «GLOBAL CLIMATE RISK INDEX 2019,» Germanwatch e.V., Bonn, 2018.

[99] C. S. H. Lance H. Gunderson, Panarchy: Understanding Transformations in Human and Natural Systems, Island Press, 2007.

[100] M. R. A. V. R. B. J. B. W. C. R. C. J. A. C. L. C. Q. D. P. D. N. K. D. O. E. I. E. C. B. F. P. F. P. F. J. F. L. G.-E. S. H. R. K. Pachauri, «(2014): Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,» Geneva, Switzerland, 2014.

[101] C. Folke, «Resilience: The emergence of a perspective for social-ecological systems analyses,» *Global Environmental Change,* 2006.

[102] D. R. Nelson, «Adaptation to Environmental Change: Contributions of a Resilience Framework,» *Annual Review of Environment and Resources,* 2007.

[103] O. F. C. N. A. L. D. J. D. a. K. S. W. J. J. McCarthy, «IPCC, 2001: Climate change 2001: impacts, adaptation and vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change,» Cambridge University Press, Cambridge, 2001.

[104] H. B. Christof Bigler, «Climate-induced shifts in leaf unfolding and frost risk of European trees and shrubs,» *Scientific Reports,* 2018.

[105] C. Carey, «The impacts of climate change on the annual cycles of birds,» *Philosophical Transactions of the Royal Society: Biological Sciences,* 2009.

[106] I.-A. C. C. F. «Biodiversity and Climate Change - a summary of impacts in the UK,» 2010.

[107] S. P. Zaichun Zhu, «Greening of the Earth and its drivers,» *Nature Climate Change ,* 2016.

[108] F. A. Galgano, «TYPES AND CAUSES OF BEACH EROSION ANOMALY AREAS IN THE U.S. EAST,» *Middle States Geographer,* 2007.

[109] J. v. d. K. M. W. M. J. D. G. N. K. K. E. P. N. A. a. A. R. Z. Brian R. Silliman, «Degradation and resilience in Louisiana salt marshes after the BP–Deepwater Horizon oil spill,» *PNAS ,* 2012.

[110] D. M. Roman, *THE EFFECT OF HURRICANE SANDY ON NEW JERSEY,* 2015.

[111] S. Connor, «Floods could overwhelm London as sea levels rise - unless Thames Barrier is upgraded,» *Independent ,* 2013.

[112] D. Carrington, «2016 hottest year ever recorded – and scientists say human activity to blame,» *The Guardian,* 2017.

[113] K. J. Á.-N. M. Á.-R. J. A. K. B. A. Hughes TP, «Global warming and recurrent mass bleaching of corals,» *Nature,* 2017.

[114] «www.pmel.noaa.gov,» 2018. [Online]. Available: https://www.pmel.noaa.gov/co2/story/What+is+Ocean+Acidification%3F.

[115] J. Bennett, «ocean.si.edu,» 2018. [Online]. Available: https://ocean.si.edu/ocean-life/invertebrates/ocean-acidification.

[116] «oceanservice.noaa.gov,» 2018. [Online]. Available: https://oceanservice.noaa.gov/facts/conveyor.html.

[117] D. W. O. P. O. J. I. R. C. M. B. R. D. I. R. H. P. M.-S. N. L. R. P. T. S. I. Y. &. L. D. K. David J. R. Thornalley, «Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years,» *Nature ,* 2018.

[118] E. P. Lothar Stamma, «Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes,» *Nature Climate Change ,* 2012.

[119] Worldbank, «data.worldbank.org,» 2018. [Online]. Available: https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS.

[120] U. Nations, «www.un.org,» 2018. [Online]. Available: https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html.

[121] K. Killgrove, «www.forbes.com,» 2015. [Online]. Available: https://www.forbes.com/sites/kristinakillgrove/2015/05/20/industrial-revolution-caused-rise-cancer-obesity-arthritis/#5568964669f7.

[122] J.-M. Robine, S. L. K. Cheung, S. Le Roy, H. Van Oyen, C. Griffiths, J.-P. Michel e F. R. Herrmann, «Death toll exceeded 70,000 in Europe during the summer of 2003,» *Comptes Rendus Biologies,* 2008.

[123] C. V. B. D. D. K. M. M. M. T. B. M. C. K. E. Y. E. R. G. B. G. E. K. A. L. S. M. P. M. a. L. W. Field, «IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,» Cambridge University Press, 2014.

[124] N. Osseiran, «www.who.int,» 2018. [Online]. Available: https://www.who.int/news-room/detail/02-05-2018-9-out-of-10-people-worldwide-breathe-polluted-air-but-more-countries-are-taking-action.

[125] N. O. a. A. Administration, «www.ncdc.noaa.gov,» 2018. [Online]. Available: https://www.ncdc.noaa.gov/billions/.

[126] N. N. C. f. E. I. (NCEI), «U.S. Billion-Dollar Weather and Climate Disasters,» 2018.

[127] M. Shepherd, «www.forbes.com,» 2018. [Online]. Available: https://www.forbes.com/sites/marshallshepherd/2018/01/09/cost-of-weather-climate-disasters-was-306-billion-in-2017-what-could-you-buy-with-that/#61485d7e71ed.

[128] M. RE, «TOPICS Geo Natural Catastrophes 2017,» 2018.

[129] W. Bank, «Groundswell : Preparing for Internal Climate Migration,» 2018.

[130] N. Stern, «Stern review: the economics of climate change,» 2006.

[131] T. D. Q. G.-K. P. M. T. S. A. J. B. A. N. Y. X. V. B. a. P. M. Stocker, «IPCC, 2013: Annex III: Glossary,» Cambridge University Press, 2014.

[132] IEA, «World Energy Outlook 2018,» Paris, 2018.

