POLITÉCNICA

Naturgy Foundation

Climate Change

Scientific bases and questions for debate

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Foreword by the Harvard University professor
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Foreword

Daniel P. Schrag
Director of the Harvard University Center for the Environment

Climate change may be the most difficult problem that humanity has ever faced for two simple reasons. First, it is a collective action at a global scale, as the atmosphere takes our greenhouse gas emissions, primarily from combustion of fossil fuels, and mixes them on a timescale of weeks within a hemisphere, and within a few years between the hemispheres. This means that emissions from the U.S. affect every part of the Earth, including every person, animal and plant. And humans are not very good at managing collective action problems. Humans are tribal, tending to act to support friends and against enemies. But climate change requires a scale of global cooperation rarely seen in the history of the world. Even during the great World Wars of the 20th century, when extraordinary sacrifice was made by people on both sides of the conflict, there were sides. People were supporting friends against enemies. For climate change, there is no enemy; or, to quote Walt Kelly, "we have seen the enemy and he is us."

The second aspect of climate change that makes it a super-grand challenge for humanity is the issue of timescale. Many components of the climate system have very long timescales, from many decades to tens of millennia. And humans – and especially human organizations – may be even worse at dealing with long timescales than they are at global collective action. The Covid-19 pandemic illustrates how poorly we manage systems with delays of four to ten weeks between a rise in cases and increases in mortality. For climate change, we are feeling the impacts today, from rising sea level and increased heatwaves, to record-breaking rainstorms and melting of mountain glaciers, but even with immediate action, we are committed to continued warming for decades to centuries.

To understand the long timescales in the climate system, consider first the carbon cycle, as elevated carbon dioxide in the atmosphere is the primary cause of global climate change. Of the nearly 40 billion tons of carbon dioxide that we emit each year from burning fossil fuels, the ocean takes up about 25%, helping to cushion us against our own actions. That rate of uptake is limited not by chemical exchange with the atmosphere, which happens across the sea surface relatively quickly, but by the mixing of the surface ocean into greater depths. It is impossible to speed up the mixing of the oceans, as that is driven by the rotation of the Earth, and by the tidal forces of the moon and other planets. Over the next several thousand years, the mixing of the oceans will take up roughly most of the CO_2 that humans have produced from fossil fuels. But what is left – roughly 20% of what is in the air – will stay there for thousands of years. In other words, the energy choices we make today will influence the composition of the atmosphere for thousands of years, forcing hundreds of future generations to adapt to environmental changes we have set in motion.

There are many other long timescales in the climate system. Of all the solar energy trapped in the Earth by greenhouse gases, more than 90% goes into heating the oceans, and this is modulated by mixing processes that occur over centuries to millennia. Indeed, one can think of the oceans as a vast reservoir of coolant, helping to slow down the climate change that is happening over the land. Heat uptake by the oceans tempers the impacts of climate change on the surface, but it only buys us time. Over the next few hundred years, temperatures in the upper third of the ocean will slowly rise, and this will drive additional warming of the surface, even if atmospheric CO_2 levels are no longer rising. This is both good and bad. It is good that ocean heat uptake is slowing down the climate response, giving us more time to adapt to the changes. But it is bad because this means that even after we stabilize the level of CO_2 in the atmosphere (i.e., when natural sinks balance our remaining emissions), the Earth's surface will keep warming for centuries, leaving future generations the obligation to manage the environmental consequences of our energy choices.

There are also many timescales in the climate system that are uncertain – such as the timescale for the demise of ice sheets in Greenland and Antarctica. These ice sheets are massive parts of our surface water budget; the ice sheet on Greenland contains the equivalent of more than seven meters of sea level; West Antarctic ice sheets contain roughly six meters of sea level equivalent; and the massive terrain of East Antarctica stores more than 50 meters of sea level equivalent. Even today, we are probably past the point of no return for Greenland, and perhaps for parts of West Antarctica. Every summer, more ice melts at the top of the Greenland Ice Sheet than is replaced by winter snow, and that process will accelerate as the elevation of the ice sheet decreases and temperatures rise. In Antarctica, it is not the melting of ice, but rather the disintegration of the ice shelves that are hold back the glaciers from flowing into the ocean driven by ocean warming. Systems such as the Thwaites Glacier may already be heading towards collapse, with several meters of sea level rise committed for the future. And we simply do not know how quickly these massive ice sheets will disappear. The timescale for the Greenland and West Antarctic ice-sheets could be hundreds of years or thousands of years. If it is thousand years, then sea level rise might remain relatively modest for any single generation. If it is hundreds of years, the disruption to human civilization, much of which exists near coastlines, is unimaginable. One thing is certain – however long it takes for these ice sheets to melt or slide into the ocean, it will take much, much longer for them to regrow, driven by the slow accumulation of snow on glaciers over tens of thousands of years. This highlights the irreversibility of climate change, at least on any timescale relevant to human society.

Another critical timescale for climate change is the timescale for building new energy systems required to eliminate greenhouse gas emissions. Unlike some technological revolutions like telecommunications or information technology, creating new energy systems requires building massive amounts of infrastructure – including huge amounts of cement and steel. And a new, non-fossil energy system, likely spearheaded by wind and solar power, will require building even more infrastructure than our current one, due to the intermittency of renewable resources. And even with the remarkable progress we have seen in bringing down the costs of renewable energy, we must face the reality that eliminating fossil fuels from our energy system is likely to require new technological innovation far beyond the capability of current energy systems. Non-fossil energy systems, from electric vehicles to hydrogen-powered airplanes, all must become much, much cheaper if they are going to compete with fossil fuels. And this requires time for research, for development, for demonstration, and ultimately for deployment.

What are the lessons from these long timescales of the carbon cycle, of the climate system, and of energy systems? I think it is essential that everyone understands the scale of the challenge in front of us – and this means understanding the dual problems of collective action and long timescale. The Earth will continue to warm as long as humans continue to emit carbon dioxide from fossil fuel, and this may be longer than we anticipate. In working towards a solution to climate change, we must confront the fact that any "solution" will be incomplete. Some amount, perhaps even a substantial amount, of climate change is unavoidable. In the face of such facts, particularly about the long timescales, some people have argued that we should dispense with trying to reduce greenhouse gas emissions and focus all our efforts on preparing for the consequences, trying to avert the impacts of climate change or at least make them less costly. The flaw in this argument is that preparing for climate change becomes more and more difficult – ultimately impossible – if we do not eliminate greenhouse gas emissions and prevent the problem from getting worse. If we simply ignore the problem, then the long timescales in the carbon and climate system and the question of strong positive feedbacks – quite possible if no mitigation steps are taken – are simply too powerful to allow adaptation in any meaningful sense. But this does not mean that we can simply focus on reducing emissions. The long timescales mean that the climate change impacts we are experiencing now will continue to worsen for many decades at least. Communities around the world must prepare for the changes that are coming, as lack of preparation will lead to massive suffering and disruption, and this will also have a global impact.

In this volume, the authors tackle many of the most critical issues associated with climate change, from the basic science of the problem, to questions about adaptation and the socio-economic responses to climate impacts. For this grandest of global challenges, these contributions help spread awareness of the complexity of the problem, including the many things we don't know, but also the simplicity of what we do know. Meeting the climate challenge will require a scale of global cooperation and commitment never before seen in the history of the world. This will only happen if the public is aware of the problem and appreciates the solutions. These contributions offer a step in that direction, as building a foundation of public awareness is essential for the road ahead.

Executive summary

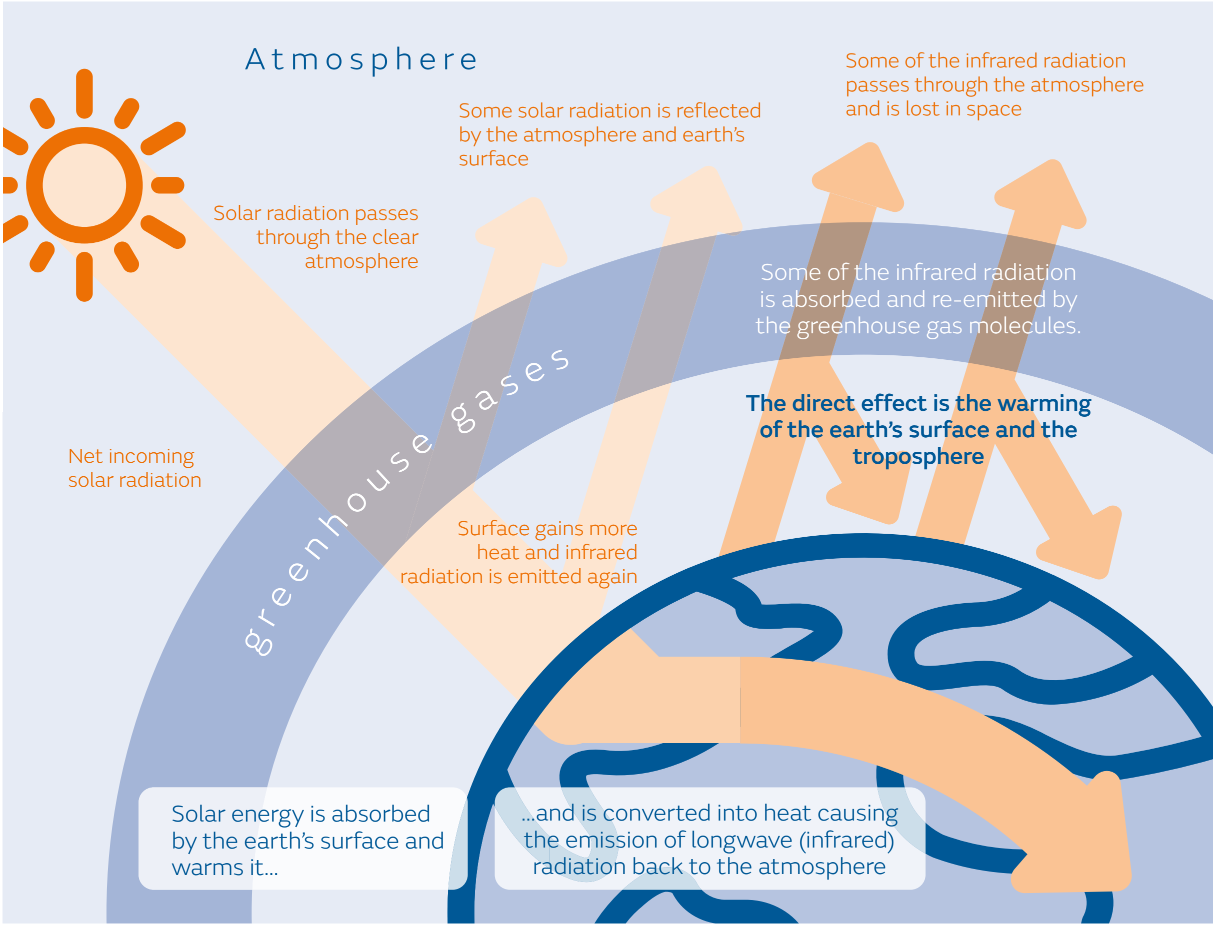
This book addresses **the main questions posed by science regarding climate change**. In this context, the term climate change refers to alterations in the state of the climate that persist over long periods of time (typically decades or longer). These changes can be identified via shifts in average values or in the variability of climate properties.

The first chapter deals with the most important concepts that are necessary in order to understand climate change. It also demonstrates the human influence on this change and the main effects that are already evident, as well as summarising scientific advances throughout history. It further explains the operation of the principal **international body for the assessment of climate change, called the Intergovernmental Panel on Climate Change (IPCC)**, which is the most rigorous scientific organisation in the field and is subjected to the scrutiny of reviewers and governments from more than 190 countries. The IPCC produces regular reports that include the scientific results of all research groups at a global level, considering both the work that demonstrates the influence of human activity on the climate and work that rejects this hypothesis, provided it is scientifically validated. After a meticulous process of preparation, consultation and examination, the documents, which constitute the primary source of information worldwide on scientific evidence concerning climate change, are approved. Due to its scientific and intergovernmental nature, the IPCC is an exceptional source of rigorous and balanced scientific information for decision makers. By embracing the contents of IPCC reports, governments acknowledge the authority of their scientific content. There is also mention of the minority groups which hold positions that are contrary to **the majority of scientific evidence which confirms the existence of climate change and its associated effects. Where scientific positions are more varied is with respect to the magnitude and type of actions that need to be taken to mitigate climate change**. Therefore, in the coming years we will have to advance in the search for a consensus that addresses this pressing and global problem.

In the second chapter, based on the current state of scientific knowledge, seven of the most internationally renowned scientists working in the field respond to recent doubts that have been raised concerning various aspects of climate change. From their different contributions, we can conclude the following:

1.- **Climate change and its associated effects are a certainty.** The increased frequency of extreme events (principally: heatwaves, extreme cold snaps, floods, droughts, storms and hurricanes) is particularly clear. There is also considerable scientific evidence on the decrease in glacial ice, which plays a crucial role in the climate, as well as on the increase in temperature, acidification and hypoxia (loss of oxygen) of the oceans. Moreover, there is a general consensus in attributing the warming observed since the second half of the 20th century to human influence. All this not only

Figure 1 • What is the greenhouse effect?



Source: Our own

affects natural systems, but it is also having socioeconomic consequences such as a reduction in the productivity of crops and marine species or increased mortality associated with heatwaves.

2.- Although **climate change** is perhaps the most daunting risk that humanity faces, **it is only one of the nine planetary boundaries that are considered to be critical for human life on Earth**. These boundaries refer to perturbations in nine environmental processes that together regulate the functioning and stability of the planetary system: depletion of the stratospheric ozone layer, loss of integrity of the biosphere, chemical pollution, acidification of the oceans, disruption of the global hydrological cycle, changes in land use, interference in nutrient (nitrogen and phosphorus) fluxes, and atmospheric aerosol loading, in addition to climate change. The main cause of overstepping planetary boundaries is agriculture, in particular industrialised resource-intensive agriculture. Our planetary system is highly interrelated and complex, which means we need to develop holistic knowledge, as well as to understand its dynamics better. Specifically, we need knowledge of the interrelation of the climate system with the terrestrial biosphere, the water cycle, the oceans and ice masses through the many processes and instances of feedback that can amplify global warming.

3.- **Our knowledge of the climate system is far from perfect, but** the evidence offered by current data and models indicates that **the warming of the climate system is irrefutable**. Moreover, it indicates that since the 1950s, many of the observed changes are unprecedented in the foregoing decades or even millennia. Other aspects of climate change are more uncertain and for this reason IPCC Reports always express the degree of uncertainty associated with each of the statements they contain. This facilitates decision-making based on the most accurate information available. More research is doubtlessly needed, however, to fill the gaps in our knowledge and to further improve our capabilities, especially in the field of modelling and measurement. In recent years, new concepts and theoretical frameworks have been developed to reconcile the response of our models with observations in some critical areas, such as interactions between aerosols and clouds or the quantification of rapid climate system adjustments. In addition to better scientific knowledge of the processes involved, new techniques of statistical analysis may help reduce uncertainties that have been present since the early history of climate simulations. Novel methods for tailoring the results of these simulations within a context of specific applications could also contribute to this goal.

4.- Despite all the uncertainties that we continue to have at present, recent studies show that **the objectives of the Paris Agreement are still technically feasible, as well as being economically desirable** since there are numerous co-benefits associated with a decarbonised future.

5.- However, it is not enough to set emission reduction targets (mitigation). A degree of climate change seems to be inevitable and **it is necessary to develop adaptation strategies to cope with the foreseeable and unavoidable impact**. Adaptation is understood here as the processes of adjusting to the expected effects, moderating or avoiding damage, and even exploiting opportunities that may present themselves. Examples include the construction of dikes to prevent flooding caused by the rising sea level and the planting of drought-resistant crops. Nonetheless, it is also clear that there are limits to adaptation when people cannot be sufficiently prepared for intolerable risks. Faced with these limits, solutions such as migrations or "transformational" adaptations have been proposed which would modify processes at a speed and scale that are greater than those of incremental solutions. These social transformations have to occur at both the global and the local scale, changing our everyday habits and focusing on the search for non-linear processes that generate adaptation within the system and that entail co-benefits (such as the nature-based solutions mentioned in Chapter 2). These transformations must also have individual people and societies at the heart: they are the principal cause of climate change and the main solution.

6.- The temporal perspective is highly relevant for adaptation and its limits. There is scientific certainty that global warming will persist for millennia and will generate additional changes in the climate system unless there are negative greenhouse gas (GHG) emissions (absorption), since once emitted, CO_2 molecules and other GHGs are "stored" in the atmosphere and become part of the carbon cycle. Therefore, **adaptation** will not only have to be sustained over a long time, but probably **will have to constitute a new normal way of life for future generations**.

7.- One of the possible methods to reduce the concentration of GHGs in the atmosphere, and even return levels to previous values, is carbon capture and sequestration (CCS). This technological solution consists of the absorption of CO_2 from gaseous industrial effluents or the atmosphere, its transport and subsequent long-term storage. The most consolidated storage strategy at present is the injection of CO_2 as a supercritical fluid into deep geological formations. Industrial absorption is usually carried out through an operation called "chemical scrubbing," which uses absorbent substances, mainly amines. Two different methods of **absorption of atmospheric CO_2**, which **could give rise to "negative emissions"**, are being considered: a) direct atmospheric capture (which is still a costly and inefficient process) and b) transfer, via photosynthesis, to biomass which is then burned in thermal power stations to produce electricity and the CO_2 is then separated from the gaseous effluent using industrial methods, resulting in a net reduction in the atmospheric concentration. Currently, operative CCS facilities store 30 million tons of CO_2 per year, which only constitutes 0.075% of global generation. Given the **high cost of these technologies**, their future will depend on introducing specific policies for their implementation or general policies, such as a carbon tax.

8.- In addition, we must be aware of the **systemic and complex nature of the challenge** climate change poses, that is, climate change is a problem that affects a set of components that operate together in an interconnected manner, with many interactions between them. Faced with this situation, linear and mechanistic solutions are not sufficient; we cannot accept or perpetuate the underlying causes of GHG emissions and neither can we consider climate change as an exogenous problem, avoiding internal changes within society. We need to come up with systemic solutions: to consider cities as a whole, entire industrial value chains, regional agricultural economies, and capital markets and financial systems all as complex climate problems.

9.- Humanity has already made **great technological advances in the mitigation of emissions** from some industrial sectors, such as electrical power generation, to the point of having implemented 100% renewable electricity generation systems in some parts of the world. However, this is not enough because the transformation we require is much broader and includes changes in our behaviour and habits, as well as modifications of entire systems.

10.- All of the foregoing confirms the need to **switch from incremental changes** (which in themselves are positive for reducing climate change, but not sufficient) to systemic **transformational changes** that address the root of the problem and produce changes at the speed and scale necessary for human life on Earth not to be threaten for future generations. That is, a fundamental transformation of the economic, social and financial systems that triggers exponential changes in decarbonisation rates and adaptation strategies. To this end, it is necessary to generate rapid and large-scale transformations of the constitutive elements of the system, which will cause spatial and temporal discontinuities. This can only be done through innovation, indeed only through systemic innovation: not only technological but also social, political, economic, financial and institutional innovation that affects the system as a whole.

11.- Such transformational change requires three paradigm shifts. The first of these is to **adopt systemic approaches**, which entails designing and implanting portfolios of projects that are implemented simultaneously, and which are connected and aligned in such a way that they constitute decarbonisation drivers, catalysing social, political and cultural changes (as opposed to the implementation of isolated, fragmented, single-discipline siloed solutions). The second is to **base the system on the ecological economy**, measuring success through social and ecological contribution, facilitating the transition towards sustainability in accordance with the universal agreement on the Sustainable Development Goals and managing a cultural evolution of human society towards ways of governance and community that are better adjusted to the conception of the world as an ecosystem. Finally, it is also necessary to **reformulate human identity**, evolving from an anthropocentric conception of the world, where human beings have the right to dominate nature using natural resources and the life of other species to support their own life and the expansion of their ambitions, to an idea of interdependence, where all species depend on each other and it is essential to care for the ecosystem in order to preserve human life, developing new ways of life and of being.

12.- **Neither going it solo, nor siloed**. The degree of complexity of the problem, together with its global nature and the urgent need for action, lead to the conclusion that the required transformational change can only occur through **deep and continuous collaborations between the different actors involved**. These include companies, research centres and universities, governments and the different components of civil society. Furthermore, the work must be **interdisciplinary**, that is, collaborative between different disciplines adopting a range of perspectives and studying problems in a comprehensive, holistic way. Thus, every actor from each discipline contributes with their abilities, capacities and differential value, all with the common objective of developing a new ecological economic model that is extremely well adapted to the variations in the climate that are already occurring and are expected to become more intense and extensive in the coming decades.

1.
Scientific bases of climate change

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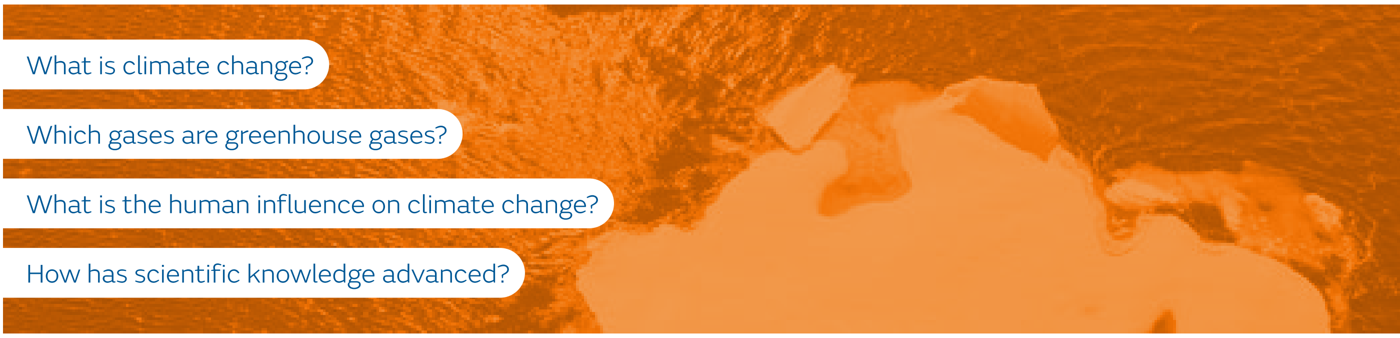
1.1 The context



What is climate change?

Climate change refers to changes in the state of the climate that can be identified via changes in the average values of certain parameters or in their variability. These changes persist over long periods of time, typically decades or even longer. So, while the weather is a description of meteorological conditions in the short term, climate corresponds to a statistical description of meteorological conditions over periods that can range from months to thousands or even millions of years.

Climate change can be caused by natural internal processes or by external forcing, which may also be natural, such as that resulting from modulations in solar cycles or volcanic eruptions. However, it can also be caused by persistent changes in the composition of the atmosphere or in land use that result from the actions of human beings. It is useful at this point to quote the United Nations Framework Convention on Climate Change (UNFCCC) which defines climate change in its Article 1 as: "change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". Thus, the UNFCCC clearly distinguishes between, on the one hand, climate change which can be attributed to humans, which includes what is commonly known as global warming; and, on the other, climate variability that can be attributed to natural causes.

According to the latest report by the Intergovernmental Panel on Climate Change (IPCC, which is discussed in the next section), the warming of the Earth's climate system is unquestionable; and since the 1950s, many of the observed changes have been unprecedented over periods ranging from decades to millennia. The atmosphere and oceans have warmed; the volumes of snow and ice on Earth have decreased; and the sea level has risen.

According to the latest report by the Intergovernmental Panel on Climate Change (IPCC, which is discussed in the next section), the warming of the Earth's climate system is unquestionable; and since the 1950s, many of the observed changes have been unprecedented over periods ranging from decades to millennia. The atmosphere and oceans have warmed; the volumes of snow and ice on Earth have decreased; and the sea level has risen.

In terms of the physical explanation of the problem, there is general agreement within the scientific community that the fundamental cause of global warming is the increased greenhouse effect: a process in which the thermal radiation emitted by the Earth is trapped in the atmosphere due to the presence of gases known as greenhouse gases (GHGs). This process begins with solar radiation passing through the atmosphere and warming the Earth's surface. Some of this heat is then radiated back out from the terrestrial surface. Of this emitted heat, part is absorbed into the atmosphere by GHG molecules and in turn radiated in all directions (in what is known as radiative forcing). This produces a warming of the Earth's surface and of the lower part of the atmosphere, which generates an average increase in temperature of 33ºC, compared to what it would be in the absence of GHGs. Therefore, if it was not for the greenhouse effect, the average temperature on Earth would be -18ºC! So, the presence of GHGs is natural and responsible for maintaining the Earth's temperature at values that make it habitable. The problem, however, lies in the increase in GHGs and thus in greater heat retention and radiative forcing than is suitable for life on Earth as we know it. One of the characteristics of GHGs is that they remain active in the atmosphere for years, and so they are often called long-lived gases.

Which gases are greenhouse gases?

They include: water vapour (H_2O), methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2) and chlorofluorocarbons (CFCs). Water vapour is the most abundant of these in the atmosphere and is involved in important feedback mechanisms with the climate. As the Earth warms, the presence of water vapour increases and consequently so too does the probability of clouds and precipitation. In other words, water vapour responds quickly to changes in temperature, through the mechanisms of evaporation, condensation and precipitation, and it increases global thermal energy and contributes to warming.

Carbon dioxide is a minor component of the atmosphere (it accounts for only some 0.04%), but it is relevant from the point of view of the climate, since it is the principal man-made GHG and is responsible for 60% of radiative forcing[1]. Despite its low concentration, its influence on atmospheric dynamics is very important as CO_2 molecules can absorb heat emitted from the Earth and then radiate it again, as explained in the preceding paragraphs. Carbon dioxide is a product of natural processes including respiration or volcanic eruptions, but it is also the result of human activities such as deforestation, changes in land use or the burning of fossil fuels. Humans have contributed to increasing the concentration of CO_2 in the atmosphere by more than a third since the start of the Industrial Revolution. This is undoubtedly the long-lived GHG that is contributing most to climate change.

Methane is a hydrocarbon that is also the result of both natural processes and human activities. These include the decomposition of waste in landfill sites, agriculture, the digestion processes of ruminants and also the management of manure from livestock. Its concentration in the atmosphere is less than that of CO_2 (around 0.002%) but it is still responsible for approximately 20% of radiative forcing. Nitrous oxide is also closely linked to agricultural activities, especially to the use of commercial and organic fertilisers, and to the combustion of fossil fuels or biomass. It constitutes around 0.0003% of the atmosphere and is responsible for 6% of the greenhouse effect. Finally, CFCs are synthetic compounds of industrial origin that have different applications. Their emission is currently quite tightly controlled thanks to international agreements to prevent them contributing to the destruction of the ozone layer.

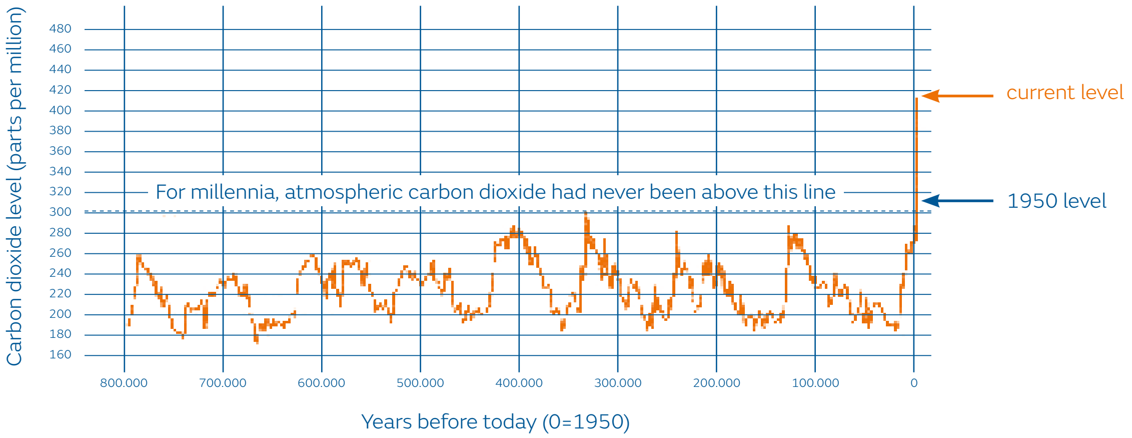
What is the human influence on climate change?

The latest IPCC report establishes that the human influence on the planet's climate system is clear, and also demonstrates that recent anthropogenic emissions of GHGs are the highest in history.

Among its other conclusions, it reports that anthropogenic GHG emissions have increased since the pre-industrial era and that this is largely a result of economic and population growth. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide (Figure 2) reaching levels never before seen on Earth, or at least not in the last 800,000 years (based on comparing

1 See the Glossary. Note that radiative forcing is not the same as the greenhouse effect.

Figure 2 ▪ Evolution of the concentration of CO_2 in the atmosphere, in parts per million, over the last 800,000 years.



Source: Luthi, D., et al. 2008; Etheridge, D.M., et al. 2010; Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO_2 record.

atmospheric samples from ice cores with the most recent direct measurements). The effects of emissions, as well as those of other anthropogenic factors, have been detected throughout the climate system and it is highly likely that they are the dominant cause of the global warming that we have been observing since the second half of the 20th century.

In recent decades, changes in the climate have had an impact on natural and human systems, on all the continents and in all the oceans. These effects are due to the climate change we have observed, whatever its cause. This indicates the heightened sensitivity of natural and human systems to climate change. The main effects have been an increase in the average global surface air temperature, an increase in the mean sea level, and also changes in many extreme meteorological and climatic phenomena.

These latter include a decrease in extreme cold temperatures, an increase in extreme warm temperatures, a rise in maximum sea levels and an increase in both the frequency and intensity of precipitation in different regions. However, in addition to its effect on physical variables, climate change has had an important impact on natural and socioeconomic systems, as has been observed and documented over the last decade. Chapter 2 includes a section dedicated to the different aspects of the impact of climate change.