[133] «www.statista.com/,» 2018. [Online]. Available: https://www.statista.com/statistics/200002/international-car-sales-since-1990/.

[134] P. M. S. B. B. R. Balramdas, «A comparison between Normal buildings and Green buildings- A case,» *International Research Journal of Engineering and Technology (IRJET),* 2016.

[135] S. P. Ahmed Alkhayyat, «Energy Consumption Analysis in Conventional Buildings: Case Study of,» *International Journal of Research Publications,* p. 1, 2017.

[136] L. G. a. M. B. G. Paul Mann, «Giant Oil and Gas Fields of the Decade, 1990–1999,,» *American Association of Petroleum Geologists,* 2009.

[137] R. 2018., «Renewables 2018 Global Status Report,» Paris, 2018.

[138] I. (2018), «Renewables 2018: Analysis and Forecasts to 2023,» Paris, 2018.

[139] T. Urmee, «Social, cultural and political dimensions of off-grid renewable energy programs in developing countries,» *Renewable Energy,* 2016.

[140] G. Grill, «Dams reshape the world's rivers,» *Nature,* 2015.

[141] D. Dudley, «www.forbes.com,» 2018. [Online]. Available: https://www.forbes.com/sites/dominicdudley/2018/01/13/renewable-energy-cost-effective-fossil-fuels-2020/#67992c504ff2.

[142] I. (2018), «Renewable Power Generation Costs in 2017,,» 2018.

[143] D. K. T. V. C. A. Stefan Weitemeyer, «Integration of Renewable Energy Sources in future power systems: The role of storage,» *Renewable Energy,* 2015.

[144] E. d. Vries, «www.windpowermonthly.com,» 2017. [Online]. Available: https://www.windpowermonthly.com/article/1435504/mhi-vestas-launches-95mw-v164-turbine-london.

[145] A. Rao, Sustainable Energy Conversion for Electricity and Coproducts: Principles, Technologies, and Equipment, 2015.

[146] «yearbook.enerdata.net,» [Online]. Available: https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html.

[147] B. O. D. H. C. d. C. M. L. a. L. M. Metz, « IPCC special report on Carbon Dioxide Capture and Storage,» 2005.

[148] J. R. a. R. Orvis, «www.forbes.com,» 2017. [Online]. Available: https://www.forbes.com/sites/energyinnovation/2017/05/03/carbon-capture-and-storage-an-expensive-option-for-reducing-u-s-co2-emissions/#4f7e9e1c6482.

[149] B. L. S. P. X. W. D. B. L. Y. H. Y. Y. S. B. P. C. J.-L. D. J. E. F. E. I. A. J. T. L. E. L. Q. L. P. M. Chuang Zhao, «Temperature increase reduces global yields of major crops in four independent estimates,» *Proceedings of the National Academy of Sciences,* 2017.

[150] E. L. M. A. L. B. María E. Ibarrarán, «Climate change vulnerability and resilience: current status and trends for Mexico,» *Environment, Development and Sustainability,* 2009.

[151] «malmo.se,» 2011. [Online]. Available: https://malmo.se/Nice-to-know-about-Malmo/Sustainable-Malmo-/Sustainable-Urban-Development/Augustenborg-Eco-City.html.

[152] «www.worldometers.info,» 2019. [Online]. Available: http://www.worldometers.info/world-population/maldives-population/.

[153] D. Carrington, «'Brutal news': global carbon emissions jump to all-time high in 2018,» *The Guardian,* 2018.

[154] influencemap.org, 2019. [Online]. Available: https://influencemap.org/report/How-Big-Oil-Continues-to-Oppose-the-Paris-Agreement-38212275958aa21196dae3b76220bddc.

[155] J. E. H. a. M. Sato, Climate Sensitivity Estimatd From Earth's Climate History.

[156] J. e. a. 2. Petit, «Vostok Ice Core Data for 420,000 Years».

[157] S. Eggleston, J. Schmitt, B. Bereiter, R. Schneider e H. Fischer, «Antarctic Ice Core 155,000 Year CO2 and Gas Stable Isotope Data».

[158] L. D. e. al., «High-resolution carbon dioxide concentration record 650,000-800,000 years before present,» 2008.

[159] B. J. e. al., «Water Vapor Feedback and Global Warming,» *Annual Review of Energy and the Environment,* 2000.

[160] I. Ribas, The Sun and Stars as the Primary Energy Input in Planetary Atmospheres, 2009, pp. 3-18.

[161] M. E. Pasyanos, «Lithospheric Thickness Modeled from Long Period Surface Wave Dispersion,» 2008.

[162] H. Zirin, «https://www.britannica.com/science/solar-constant,» [Online].

[163] J. L. L. G. Kopp, «A new, lower value of total solar irradiance: Evidence and climate significance,» *Geophysical Research Letters,* 2011.

[164] L. Tisza, «Generalized Thermodynamics,» *M.I.T Press,,* 1966.

[165] U. o. Oslo, «https://www.uio.no/studier/emner/matnat/fys/nedlagte-emner/FYS3610/h09/undervisningsmateriale/compendium/Ozone_and_UV_2009.pdf,» 2009. [Online].

[166] A. Voiland, «https://earthobservatory.nasa.gov/Features/Aerosols,» 2010. [Online].

[167] C. J. W. a. M. T. Deser, «Arctic Sea Ice Variability in the Context of Recent Atmospheric Circulation Trends,» *J. Climate,* 2000.

[168] S. L. e. al., «Seasonal Contrast of Some Anthropic Pollution Parameters in Water Retention in Mountainous Area under Sahelian Climate: Elementary Dynamics and Space Distribution,» 2016.

[169] D. Carrington, «'Brutal news': global carbon emissions jump to all-time high in 2018,» *The Guardian,* 2018.