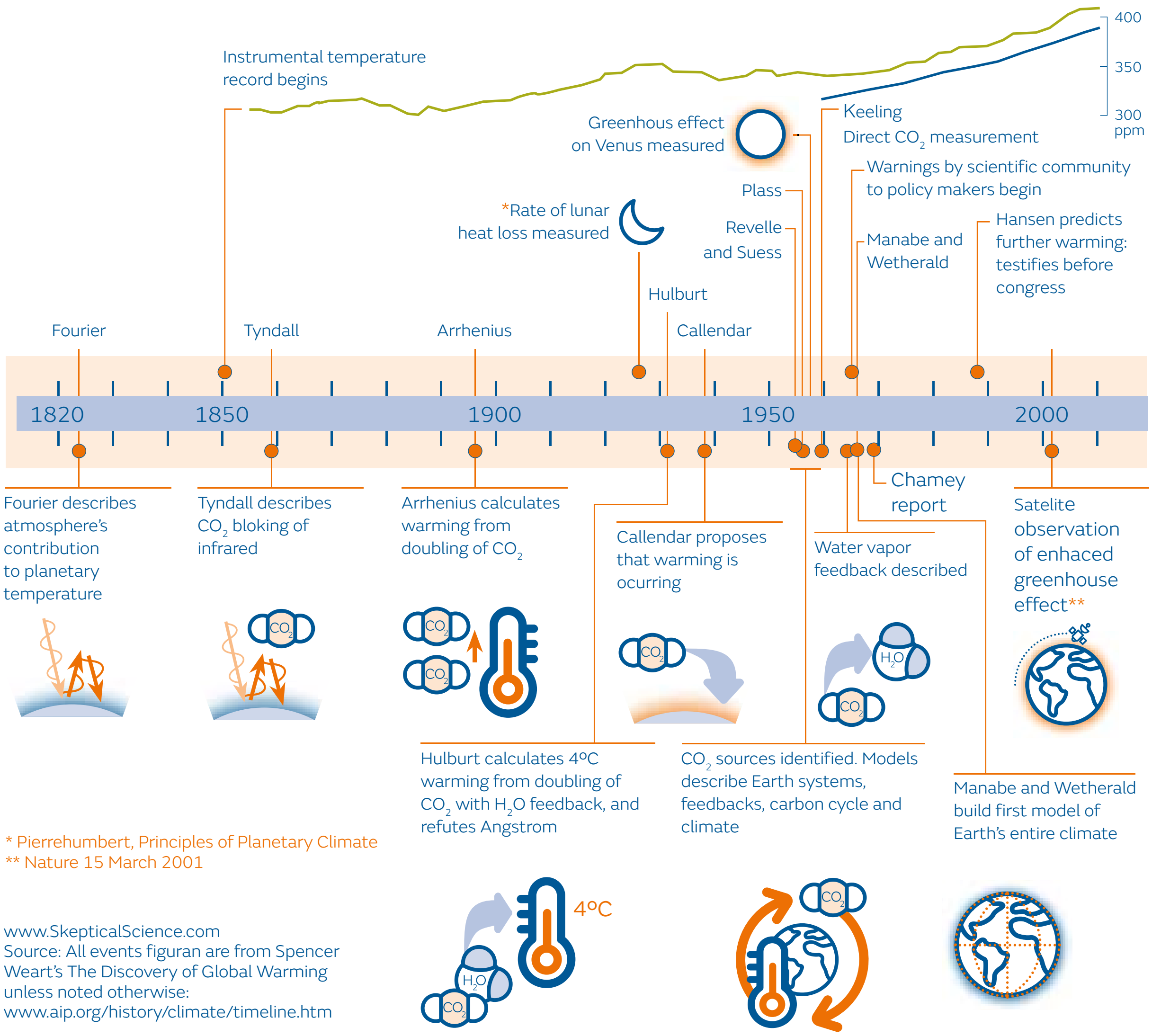
Carbon dioxide is a minor component of the atmosphere (it accounts for only some 0.04%), but it is relevant from the point of view of the climate, since it is the principal man-made GHG and is responsible for 60% of radiative forcing. Despite its low concentration, its influence on atmospheric dynamics is very important as CO_2 molecules can absorb heat emitted from the Earth and then radiate it again.

How has scientific knowledge advanced?

Climate change science relating the phenomenon to GHGs began back in 1824, when Fourier proposed the idea that the atmosphere retained infrared radiation emitted by the Earth, and that the degree of that retention could vary depending on human activity. The greenhouse effect of different gases was then analysed by Eunice Foote (1856) and by John Tyndall (1859). Arrhenius (1896) later combined these ideas and calculated the impact of changes in the concentrations of GHGs on temperature. All of these advances were the fruit, like many others at the time, of individuals working in isolation.

However, concern over environmental issues began to grow in the 1960s and 1970s, and led

Figure 3 ▪ Principal milestones in climate science



* Pierrehumbert, Principles of Planetary Climate
** Nature 15 March 2001

www.SkepticalScience.com
Source: All events figuran are from Spencer Weart's The Discovery of Global Warming unless noted otherwise:
www.aip.org/history/climate/timeline.htm

to more accurate measurements of the changes in the concentration of CO_2 in the atmosphere that Keeling had begun to study in 1956. This concern also resulted in larger research groups and programmes being established at universities and public organisations, such as NASA. This increase in scale meant that it was possible to develop complex computational models and more reliable measurements. All of this culminated in the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988.

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1.2 The scientific institutions

What is the IPCC?

The IPCC is the most rigorous scientific organisation in the field of climate change and, moreover, its work is scrutinised by reviewers and governmental organisations from over 190 countries. The IPCC is the primary international body for assessing climate change. It was created by the United Nations Environment Programme (UNEP) and the World Meteorological Organisation (WMO) in 1988 to provide a scientific overview of the state of knowledge on climate change at the time, as well as its potential environmental and socioeconomic impact.

The IPCC is a scientific body and as such it provides comprehensive assessments of the state of scientific, technical and socioeconomic knowledge on climate change, its causes, possible repercussions and response strategies. The body does not itself carry out any research or monitor data or parameters related to the climate, it simply collects and evaluates the work of the scientific community as a whole. To this end, the IPCC evaluates the scientific and technical documentation available in learned scientific journals, other publications made available to the IPCC, and documentation from other public and private organisations, including those from different industrial sectors. As it is an intergovernmental body, all member states of the United Nations and the WMO can form part of the IPCC: currently 195 countries are members.

The Panel meets in Plenary Sessions at least once a year. It is made up of representatives of the governments of member states. Here, the main decisions regarding the work programme are taken and the members of the IPCC Bureau are elected, including the IPCC Chair. Via the Panel, governments also participate in discussions on the scope of reports, the selection of authors, the review process, and they accept, adopt and approve IPCC Reports in Plenary Sessions.

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Due to its scientific and intergovernmental nature, the IPCC is an exceptional source of rigorous and balanced scientific information for decision makers. By accepting the contents of IPCC Reports, governments acknowledge the authority of their scientific content. Thus, the work of the IPCC is relevant to policymaking and yet neutral: it is never prescriptive. In other words, the IPCC analyses the scientific evidence and makes proposals for measures to be implemented, but these are never mandatory.

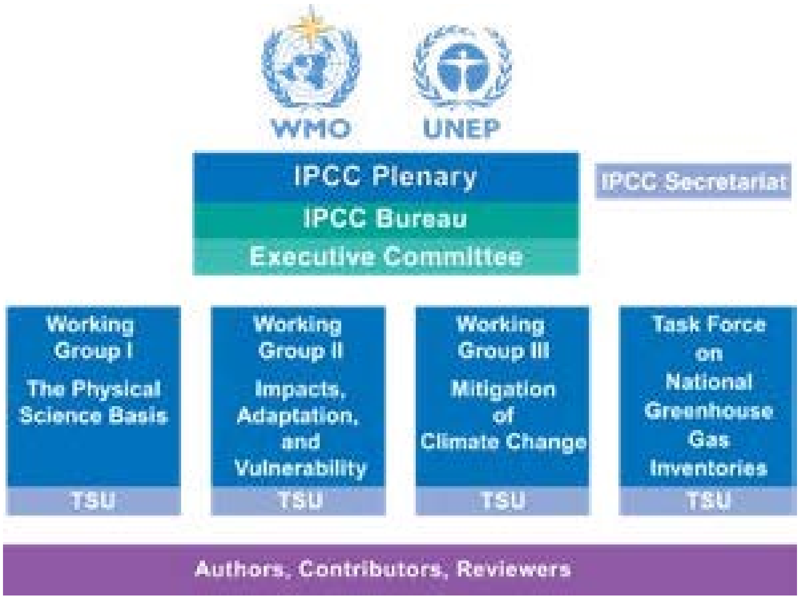


Figure 4 ▪ Structure of the IPCC.

Source: "How does the IPCC work?" from IPCC Website, Structure. https://archive.ipcc.ch/organization/organization_structure.shtml

The IPCC is organised into three Working Groups and a Special Task Force (Figure 4). Working Group I deals with the physical science underpinning climate change; Working Group II assesses the impact of climate change and how to adapt to it; and Working Group III addresses the mitigation of climate change. The additional Task Force oversees national GHG inventories. Its objective is to develop and refine a methodology for the calculation and reporting of national GHG emissions and removals.

Thousands of scientists from around the world contribute to the work of the IPCC on a voluntary basis as authors, contributors and reviewers.

What documents does the IPCC produce?

Since its inception, the IPCC has prepared five Assessment Reports, and the sixth (AR6) is due to be published in 2021. These Reports undergo a multi-stage drafting and review process to ensure a comprehensive and objective outcome, and they are produced in an open and transparent manner. Thousands of experts contribute as reviewers to ensure that all the views of the scientific community are reflected. Via careful supervision mechanisms, various teams of editors and reviewers ensure that all the comments made during the review process are taken into account.

Since its inception, the IPCC has prepared five Assessment Reports, and the sixth (AR6) is due to be published in 2021. These Reports undergo a multi-stage drafting and review process to ensure a comprehensive and objective outcome, and they are produced in an open and transparent manner. Thousands of experts contribute as reviewers to ensure that all the views of the scientific community are reflected.

The process of preparing IPCC Reports consists of several drafting and review stages (Figure 5). The different stages of review are an essential part of the IPCC working process that are designed to ensure a thorough, objective and transparent assessment of current scientific knowledge. The authors prepare a preliminary draft report based on the scientific, technical and socioeconomic literature in learned journals and other relevant publications. This literature is taken from peer-reviewed academic publications, but also includes documentation submitted to the IPCC for review, as well as other non-peer-reviewed publications.

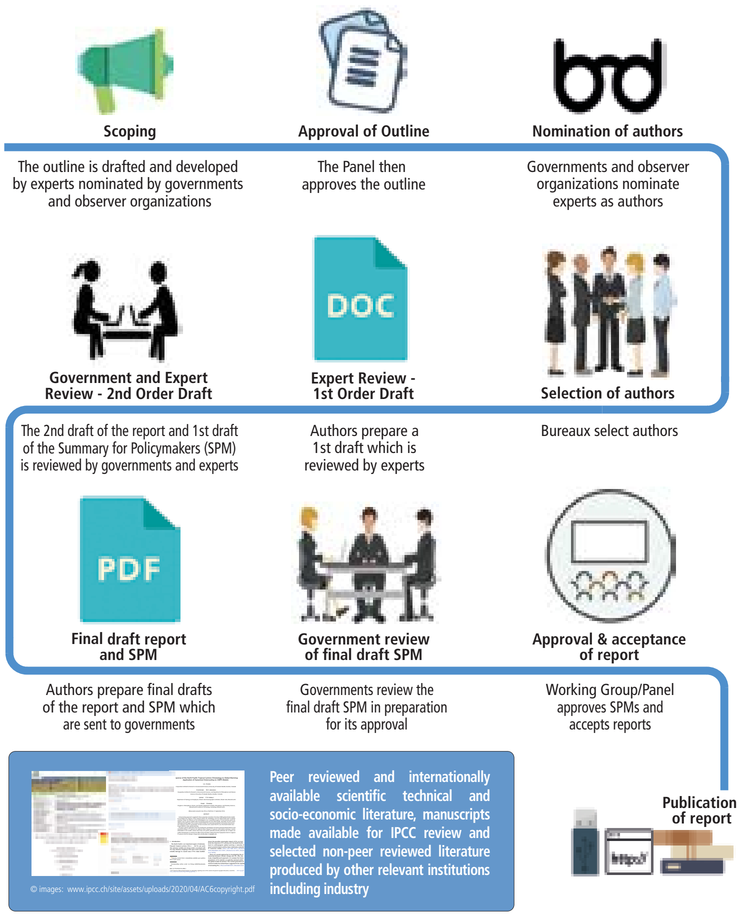


Figure 5 ▪ Process of preparing IPCC reports.

Source: "How the IPCC prepares its reports" from IPCC, 2020: *The IPCC and the Sixth Assessment cycle*, p.4
https://www.ipcc.ch/site/assets/uploads/2020/05/2020-AC6_en.pdf

After the expert review of the first-order draft, the teams of authors prepare a second-order draft which takes into account the comments received. An initial version of the Summary for Policymakers (SPM) is also drawn up. Both documents are simultaneously reviewed by experts and governments. After receiving the comments, the teams of authors then prepare a final draft version of the Report and SPM, taking into account the comments received. The final draft version of the Report is distributed to the different governments for them to submit their concluding observations on the SPM in writing before the final Plenary Session of the Panel. At this meeting, the SPM is approved line by line and the full Report is adopted.

By way of example, Figure 6 shows the number of comments made on the last Report published (AR5).

What do the IPCC Reports say?

To date, five Reports have been written. Each new report reflects the scientific progress since the previous Report and also sets out in which areas new research is needed. The first, AR1, was published in 1990 and formed the basis for successive reports since it was structured around the three working groups mentioned above. In that first report, the scientific evaluation was already perfectly clear and certain that "there is a natural greenhouse effect that already keeps the Earth warmer than it otherwise would be" and that "emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases carbon dioxide, methane, chlorofluorocarbons (CFCs) and nitrous oxide. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface. The main

Figure 6 ▪ Number of review comments on Fifth Assessment Report.

		Number of comments	Experts	Governments
Working Group I	First Order Draft	21,400	659	-
	Second Order Draft	31,422	800	26
Working Group II	First Order Draft	19,598	563	-
	Second Order Draft	28,544	452	33
Working Group III	First Order Draft	16,169	602	-
	Second Order Draft	19,554	444	24
Synthesis Report	First Order Draft	5,944	85	42
Total		142,631	-	-

Note: some experts register for more than one Working Group and the Synthesis Report

Source: IPCC, 2020. IPCC Factsheet: "How does the IPCC review process work?"
https://www.ipcc.ch/site/assets/uploads/2018/04/FS_review_process.pdf

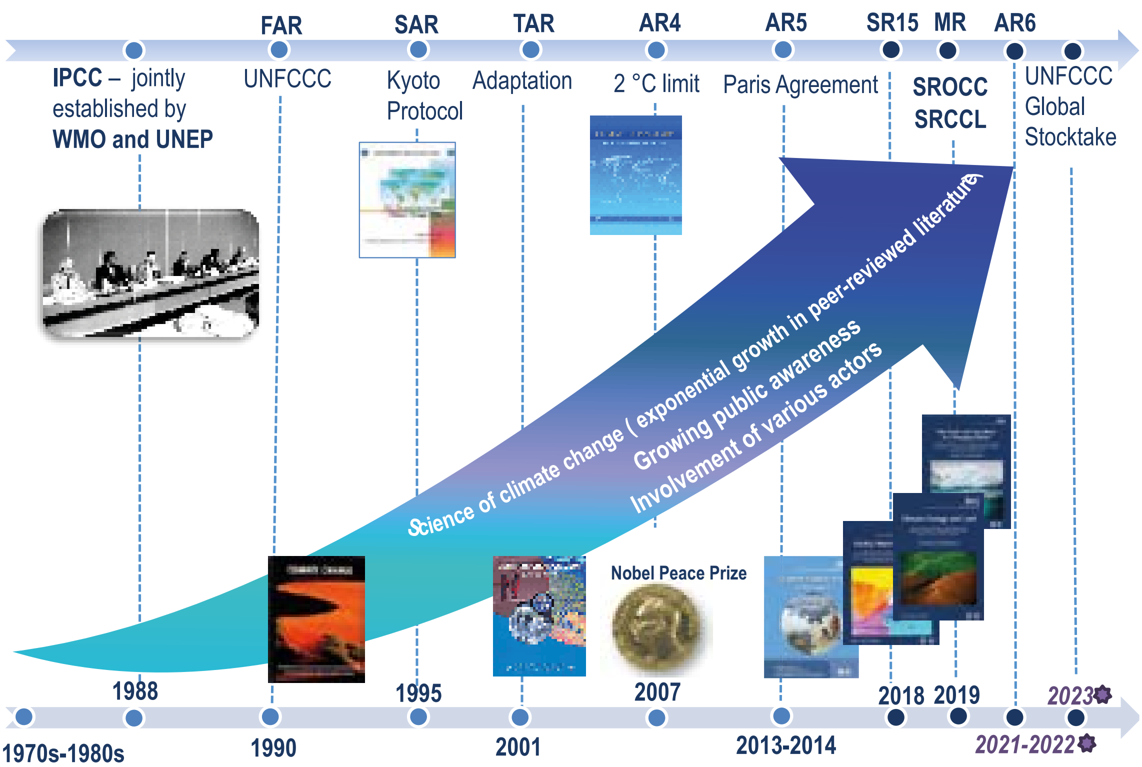
greenhouse gas, water vapour, will increase in response to global warming and further enhance it". The report also served as the basis for the negotiation of the United Nations Framework Convention on Climate Change (UNFCCC), which was adopted in 1992 and entered into force in 1994.

The second Report, published in 1995, emphasises the objective of mitigating climate change through achieving the ultimate objective of the UNFCCC, as expressed in its Article 2: "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner". So the document presents scientific, technical and socioeconomic information that could be used to tackle the challenges that arise from attempting to achieve this objective, which are summarised by way of determining the concentrations of GHGs that could be considered "dangerous anthropogenic interference with the climate system" and preparing for a future that allows sustainable economic development.

The third Report was published in 2001 and answers a series of questions related to clarifying just what constitutes "dangerous anthropogenic interference with the climate system" and how to deal with the problem of climate change within the context of sustainable development. It also addresses the identification of the causes of the changes observed in the climate and ecological systems since pre-industrial times. A further concern it tackles is the assessment of the impact on the climate of future emissions of GHGs and sulphate aerosol precursors, if specific policies for the mitigation of climate change are not applied. It suggests how to understand the inertia inherent to the climate, to ecological systems and also to socioeconomic sectors, and the consequences of that inertia for mitigation measures and adaptation to the effects of climate change. The Report discusses the short- and long-term consequences for the climate, ecology and socioeconomic sectors of the stabilisation of atmospheric concentrations of GHGs. It evaluates the technologies, policies and costs of measures for the mitigation of GHG emissions in the short and long term; and it also identifies interactions between climate change, other environmental problems and development, together with addressing key uncertainties.

To date, five Reports have been written. Each new report reflects the scientific progress since the previous Report and also sets out in which areas new research is needed. The first, AR1, was published in 1990 and formed the basis for successive reports since it was structured around the three working groups mentioned above.

Figure 7 ▪ Evolution of climate change science since the 1970s



Source: "IPCC contribution to climate science and policymaking" from IPCC, 2020: *The IPCC and the Sixth Assessment cycle*, p.3 https://www.ipcc.ch/site/assets/uploads/2020/05/2020-AC6_en.pdf

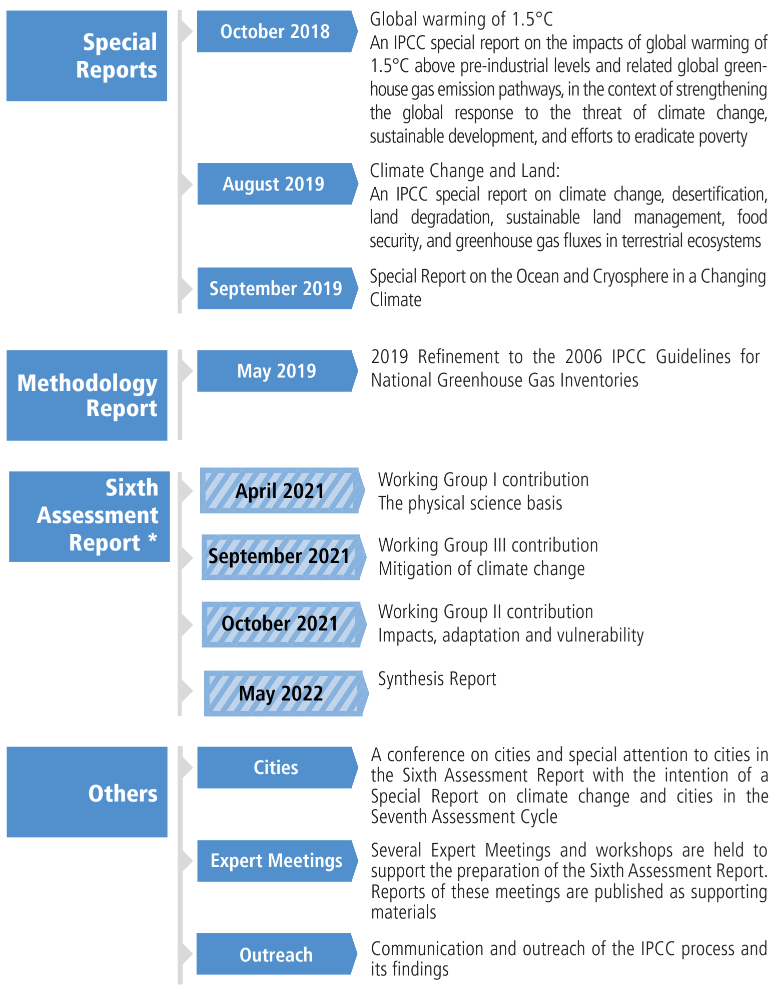
The fourth Report, published in 2007, is organised around six themes. One is observed changes in the climate and the effects of climate change. Another is the causes of the change, considering their natural and anthropogenic origins. The third concerns projections of future climate change and its impact; and the fourth adaptation and mitigation options and responses (in particular, up until 2030), as well as the interrelationships between climate change, response measures and sustainable development. The fifth addresses the long-term perspective as well as the scientific, technical and socioeconomic aspects of adaptation and mitigation, in line with the objectives and provisions of the UNFCCC; while the remaining theme is robust conclusions and key uncertainties.

The fifth and last available Report was presented in 2014, and it places emphasis on assessing: the socioeconomic aspects of climate change and their consequences for sustainable development; regional aspects; risk management; and the development of a response through adaptation and mitigation. It also presents more than 100 pieces of evidence of the impact produced by climate change. It is structured around four themes: observed changes and their causes; future climate changes, risks and impacts; future trajectories of adaptation, mitigation and sustainable development; and adaptation and mitigation.

The sixth assessment cycle (AR6) began its process in 2018 and the publication of the corresponding reports is scheduled between April 2021 and May 2022 (Figure 8). To date, the Methodology Report and three Special Reports have been published: 1) Special Report on the impacts of global warming of 1.5ºC above pre-industrial levels and related global GHG emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty[2]; 2) Special

2 Available at: https://www.ipcc.ch/sr15/

Figure 8 ▪ The IPCC Sixth Assessment Cycle



Source: "The Sixth Assessment cycle" from IPCC, 2020: *The IPCC and the Sixth Assessment cycle*, p.2
https://www.ipcc.ch/site/assets/uploads/2020/05/2020-AC6_en.pdf

Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems[3]; and 3) Special Report on the ocean and cryosphere in a changing climate[4]. The five fundamental elements that will constitute the Report have also been defined: global stocktake; interaction among emissions, climate, risks and development pathways; social and economic costs and benefits of mitigation and adaptation in the context of development pathways; adaptation and mitigation actions in the context of sustainable development; and financing and means of support.

Are there contrary positions with respect to climate change?

Due to its very nature, the IPCC aims to include the scientific results of all research groups at a global level, considering both work that demonstrates anthropogenic influences on the climate, and that which rejects this hypothesis, provided they are scientifically validated. The experts who contribute to the IPCC Reports evaluate all scientific research and reflect the findings, with greater or lesser importance, in the Reports, depending on their relevance. Therefore, it cannot be said that there are groups

3 Available at: https://www.ipcc.ch/srccl/

4 Available at: https://www.ipcc.ch/srocc/

of scientists outside the IPCC, since all of their work is reflected in its Reports.

In fact, the certainty of the claims made in the IPCC Reports depends on the degree of consensus on the different scientific contributions. There are, however, some organisations that bring together people (who are not necessarily scientists) who hold positions that are contrary to the majority scientific position, such as the Heartland Institute[5], or the "Climate Intelligence[6]" foundation, which published a letter to the Secretary General of the United Nations in September 2019 indicating that, in their opinion, there is no climate emergency. In any case, these are minority groups and, as indicated, the scientific evidence they produce is included in the IPCC Reports.

Notwithstanding this, it should be noted that there is a greater degree of variation in the scientific position regarding the magnitude of the actions to be taken against climate change. This is illustrated by the debate between Nordhaus and Stern, which shows the lack of agreement between two scientists of recognised prestige on the most effective measures to mitigate climate change. This originates in their discrepancies concerning the role of the discount rate in climate models, the technical progress of mitigation costs and climate sensitivity[7]. Also in this domain there are "contrary" and minority positions such as those adopted by Bjorn Lomborg and his Copenhagen Consensus Center[8], which considers many of the policies aimed at limiting climate change to be mistaken.

The fifth and last available Report was presented in 2014, and it places emphasis on assessing: the socioeconomic aspects of climate change and their consequences for sustainable development; regional aspects; risk management; and the development of a response through adaptation and mitigation. The sixth assessment cycle (AR6) began its process in 2018 and the publication of the corresponding reports is scheduled between April 2021 and May 2022

5 https://www.heartland.org/Center-Climate-Environment/

6 https://clintel.org

7 An article containing the details of the debate can be accessed at: https://www.feem.it/en/publications/feem-working-papers-note-di-lavoro-series/disentangling-the-stern-nordhaus-controversy-beyond-the-discounting-clash/

8 https://www.copenhagenconsensus.com

2.
The big questions surrounding climate change

José Manuel Moreno

Professor of Ecology at the University of Castilla-La Mancha. His work centres on the ecology of forest fires and their relationship with climate change. He was commissioned Dean of the Faculty of Environmental Sciences of the University of Castilla-La Mancha when it was inaugurated. In addition, he founded the Institute of Environmental Sciences and the Fire Research Centre of the Castilla-La Mancha General Environmental Foundation. He has been a member of the management committees of European Commission environmental programmes (STEP, EPOCH, ENVIRONMENT), and has participated in numerous European groups and institutions. He is currently Vice-Chair of Group II of the IPCC, as well as Review Editor of several chapters of the reports.

2.1 Is the greenhouse effect becoming stronger? Are we suffering its effects?

- What is the Earth's energy balance and how does it maintain an equilibrium?
- Why do levels of CO_2 and other greenhouse gases tend to increase?
- What trends are observed in the climate, cryosphere and oceans?
- Which impacts of climate change can be attributed to anthropogenic causes?
- What impact does climate change have on different systems and sectors?

What is the Earth's energy balance and how does it maintain an equilibrium?

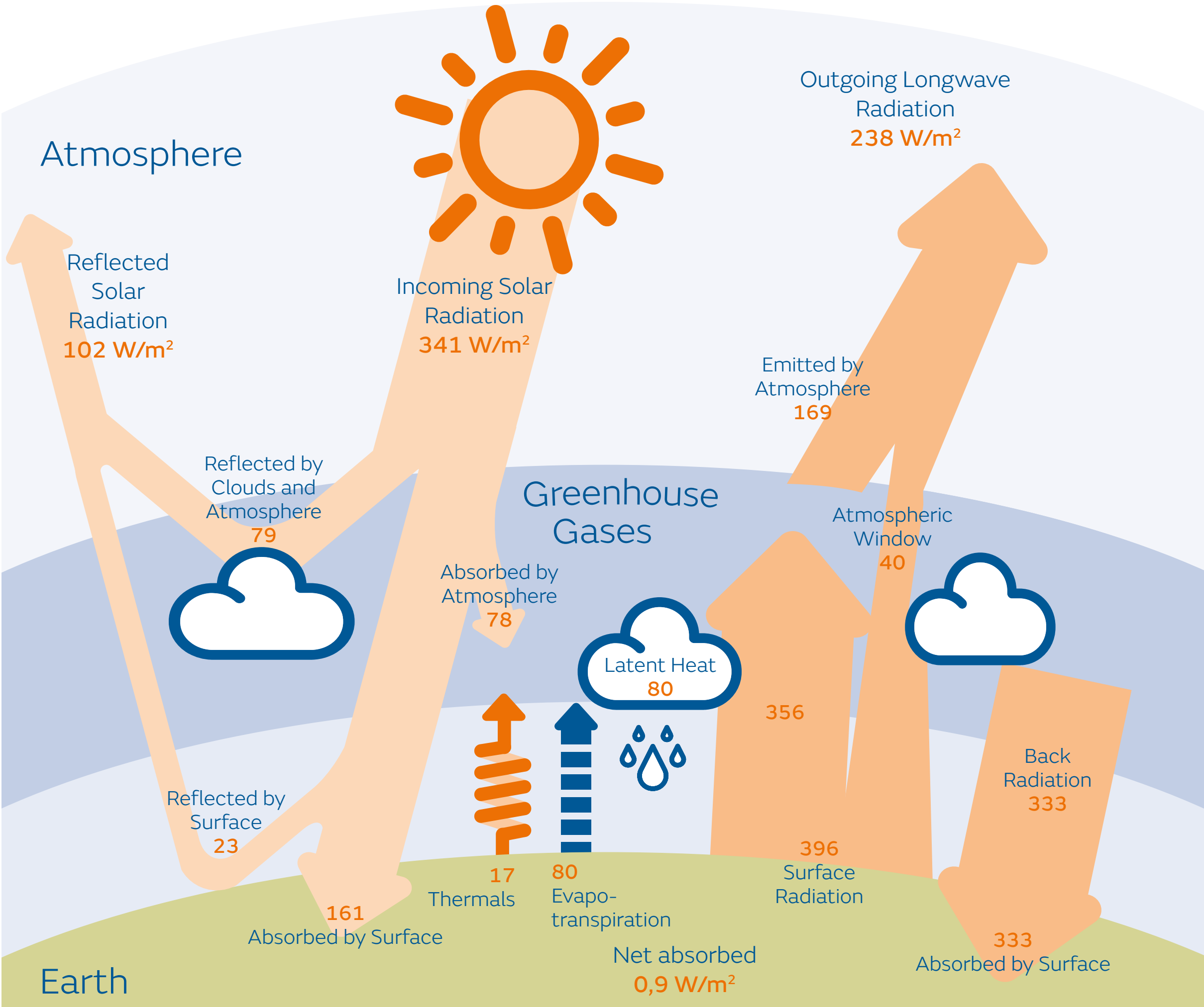
To understand why the Earth is warming, we need to consider its energy balance, that is, the difference between the energy that the planet receives and the energy that it gives off, as well as the factors that regulate this process. Nearly all the energy that reaches the Earth's surface comes from the Sun; the amount of energy that arrives at the surface from deep inside the planet is negligible by comparison. The Earth's upper atmosphere receives radiation at a rate of 341 W/m^2. That is, each square metre of the upper atmosphere oriented perpendicular to our star receives 341 watts, which is 341 joules of energy every second. This is what is known as the solar constant, and it varies only slightly throughout solar cycles (~ 0.25 W/m^2). The visible band of the electromagnetic spectrum contains the wavelength at which this radiation is at its maximum and the Earth's atmosphere is transparent to it. Even so, not all the energy that is incident on the upper atmosphere reaches the Earth's surface: part of it is reflected or absorbed by the atmosphere (Figure 9). Of the energy that does reach the surface, a further fraction is reflected by the planet itself, and in fact just 47% of the total incident energy is absorbed by the planet and warms us[9].

Every hot body emits radiation at a wavelength that is inversely proportional to its temperature. The average temperature of the Earth's surface is about 15ºC, and it therefore emits radiation in the infrared section of the spectrum, known as thermal radiation. The atmosphere is virtually opaque to this type of radiation, which means that of the 396 W/m^2 of thermal radiation that the Earth's surface emits, 333 W/m^2 is returned to it (Fig. 1). In the end, all the energy will be radiated back into space. However, the fact that this does not occur instantly and some energy is temporarily retained means that the planet stays warmer than it would be if we did not have an atmosphere; this is the well-known greenhouse effect. If there was no atmosphere and no such effect, the average surface

The annual net energy input and output balance at the beginning of the 21st century was positive. That is, there was an energy imbalance as the total energy input was greater than the total output. This implies that the Earth is accumulating energy, and heating up. If we change the surface temperature, then we also modify other climate variables that depend on it, such as the amount of water vapour in the atmosphere and the global hydrological cycle in general, among others.

9 Trenberth, K.E., J.T. Fasullo, and J. Kiehl, *Earth's global energy budget*. Bulletin of the American Meteorological Society, 2009. 90(3): p. 311-324.

Figure 9 · The earth's annual mean energy flows (in w/m²) from March 2000 to May 2004.



The left side shows the energy that flows from the Sun (visible radiation) and the right side shows energy flowing from the Earth's surface out into space (infrared radiation). The width of the branches is proportional to the magnitude of the energy flows.

Source: Trenberth, K.E., J.T. Fasullo, and J. Kiehl, *Earth's global energy budget*. Bulletin of the American Meteorological Society, 2009. 90(3): p. 311-324.

temperature of the Earth would be -18ºC, turning the planet into one big ball of ice.

Since humans have altered both the Earth's atmosphere and its surface (bear in mind that we have deforested more than half of the planet for agricultural purposes), it is a good idea to establish what position the Earth's energy balance is in. This is certainly no straightforward task, but it has been made possible by the recent quantifications that we have managed to arrive at thanks to satellites that allow us to measure the energy that enters and leaves the upper atmosphere. The annual net energy input and output balance at the beginning of the 21st century was positive, at +0.9 W/m².

That is, there was an energy imbalance as the total energy input was greater than the total output. This implies that the Earth is accumulating energy, and heating up (Figure 9). As we will see later, this is the proof that changing the factors that regulate the planet's energy balance, such as the composition of the atmosphere or aspects of the Earth's surface, can indeed warm the planet. If we change the surface temperature, then we also modify other climate variables that depend on it, such as the amount of water vapour in the atmosphere and the global hydrological cycle in general, among others. This is precisely what we have been doing and continue to do.

The idea that the atmosphere plays a crucial role in our planet's climate is not new. It was proposed by the French mathematician Joseph Fourier in 1824, and then experimentally demonstrated by the Irish physicist John Tyndall in 1863. Tyndall's observation that some gases, such as water vapour and CO_2, were practically opaque to thermal radiation laid the foundations for understanding the greenhouse effect and the role the atmosphere plays in determining the climate. A few years later, in 1896, the Swedish chemist who won the Nobel Prize in Chemistry, Svante Arrhenius, calculated for the first time what the effect would be if the concentration of carbon dioxide doubled. As mentioned, CO_2 is one of the gases that contribute to the greenhouse effect, now commonly known as greenhouse gases (GHGs), which are: water vapour, clouds, CO_2 and other compounds (CH_4, N_2O, O_3 and chlorofluorocarbons (CFCs)), and contribute 50%, 25%, 20% and 5%, respectively, to the effect. Suspended atmospheric particles (dust and aerosols) are the other contributors to the greenhouse effect[10]. Although CO_2 is not the principal component, its role is particularly important because as its atmospheric concentration increases, so too does the temperature, and with it, the amount of water vapour and clouds. Doubling the pre-industrial concentration of CO_2 would increase energy absorption by some 4 W/m^2, but if we include the indirect effects of this on water vapour and clouds[11] The idea that the atmosphere plays a crucial role in our planet's climate is not new. It was proposed by the French mathematician Joseph Fourier in 1824, and then experimentally demonstrated by the Irish physicist John Tyndall in 1863. Tyndall's observation that some gases, such as water vapour and CO_2, were practically opaque to thermal radiation laid the foundations for understanding the greenhouse effect and the role the atmosphere plays in determining the climate. A few years later, in 1896, the Swedish chemist who won the Nobel Prize in Chemistry, Svante Arrhenius, calculated for the first time what the effect would be if the concentration of carbon dioxide doubled. As mentioned, CO_2 is one of the gases that contribute to the greenhouse effect, now commonly known as greenhouse gases (GHGs), which are: water vapour, clouds, CO_2 and other compounds (CH_4, N_2O, O_3 and chlorofluorocarbons (CFCs)), and contribute 50%, 25%, 20% and 5%, respectively, to the effect. Suspended atmospheric particles (dust and aerosols) are the other contributors to the greenhouse effect. Although CO_2 is not the principal component, its role is particularly important because as its atmospheric concentration increases, so too does the temperature, and with it, the amount of water vapour and clouds. Doubling the pre-industrial concentration of CO_2 would increase energy absorption by some 4 W/m^2, but if we include the indirect effects of this on water vapour and clouds , this figure reaches 20 W/m^2. This explains why, although CO_2 exists in very small quantities, its effect on the climate is so important, as we will see below.

Why do levels of CO_2 and other greenhouse gases tend to increase?

The average concentration of CO_2 in the atmosphere before the Industrial Revolution was 278 ppm (parts per million, by volume). During the most intense stages of the last ice age, its concentration was 180-200 ppm. The variation in atmospheric CO_2 concentration between warmer interglacial periods and cold glacial periods has remained at around 80-100 ppm throughout the most recent glacial cycles the Earth has undergone, with the concentration being higher at warm moments of the glacial cycle than in colder periods[12].

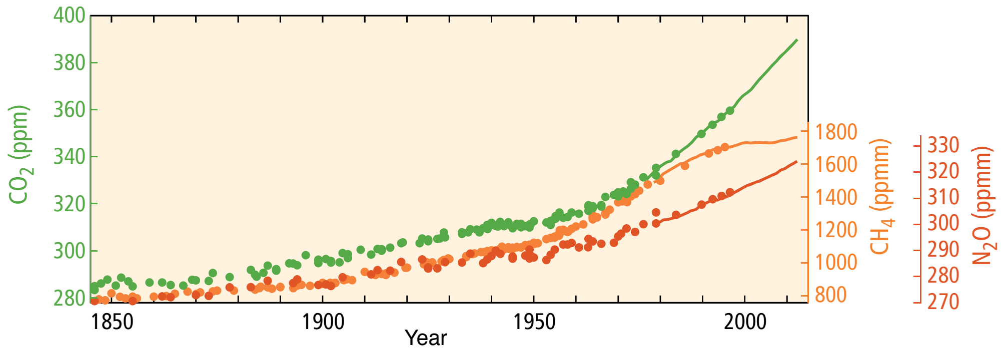
The atmospheric concentration of CO_2 also increases because it is emitted during combustion processes, and in the manufacture of cement, or as a result of deforestation and the consequent oxidation of organic matter accumulated in soil and plants. Between 1750 and 2011, it has been calculated that 2010 $GtCO_2$, (that is gigatons –109 tons– of CO_2) was emitted into the atmosphere, half of

10 Lacis, A.A., et al., *Atmospheric CO_2: Principal control knob governing Earth's temperature*. Science, 2010. 330(6002): p. 356-359.

11 Schmidt, G.A., et al., *Attribution of the present-day total greenhouse effect*. Journal of Geophysical Research: Atmospheres, 2010. 115(D20).

12 Lüthi, D., et al., *High-resolution carbon dioxide concentration record 650,000–800,000 years before present*. Nature, 2008. 453(7193): p. 379-382.

Figure 10 ▪ Trends in the variation of some of the principal greenhouse gases (CO_2, N_2O and CH_4) since 1850.



Source: SPM.1 (panel (c)) from IPCC, 2014: Summary for Policymakers. In: *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* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland. https://www.ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_SPM.pdf

which has been emitted since 1970![13] In other words, the rate of emission has accelerated in recent decades. In accordance with this, the atmospheric concentration of CO_2 increased gradually after the start of the Industrial Revolution, up until the middle of the last century, when its concentration had reached some 320 ppm. Since then, this concentration has increased rapidly; so much so that the current measurement (May 2020) at the reference observatory in Mauna Loa, Hawaii, USA, was 417 ppm (50% higher than the pre-industrial concentration)[14]. Concentrations such as these have not been recorded on Earth since the Pliocene, 2.5-3.0 million years ago. The trends for other GHGs are similar. At the end of 2019, the concentration of CH_4 was 1,869 ppb (parts per billion –109– by volume) while that of N_2O was 331 ppb, representing increases of 259% and 143%, respectively, relative to pre-industrial levels[15] (Figure 10).

To these changes in the concentrations of the principal GHGs, we must add changes in ozone (both tropospheric and stratospheric), CFCs, aerosols and dust. In addition, for the energy balance to be complete, changes in the terrestrial albedo must be added. The albedo is the fraction of solar radiation that is reflected by the ground, sea, snow and ice, which is equivalent to 7% of the incident radiation. Snow and ice have a high albedo (close to 1) since they reflect nearly all of the radiation that is incident on them; and as they disappear, the warming of the planet will increase. Vegetation and the oceans have low albedos: they absorb incident radiation. Deforestation eliminates vegetation and exposes soil to a greater or lesser extent, depending on the crops that are grown. The albedo of soil depends on its colour and humidity, among other factors, and it tends to be less than that of the vegetation that covers it.

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The reports of the Intergovernmental Panel on Climate Change (IPCC) calculate the resulting effect of all these changes that are occurring on Earth, by calculating what is called radiative

13 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* 2014: IPCC, Geneva, Switzerland.

14 Keeling, R.F. and C.D. Keeling, *Atmospheric Monthly In Situ CO_2 Data - Mauna Loa Observatory, Hawaii, in Scripps CO_2 Program Data. UC San Diego Library Digital Collections.* 2017.

15 WMO, *WMO Statement on the State of the Global Climate in 2019*. 2020.

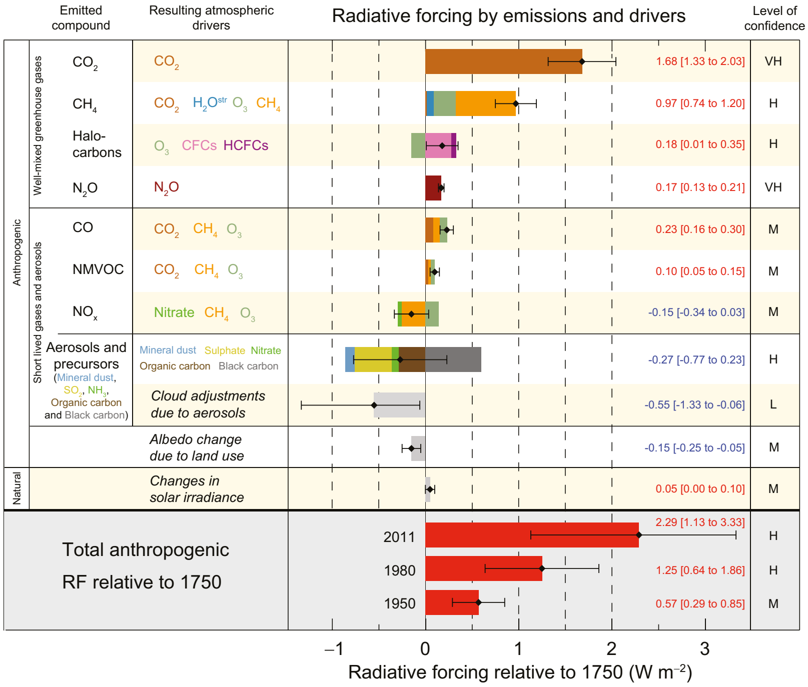


Figure 11 ▪ Mean values and uncertainty (5% to 95%) of the contribution of different gases and agents to average global radiative forcing (solid colours) or to the average effective global radiative forcing (this includes water vapour and cloud adjustments) (hatched colours) for the period 1750 to 2011.

Source: SPM.5 from IPCC, 2013: Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–30, doi:10.1017/CBO 9781107415324.004.
https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_SPM_FINAL.pdf

forcing or climate forcing: the capacity to absorb or transmit energy that results from each of the changes we make to the Earth's surface or in the atmosphere. Positive forcing means that the planet heats up; while if the result is negative, it cools down. Total anthropogenic forcing has grown steadily from pre-industrial times to the present. If we set this value to 0 W/m^2 in 1750, the reference year against which the calculations are made, then in 1950 it was +0.57 W/m^2; in 1980, +1.25 W/m^2; and in 2011, the date of the data in the last IPCC report[16], +2.29 W/m^2. A good part of the total radiative forcing is due to CO_2, whose emissions in 2011 represented a forcing of +1.68 W/m^2 (Figure 11): 75% of the total. By 2019[17], that figure had increased to +2.07 W/m^2.

What trends are observed in the climate, cryosphere and oceans?

In line with GHG emissions and other planetary changes, and the corresponding climate forcing, by the end of 2019 the average temperature of the Earth's surface had increased by 1.1ºC. The warming has been much greater in recent years with each decade since the 1980s being warmer than the previous one, which had never happened before in the period of observations beginning in 1850. To date, 2019 has been the second warmest year since records began, and the same is true of the last five years[18]. This warming is not distributed evenly between the land and oceans, or from one region to the next: some areas warm more than the average. This is the case of polar zones and the Mediterranean region[19]. Thus, in Spain, we have seen warming

16 Myhre, G., et al., *Anthropogenic and natural radiative forcing. Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 659–740.* 2013, Cambridge: Cambridge University Press.

17 NOAA. *The NOAA Annual Greehouse Gas Index (AGGI).* 2020 [cited 2020 May/25]; Available from: https://www.esrl.noaa.gov/gmd/aggi/aggi.html.

18 WMO, *WMO Statement on the State of the Global Climate in 2019.* 2020.

19 Seneviratne, S.I., et al., *Allowable CO_2 emissions based on regional and impact-related climate targets.* Nature, 2016. 529(7587): p. 477-483.

equivalent to an increase of 1.7ºC to date. This increase is particularly notable during the summer, which now lasts about five weeks longer than it did in the 1980s. Over this period, the number of nights that can be classified as “torrid” (with minimum temperatures remaining above 25ºC) in Spanish cities has increased 10-fold; the days that are considered to be part of a heatwave have doubled, while cold days have seen a 25% reduction; and summer heatwaves are also now 10 times more. Meanwhile, precipitation has decreased moderately (-18.7 mm per decade, with an accumulated reduction of 16% over the last five decades)[20].

Ice that forms part of glaciers in mountain ranges, Greenland, the Arctic, and Antarctica also plays a crucial role in determining the climate. Most mountain glaciers have been losing their total ice content for some time. In Spain, such glaciers now cover barely 10% of the surface area they occupied a hundred years ago. Pyrenean glaciers, which are the most important in Spain, now hold only some 3.3% of the 886 hm^3 of water that they contained at the end of the 19th century[21]. The extent of the Arctic ice is continuously decreasing and already in this century we have recorded historic minimum values of both the minimum extension of the ice cover in September and its maximum in March. Greenland’s ice is also melting in increasing amounts; and just as in the Arctic, the greatest losses have been recorded in this century. Between 2002 and 2006, 260 Gt of ice was lost each year, which is equivalent to a rise in the sea level of 0.72 mm. Antarctica had been experiencing a slight gain in ice up until 2016, when that trend was reversed; since then, it has remained at relatively low levels. It was thought the ice in Antarctica was stable, but recent discoveries have brought that assumption into question, and the reduction of some of its

The oceans absorb a quarter of the CO_2 released into the atmosphere, making them a useful ally in the fight to reduce the greenhouse effect. However, this absorption has consequences since the solubility of CO_2 in water increases as the atmospheric concentration of the gas increases. As CO_2 dissolves and reacts with water, it creates carbonic acid, which dissociates producing protons and bicarbonate anions.

largest ice masses may have already begun. The warming of the sea and the addition of water coming from melting glaciers and supposedly stable polar ice caps mean that the mean sea level is rising, with its average annual rise having been 3.3 mm over the last 27 years. This increase has been accelerating, above all due to the incorporation of water from glaciers[22].

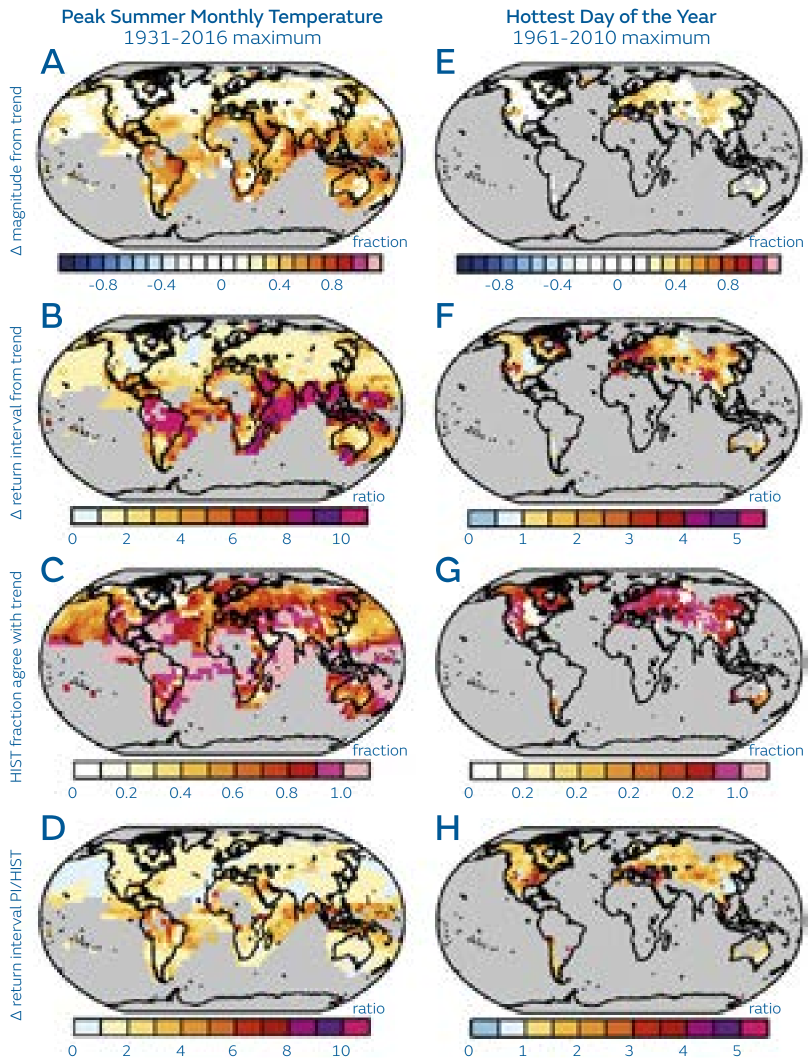
The oceans absorb a quarter of the CO_2 released into the atmosphere, making them a useful ally in the fight to reduce the greenhouse effect. However, this absorption has consequences since the solubility of CO_2 in water increases as the atmospheric concentration of the gas increases. As CO_2 dissolves and reacts with water, it creates carbonic acid, which dissociates producing protons (H+) and bicarbonate anions (HCO_3-). This causes the pH of the seawater to decrease, or in other words, it becomes more acidic. Since the 1980s, surface ocean waters have acidified at a rate of -0.017 to -0.027 pH units per decade, which is 50 times more quickly than we know of at other time in history. Acidification has extremely negative effects for many marine organisms which use structures based on calcium carbonate, such as corals, zooplankton and shellfish, many of which are at the base of the food chain. Meanwhile, ocean water also loses oxygen when it warms up. It

20 Vicente-Serrano, S.M., et al., *Temporal evolution of surface humidity in Spain: recent trends and possible physical mechanisms*. Climate Dynamics, 2014. 42(9): p. 2655-2674.
Vicente Serrano, S.M., et al., *An updated review on recent trends in observational surface atmospheric variables and their extremes over Spain.* Cuadernos de investigación geográfica/Geographical Research Letters, 2017(43): p. 209-232.

21 MITECO. *Glaciares - Evolución y Situación.* 2020 [cited 2020 20/05]; Available from: https://www.miteco.gob.es/ca/agua/temas/evaluacion-de-los-recursos-hidricos/ERHIN/glaciares-evolucion/default.aspx.

22 WMO, *WMO Statement on the State of the Global Climate in 2019*. 2020.
Meredith, M., et al., *Polar Regions, in IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, H.-O. Pörtner, et al., Editors. 2019, Cambridge University Press, Cambridge, U.K. p. 206-320.

Figure 12 ▪ Attribution measurements carried out over a global grid for: (A - D) the highest peak monthly temperature in summer and (E - H) the maximum hottest day of the year. (A and E)



The contribution of the observed trend to the magnitude of the event. Note the dominance of dark yellow colours, which indicate contributions to the observed trend in the magnitude of the extreme events analysed of a proportion of around 0.4, or 40%. (B and F) The median contribution of the observed trend to the probability of the event. Note that the dominant colours indicate that the probability of these events occurring has increased by at least 5 times across large areas of the planet, that is, they are much more likely in the current climate than they were in the unperturbed climate. (C and G) The probability of the trend observed occurring in the simulations of the historical climate model, where we can observe that this is much more likely to occur in the observed historical climate (HIST) than in the pre-industrial (PI) unperturbed climate. (D and H) The median contribution of the historical forcing to the probability of the event, noting that wide areas show a greater probability of exceeding the maximum value in the historical simulations, that is, in the perturbed climate, than in the pre-industrial or unperturbed climate, with this probability having increased 4-fold or more across large areas of the world.

Source: Noah S. Diffenbaugh, Deepti Singh, View ORCID ProfileJustin S. Mankin, Daniel E. Horton, Daniel L. Swain, Danielle Touma, Allison Charland, Yunjie Liu, Matz Haugen, Michael Tsiang, and Bala Rajaratnam. *Quantifying the influence of global warming on unprecedented extreme climate events*. PNAS May 9, 2017 114 (19) 4881-4886; first published April 24, 2017

https://www.pnas.org/content/114/19/4881

is estimated that since the middle of the last century, between 1% and 2% of the oxygen has been lost from surface ocean waters. Recent studies show that the combination of increased temperatures, acidification and hypoxia poses one of the greatest threats to ocean ecosystems[23].

The most disastrous effects of climate change manifest themselves through what are known as extreme events: unusually rare meteorological or climatic phenomena, usually outside the 10th to 90th percentile range of the probability density function derived from past observations.

Heatwaves, floods, droughts, storms and hurricanes are some of the most significant extreme events. In general, these are all increasing worldwide, although not all of them are behaving in the same way. Furthermore, this growth is progressively related to anthropogenic climate change. This association is established through studies that analyse whether the probability or severity of a certain event (for example, the heatwave that affected the Iberian Peninsula in the summer of 2018) was the same in the "normal" or pre-industrial climate (that is, the climate as it existed before it was altered by human activity) as in the current or

23 Bindoff, N.L., et al., *Changing Ocean, Marine Ecosystems, and Dependent Communities, in IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, H.-O. Pörtner, et al., Editors. 2019, Cambridge University Press, Cambridge, U.K. p. 448-547.

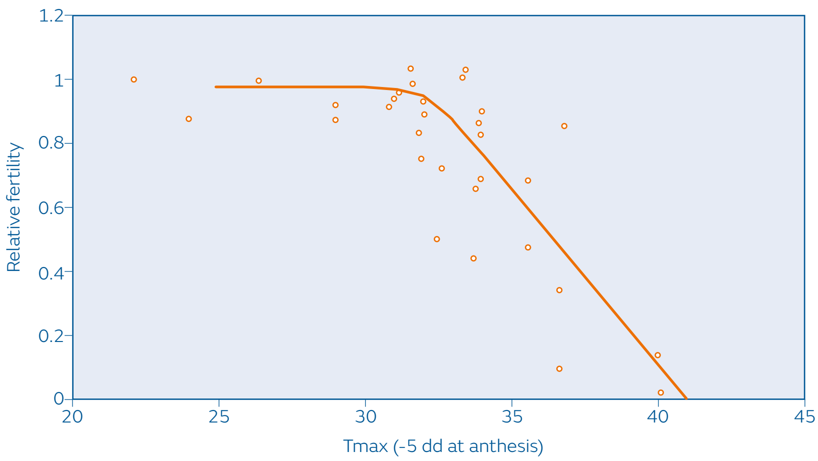
"perturbed" climate. This type of study is known as "attribution," since it aims to attribute cause (anthropogenic climate change) to an observed phenomenon. The global warming experienced to date has resulted in the severity of the warmest month or the warmest day of the year worldwide having more than an 80% probability of being more extreme. Similarly, the probability of a year being the driest or including the wettest five-day period has increased by 57% and 41%, respectively[24] (Figure 12). The number of extreme events partly caused by climate change continues to grow.

> The difficulty in associating the different effects with climate change, whether anthropogenic or not, should not be underestimated, as in order to make such an association, long series of data are required together with phenomena in which it is possible to differentiate human action from that of climate, which is extraordinarily difficult given the extent and magnitude of our influence on the planet.

Which impacts of climate change can be attributed to anthropogenic causes?

Climate change increases the risks that both natural systems and human goods or services are exposed to, and that includes human lives themselves. Risks emerge as a consequence of climate hazards and variability, as well as climate change, but not only these. Exposure and vulnerability are determining factors of risk and these are highly dependent on social systems and governance. Therefore, we must bear in mind that the transformation of risks into negative effects is not only due to what we do not control (the climate), but also to what our societies create through the way we live and organise ourselves[25]. The effects of climate change have been observed around the whole world in the different sectors and systems that have been analysed. The IPCC Fifth Assessment Report[26] concluded that, throughout the world, both on land and in the sea, on all the continents and in all the oceans, and for different natural or socio-ecological systems, effects could be detected that, with a greater or lesser degree of

Figure 13 ▪ Relative fertility of the wheat sprout as a function of the maximum temperature in the five-day period prior to anthesis.



Thirty-five grains per sprout was considered as maximum fertility (=1). Note that sprout fertility greatly decreases as ~32ºC is exceeded.

Source: Moriondo, M., C. Giannakopoulos, and M. Bindi, *Climate change impact assessment: the role of climate extremes in crop yield simulation.* Climatic Change, 2011. 104(3): p. 679-701.

24 Diffenbaugh, N.S., et al., *Quantifying the influence of global warming on unprecedented extreme climate events.* Proceedings of the National Academy of Sciences, 2017. 114(19): p. 4881-4886.

25 Moreno, J.M., et al., *Marco conceptual y contexto regional, in Adaptación frente a los riesgos del cambio climático en los países iberoamericanos – Informe RIOCCADAPT*, J.M. Moreno, et al., Editors. 2020, McGraw-Hill: Madrid, España. p. 1-47.

26 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* 2014: IPCC, Geneva, Switzerland.

uncertainty, are associated with the observed climate change.

The difficulty in finding studies that make an attribution in the manner discussed above, meant that it was not possible to differentiate between the overall observed climate change and anthropogenic climate change. Even so, we can say that the effects of the observed climate change are already widespread, although we cannot accurately attribute them to human activity. We should recall that the data used in that report were based on a global temperature rise that was almost 0.4ºC lower than the increase we are currently experiencing. The difficulty in associating the different effects with climate change, whether anthropogenic or not, should not be underestimated, as in order to make such an association, long series of data are required together with phenomena in which it is possible to differentiate human action from that of climate, which is extraordinarily difficult given the extent and magnitude of our influence on the planet. Furthermore, few observations of the natural world have a history like that of meteorological ones, which have been recorded regularly for decades.

What impact does climate change have on different systems and sectors?

Water

The reduction in precipitation that is occurring in the subtropical regions of the planet, such as areas with a Mediterranean climate, manifests itself in Spain through a reduction in river flow rates. Analysis of 74 unaltered headwaters of different rivers throughout Spain over the last four decades of the 20th century shows that 98% of them experienced a diminished flow rate, with an average change of -1.45% per year, which is equivalent to a total reduction of 153 hm^3 in annual flow[27]. This decrease is greatest in spring and summer. The fact that significant negative trends have been identified in the headwaters of Mediterranean rivers, which are characterised by their considerable irregularity, demonstrates just how powerful the signs of climate change are in Spain.

Food production

Livestock farming has suffered direct effects of the increase in temperature, particularly during heatwaves. This has reduced the productivity of farm animals, although not all species are equally sensitive. The effects are also indirect, due to a decrease in the quantity or quality of fodder and foraging in the areas that have suffered the greatest reductions in precipitation or increase in drough[28].
With regard to aquaculture, rising mean seawater temperatures, marine heatwaves, eutrophication, hypoxia, harmful algal blooms, acidification and an increase in diseases are all factors that have contributed to a decline in productivity in a sector that has become increasingly important for food production[29]. The production of crops watered exclusively by rain is becoming threatened, with a decreasing trend due to the decrease and variability of rainfall. Between 1989 and 2009, the observed climate change has reduced the yields of wheat, corn, barley and beets in Spain[30]. High temperatures, and in particular heatwaves, have played a particularly important role, especially when they occur in the period of grain formation, which can have a major impact on the final crop production[31].

Continental aquatic and terrestrial ecosystems

The increase in temperature, a lack of precipitation and changes in the seasonality of rainfall are

27 Martínez-Fernández, J., N. Sanchez, and C.M. Herrero-Jimenez, *Recent trends in rivers with near-natural flow regime: The case of the river headwaters in Spain.* Progress in Physical Geography, 2013. 37(5): p. 685-700.

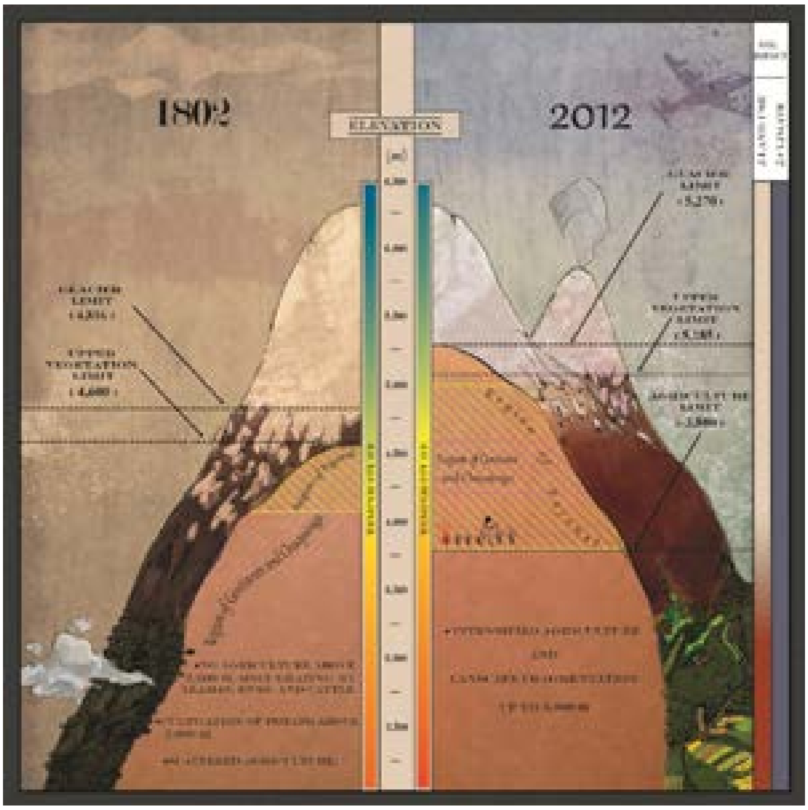
28 Rivera-Ferre, M.G., et al., *Re-framing the climate change debate in the livestock sector: mitigation and adaptation options*. WIREs Climate Change, 2016. 7(6): p. 869-892.

29 Rosa, R., A. Marques, and M.L. Nunes, *Impact of climate change in Mediterranean aquaculture*. Reviews in Aquaculture, 2012. 4(3): p. 163-177.

30 Moore, F.C. and D.B. Lobell, *The fingerprint of climate trends on European crop yields.* Proceedings of the National Academy of Sciences, 2015. 112(9): p. 2670-2675.

31 Moriondo, M., C. Giannakopoulos, and M. Bindi, *Climate change impact assessment: the role of climate extremes in crop yield simulation.* Climatic Change, 2011. 104(3): p. 679-701.

Figure 14 ▪ An update of Humboldt's Tableau



Showing a summary of the main changes at the general limit of vegetation, the average limit of glaciers and the upper vegetation on Chimborazo from 1802 to 2012. The climate and changes in land use, the main drivers of change, are represented by the bars on the right and show a constant effect of climate change on altitude, in particular an increase in temperature, a greater relative impact of land use at lower areas—mainly through the intensification of agriculture—and the effect of grass harvesting and local burning on intermediate areas, which are much higher up than the areas that were formerly cultivated. The representation of the glaciers is approximate.

Source: Morueta-Holme, N., et al., *Strong upslope shifts in Chimborazo's vegetation over two centuries since Humboldt*. Proceedings of the National Academy of Sciences, 2015.

producing alterations in terrestrial ecosystems, both at the level of primary producers and throughout the rest of the trophic web. Drought is particularly harmful, with losses of productivity having been detected in forests, particularly in Mediterranean areas, as well as increases in defoliation due to the increased emergence of insects and fungi, together with other alterations of the food network[32].

Differences in the levels of sensitivity to warming of plants and their dependent herbivores produce advances in foliation and flowering, as well as delays in leaf-fall, which lead to a lack of synchrony between herbivores and the plants that support them, which are coupled to the cycles of predators. This produces alterations in populations of plants and animals. The loss of established climate niches is causing many species to become threatened where they had previously been well adapted. Species that are at home in cooler environments are moving to higher ground or to more polar latitudes[33]. One of the best examples of the changes in vegetation and ice cover that result from climate change and alterations in land use, can be found in the comparison of the altitudinal pattern of the distribution of vegetation, cultivated areas and glaciers recorded by Alexander von Humboldt and Aimé Bonpland during their ascent of Chimborazo, Ecuador, in 1802, with the situation two centuries later. The precision of the notes they took in 1802 allows us to discern clearly the ascent of vegetation and the retreat of glaciers, among other changes (Figure 14). The reduction of climatic niches is particularly important for species that have a reduced distribution, are not very abundant, or that inhabit "islands" (understood in a literal or ecological sense, as in the occupation of mountain

32 Renner, S.S. and C.M. Zohner, *Climate Change and Phenological Mismatch in Trophic Interactions Among Plants, Insects, and Vertebrates*. Annual Review of Ecology, Evolution, and Systematics, 2018. 49(1): p. 165-182.
Carnicer, J., et al., *Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought*. Proceedings of the National Academy of Sciences, 2011. 108(4): p. 1474-1478.

33 Chen, I.-C., et al., *Rapid range shifts of species associated with high levels of climate warming*. Science, 2011. 333(6045): p. 1024-1026.
Morueta-Holme, N., et al., *Strong upslope shifts in Chimborazo's vegetation over two centuries since Humboldt*. Proceedings of the National Academy of Sciences, 2015. 112(41): p. 12741-12745.

peaks, soils with particular characteristics, or other isolated niches), in which case there simply are no other available areas to colonise. Invasions of alien species are increasing due to the extended niches of these species[34]. Aquatic ecosystems are experiencing increases in temperature which, combined with other stress factors due –for example– to eutrophication or a decrease in water flows, are altering the composition of aquatic communities[35].

Marine ecosystems and costal zones
Marine organisms face changes in their physiology as a consequence of temperature increase. This leads them to seek out environments that are more conducive to their survival. Generalised movements of marine biota have been observed, both in phytoplankton and in zooplankton, as well as in the species that prey on them, in a direction towards the poles or to greater depth, in search of colder waters. Marine productivity is declining as a consequence of the increase in temperature, and decreases in both pH and the concentration of dissolved oxygen. Zones that suffer from marine hypoxia are increasing[36]. The rise in mean sea level endangers the configuration of coastlines, as well as the structure and function of coastal ecosystems that play a fundamental role in dissipating wave energy or in climate mitigation[37]. This endangers some coastal infrastructures and one of the resources that underpins the current tourism industry.

Human health
Human health is directly threatened by rising temperatures, and in particular by heatwaves[38]. Mortality resulting from these causes increases each year, with this being one of the extreme climatic events that have been attributed to climate change

Differences in the levels of sensitivity to warming of plants and their dependent herbivores produce advances in foliation and flowering, as well as delays in leaf-fall, which lead to a lack of synchrony between herbivores and the plants that support them, which are coupled to the cycles of predators.

in the greatest number of cases. The effect of high temperatures depends closely on the relative humidity of the air: the higher the latter is, the less efficiently the human body can cool itself. Humans have a wet-bulb temperature tolerance limit of 35ºC. In some areas of the planet, if we measure the temperature in this way, it has more than doubled over the last four decades; meaning that with climate change, large areas of the planet may become uninhabitable[39].

Another effect that is indirectly related to temperature is mortality in cities due to air pollution. Fine particles with a width of 2.5 micrometres or less (PM2.5), which are formed by the internal combustion engines of motor vehicles, or tropospheric ozone, which is formed by the interaction of combustion gases with solar radiation, are of particular concern here. An estimated 3.3 million people worldwide die prematurely each year due to air pollution, and that figure is projected to double by halfway through this century[40], This is surely a powerful reason to take action to mitigate climate change. At present the most common way to escape the heat is by using air conditioning, which reinforces the greenhouse effect and aggravates global warming: a clear example of maladaptation.

34 Seebens, H., et al., *Global rise in emerging alien species results from increased accessibility of new source pools.* Proceedings of the National Academy of Sciences, 2018. 115(10): p. E2264-E2273.

35 Erol, A. and T.O. Randhir, *Climatic change impacts on the ecohydrology of Mediterranean watersheds*. Climatic Change, 2012. 114(2): p. 319-341.

36 Bindoff, N.L., et al., *Changing Ocean, Marine Ecosystems, and Dependent Communities, in IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, H.-O. Pörtner, et al., Editors. 2019, Cambridge University Press, Cambridge, U.K. p. 448-547.

37 Duarte, C.M., et al., *The role of coastal plant communities for climate change mitigation and adaptation.* Nature Climate Change, 2013. 3(11): p. 961-968.

38 Mora, C., et al., *Global risk of deadly heat.* Nature Climate Change, 2017. 7(7): p. 501-506.

39 Raymond, C., T. Matthews, and R.M. Horton, *The emergence of heat and humidity too severe for human tolerance.* Science Advances, 2020. 6(19): p. eaaw1838.

40 Lelieveld, J., et al., *The contribution of outdoor air pollution sources to premature mortality on a global scale*. Nature, 2015. 525(7569): p. 367-371.

The third most important element of the impact of climate change on human health is the increase in vector-borne diseases. The expansion of the vectors to areas that they did not previously inhabit, due to an unfavourable climate for their biology, is causing the diseases they transmit to become endemic in areas where they were previously virtually unknown[41]. This is particularly harmful in countries with poor healthcare systems, which already experience difficulties in coping with the everyday situation[42]. Pandemics such as Covid-19 are additional elements of stress which can make us forget about other health problems, and thereby aggravate them.

Society

The distribution of wealth is unequal between countries and within each country, which means that in every country there exist groups of people who are marginalised. These groups are larger in the underprivileged countries whose economies are still developing and less numerous in the more advanced and egalitarian countries. We must therefore be aware that in every county there are large groups of people who are not in a position to resolve the adversities that affect them. We are currently faced with a situation in which the Covid-19 pandemic makes this all too clear to us. The long queues of people at food banks whose only objective is to access the most basic requirements of life is a reflection of the inequality that exists in our societies, even in those we believe to be among the most egalitarian. This is a clear indication that when faced with extreme climatic events that affect livelihoods or are responsible for new disasters, such vulnerable groups of people will be exposed to deprivation[43]. There has been speculation regarding the role played by the drought that affected much of Syria in 2009 in the conflict that has continued to plague that country; and that drought was partly caused by climate change[44]. The food shortages meant that many farmers migrated to the cities in search of a future which was simply non-existent for them, and this only accentuated social unrest. Although such a view has been questioned[45], it is clear that migration is often the last option left open to people when they cannot feed themselves and their future existence is in danger. Migration knows no borders. We have seen how the European Union was overwhelmed by the mass arrival of people fleeing hunger, war and a lack of future prospects. I cannot help but think that we need to take account of these direct or indirect warnings of climate change and begin to mitigate all its effects in order to avoid the worst consequences it may have.

Covid-19 has shown us the Herculean task that lies ahead, with GHG estimations that will have fallen by 4% in 2020 if normal activity is resumed by June 2020 or by 7% if that does not happen until the end of the year[46]. In order to maintain global warming within the limits set out by the Paris Agreement, by the middle of the 21st century we will have to have reduced emissions annually by only slightly less than envisaged in the worst-case Covid-19 scenario. That is certainly a challenge. Without a doubt nobody can say that science has not warned of the climate emergency[47], to the shame of those who could enact what must be done but fail to do so, knowing that by acting they would prevent enormous harm and benefit the whole of humanity. There is not even time to talk of those who deny the climate emergency to justify inaction; they are simply amoral.

41 Semenza, J.C. and J.E. Suk, *Vector-borne diseases and climate change: a European perspective*. FEMS Microbiology Letters, 2017. 365(2).

42 Moreno, A.R., et al., *Salud humana, in Adaptación frente a los riesgos del cambio climático en los países iberoamericanos – Informe RIOCCADAP*, J.M. Moreno, et al., Editors. 2020, McGraw-Hill: Madrid, Spain. p. 651-697.

43 Olsson, L., et al., *Livelihoods and poverty, in 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* C.V. Field, et al., Editors. 2014, Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA. p. 793-832.

44 Kelley, C.P., et al., *Climate change in the Fertile Crescent and implications of the recent Syrian drought.* Proceedings of the National Academy of Sciences, 2015. 112(11): p. 3241-3246.

45 Selby, J., et al., *Climate change and the Syrian civil war revisited.* Political Geography, 2017. 60: p. 232-244.

46 Le Quéré, C., et al., *Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement*. Nature Climate Change, 2020.

47 Hoegh-Guldberg, O., et al., *The human imperative of stabilizing global climate change at 1.5°C*. Science, 2019. 365(6459): p. eaaw6974.

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2.2 What is the anthropogenic contribution to climate change and to transgressing other planetary boundaries?

- How does climate change fit into the larger context of the Earth system?
- What is the anthropogenic contribution to climate change?
- What are the causes of other transgressions of planetary boundaries?
- How should complexity be integrated into the study of the climate system?

How does climate change fit into the larger context of the Earth system?

The present Anthropocene epoch is characterized by increasing and multiple anthropogenic pressures on the Earth system[48]. Arguably, climate change may turn out to be the gravest of these pressures, as it basically affects the entire globe in multi-faceted ways, over long time scales and potentially irreversibly. At the same time, however, other human drivers such as widespread land use change, excessive freshwater use and contamination with chemicals all produce their own impacts, closely intermingled with those of climate change. For instance, three quarters of Earth's surface area are now altered by human activities, and up to a third of land's potential net primary production is being appropriated for food, feed, fibre, timber and energy. As a consequence, aquatic, terrestrial and marine ecosystems and biodiversity are rapidly degrading[49]. These realities pose the question, how resilient is the Earth system – and the human civilization that inhabits it – to these massive changes and shocks?

Adopting this perspective of our planet's long-term resilience, the scientific framework of "planetary boundaries" unites the most important Earth system processes – of which climate change is but one – and the criticality of their modifications in a single multidimensional approach[50]. Its central premise is that nine key environmental processes together regulate the functioning and stability of the Earth system: namely stratospheric ozone depletion; loss of biosphere integrity (biodiversity loss and extinctions); chemical pollution and release of novel entities; climate change; ocean acidification; freshwater consumption and the global hydrological cycle; land-system change; nutrient (nitrogen and phosphorus) flows to biosphere and oceans; and atmospheric aerosol loading. For all of these processes, the framework suggests estimates for where to position planetary boundaries (and underlying subglobal boundaries) that would guarantee a sufficient distance to critical gradual or

48 Steffen, W., Broadgate, W., Deutsch, L. et al. 2015a. The trajectory of the Anthropocene: the great acceleration. *Anthrop. Rev.* 2, 81–98.

49 IPCC 2020. *Climate Change and Land*. IPCC Secretariat.
IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) 2019. *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. IPBES Secretariat.

50 Rockström, J., Steffen, W., Noone, K. et al. 2009. A safe operating space for humanity. *Nature* 461, 472–475.
Steffen, W., Richardson, K., Rockström, J. et al. 2015b. Planetary boundaries: guiding human development on a changing planet. *Science* 347, 1259855.

abrupt developments that may occur if the boundaries are transgressed. The reference for the 'safe' Earth system state demarcated by the nine planetary boundaries is the Holocene (i.e. the past ~11,700 years after the last Ice Age). According to a precautionary principle, this state is to be basically preserved (as far as humanity can influence it) as the climatic and other biogeophysical conditions were relatively stable in the Holocene, and certainly because this period is the only known condition of the Earth system that enabled development of the human civilization with billions of people.

The planetary boundary for climate change is defined as an atmospheric CO_2 concentration level of 350 ppm (and/or a maximum change in radiative forcing of +1 W/m^2). This value represents the lower end of an uncertainty range of 350–450 ppm, following the rationale that Earth was largely ice-free until CO_2 concentration fell to 450 ppm ±100 ppm[51]. While not directly comparable, the boundary is broadly in line with the internationally agreed climate mitigation goal of limiting mean global warming to <2°C above the preindustrial level[52]. This goal in turn is grounded in a vast number of projections, which indicate that impacts will become the more widespread and severe the higher atmospheric CO_2 concentration grows and the stronger temperature and precipitation thus change (e.g.[53]). With a current atmospheric CO_2 concentration far above the preindustrial value of 280 ppm (i.e. 407 ppm averaged over year 2018[54]) and a radiative forcing of >2 W/m^2, the climate change planetary boundary is considered to be transgressed already, increasing the risk of significant and large-scale impacts. Similarly, calculations suggest that the planetary boundaries for biosphere integrity, land-system change and nutrient flows are also crossed, as are subglobal boundaries for freshwater use. But it has to be noted that most of these other boundaries are by now only provisionally defined or no global values have been identified yet.

Adopting this perspective of our planet's long-term resilience, the scientific framework of "planetary boundaries" unites the most important Earth system processes – of which climate change is but one – and the criticality of their modifications in a single multidimensional approach.

What anthropogenic contribution to climate change?

Since its emergence, planet Earth has experienced substantial and sometimes rather abrupt climatic fluctuations, controlled by both external (astronomic) and internal factors. For instance, the last three million years have seen cycles of glacials and interglacials, the Holocene being an interglacial period. Recently, however, atmospheric CO_2 concentration has reached a level that is unprecedented for the past 800,000 years and possibly even the past 23 million years[55], in synchrony with a fast and strong rise in global mean surface temperature that is now ~1°C above the preindustrial level.

Volcanic, geothermal, solar and other natural processes have been ruled out as a cause of this steep recent increase in temperature,

51 Rockström, J., Steffen, W., Noone, K. et al. 2009. A safe operating space for humanity. *Nature* 461, 472–475.

52 Mathias, J.-D., Anderies, J.M., Janssen, M.A. 2017. On our rapidly shrinking capacity to comply with the planetary boundaries on climate change. *Sci. Rep.* 7, 42061.

53 Rückamp, M., Falk, U., Frieler, K. et al. 2018. The effect of overshooting 1.5 °C global warming on the mass loss of the Greenland ice sheet. *Earth Syst. Dynam*. 9, 1169–1189.
IPCC (Intergovernmental Panel on Climate Change) 2019. *Global Warming of 1.5°C. An IPCC Special Report*. IPCC Secretariat.

54 Friedlingstein, P., Jones, M.W., O'Sullivan, M. et al. 2019. Global Carbon Budget 2019. *Earth Syst. Sci.* Data 11, 1783–1838.

55 Cui, Y., Schubert, B.A., Jahren, A.H. 2020. A 23 m.y. record of low atmospheric CO_2. *Geology* 48, 888–892.

as their contributions are marginal if not opposite (i.e. rather producing a slight cooling[56]). Hence, anthropogenic emissions of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs) are the single most important factor determining the contemporary global warming. The underlying reason is that these gases (like water vapour and ozone) absorb energy within specific wavelengths and radiate it back to the Earth surface. Their massive accumulation in the atmosphere thus produces a disequilibrium of the planet's energy balance between incoming solar radiation and the heat released back into space, which eventually leads to the warming. The gases have different global warming potentials, i.e. the heat they absorb is multiple times higher than that absorbed by the same mass of CO_2 (e.g. the warming potential over a 100-yr timescale is 28–36 for CH_4, 265–298 for N_2O, and even higher for CFCs). To standardise these differences, weights or concentrations of greenhouse gases are usually expressed in carbon dioxide equivalents (CO_{2eq}).

Anthropogenic CO_2 emissions to the atmosphere from fossil fuel combustion, as well as oxidation from all energy and industrial processes and cement production, are noticeably increasing since around 1850 and became dominant from around 1950; since, they further increased up to a current (2009–2018) value of 9.5 (±0.5 standard deviation) GtC/yr (Friedlingstein et al. 2019). During this past decade, the emissions have grown by 1.3%/yr, with China and also India dominating the global trend and e.g. member states of the EU demonstrating a certain decrease. An additional 1.5±0.7 GtC/yr stem from deliberate human activities on land including deforestation and other land cover and land use change (without a clear global trend). After accounting for the natural carbon sinks (see below), this has led to a growth rate in atmospheric concentration of 4.9±0.02 GtC/yr (or 2.3 ppm/yr). Regarding total emission of greenhouse gases including e.g. N_2O but excluding land use change, agriculture is estimated to contribute a total ~5.0–5.8 Gt CO_{2eq}/yr (based on a 100-yr time scale) or ~11% of total anthropogenic greenhouse gas emissions. Detailed specifications of regional/national distribution of emissions from the various sectors can be found e.g. in the annually updated Global Carbon Budget or IPCC Assessment Reports[57](next reports to be released in 2021).

Anthropogenic CO_2 emissions to the atmosphere from fossil fuel combustion, as well as oxidation from all energy and industrial processes and cement production, are noticeably increasing since around 1850 and became dominant from around 1950.

According to this evidence, strongly reducing anthropogenic greenhouse gas emissions across sectors (e.g. agriculture, construction, finance, manufacturing, transport) is the prime measure to mitigate climate change, alongside CO_2 removal from the atmosphere such as by afforestation or biomass plantations. Simulations show, for example, that mean global temperature rise could still go down to zero 50 years after curtailing CO_2 emissions to zero[58]. Note that while the coronavirus crisis may unintentionally (and temporarily) produce the largest ever annual drop in CO_2 emissions in 2020, this is still likely to be somewhat below the emissions cuts needed annually this decade in order to limit global warming to <1.5 K[59]).

56 Lockwood, M., Fröhlich, C. 2007. Recent oppositely directed trends in solar climate forcings and the global mean surface air temperature. *Proc. R. Soc.* A 463, 2447–2460.

57 Blanco, G., Gerlagh, R., Suh, S. et al. 2014. Drivers, Trends and Mitigation. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 351–411. Cambridge University Press.

58 MacDougall, A.H., Frölicher, T.L., Jones, C.D. et al. 2020. Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2. *Biogeosci.* 17, 2987–3016.

59 Le Quéré, C., Jackson, R.B., Jones, M.W. 2020. Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement. *Nature Clim. Change* 10, 647–653.

Also, a precondition for permanent decarbonisation to be effective is that Earth remains resilient against nonlinear feedbacks (see below), and that the natural cycling of carbon between atmosphere, ocean and land as well as the large net natural carbon 'sinks' are preserved – the terrestrial biosphere and the oceans presently provide an estimated 3.2±0.6 GtC/yr and 2.5±0.6 GtC/yr sink, respectively, which means they capture about half of the annual CO_2 emissions[60]. This reaffirms that the climate system needs to be considered in the context of whole Earth system dynamics and planetary boundaries.

What are the causes of other transgressions of planetary boundaries?

A number of studies have improved the (spatially detailed) quantification of planetary boundaries and their current status[61]. But, individual contributions of different drivers of boundary transgressions have not yet been elucidated as systematically and comprehensively as for climate change, at least not strictly following current boundary definitions. Regarding stratospheric ozone depletion, the prime factor is the release of ozone-depleting substances (CFCs), such that their ban according to the Montreal Protocol has reverted the boundary transgression via a strong reduction in the size of the Antarctic "ozone hole". Similar to climate change, ocean acidification is strongly responsive to atmospheric CO_2, absorption of which eventually causes acidification, anoxia and marine biological impacts. For aerosol loading and novel entities, planetary boundary values even have not been quantified, such that an attribution of causes of their potential (regional or global) crossing is not yet possible.

As for the transgression of terrestrial planetary boundaries, agriculture – and especially industrial and resource-intensive agriculture in its various forms – is the by far most relevant cause, as it is the main driver of land cover and land use change, of nitrogen and phosphorus release into soils and waterbodies, and of biodiversity loss.

As for the transgression of terrestrial planetary boundaries, agriculture – and especially industrial and resource-intensive agriculture in its various forms – is the by far most relevant cause, as it is the main driver of land cover and land use change, of nitrogen and phosphorus release into soils and waterbodies, and of biodiversity loss. One study[62] (Figure 15) has compiled evidence from many and diverse sources, which cannot be straightforwardly compared but still allow a first guess of world agriculture's contribution to the current status of planetary boundaries. They find this share to be as high as 80% regarding the boundary for land-system change (due to deforestation); tentatively 80% regarding biosphere integrity (loss of genetic and functional biodiversity in terrestrial ecosystems); 84% regarding freshwater consumption; and ~85% and >90% regarding the boundary for nitrogen and phosphorus flows, respectively. The comparably minor contributions of factors other than agriculture have not yet been calculated but could be derived from analogous estimates. For example, the remaining 16% of freshwater consumption are from the industrial and household sectors, yet with distinct regional patterns[63]. Regarding

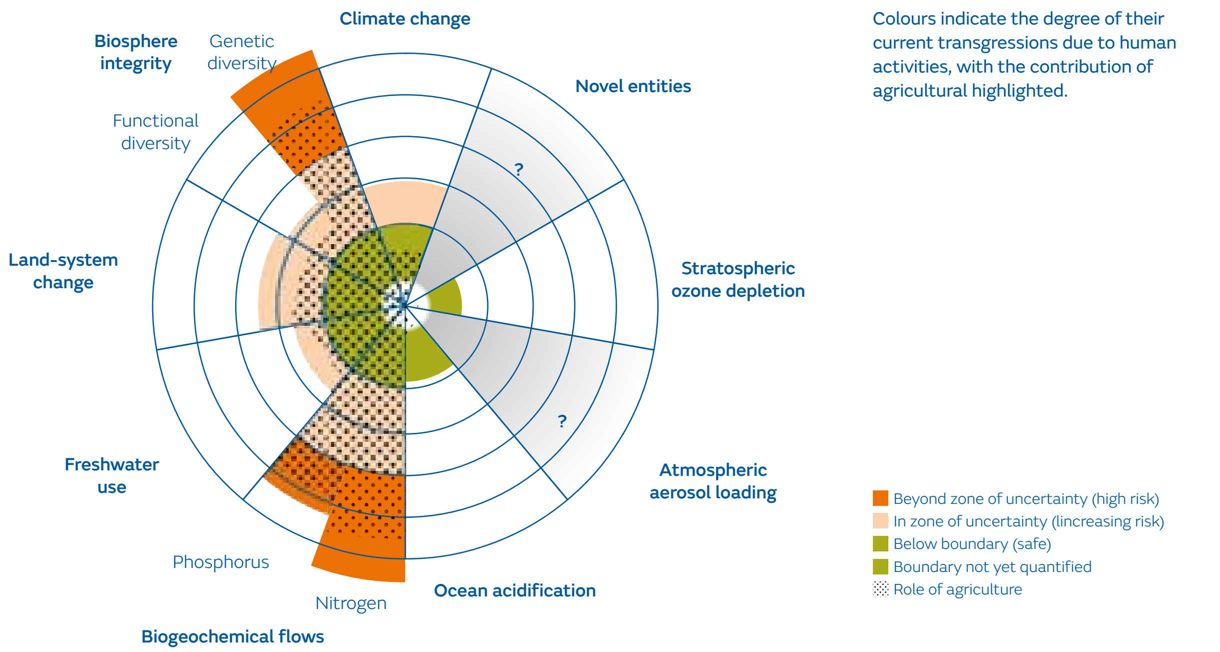
60 Friedlingstein, P., Jones, M.W., O'Sullivan, M. et al. 2019. Global Carbon Budget 2019. *Earth Syst. Sci. Data* 11, 1783–1838.

61 Véase Steffen et al., 2015b, y revisiones posteriores, por ejemplo, Gleeson et al., 2020 para agua dulce.
Steffen, W., Richardson, K., Rockström, J. et al. 2015b. Planetary boundaries: guiding human development on a changing planet. *Science* 347, 1259855.
Gleeson T., Wang-Erlandsson, L., Zipper, S.C., et al. 2020. The Water Planetary Boundary: Interrogation and Revision. One Earth 2, 223-234.

62 Campbell, B.M., Beare, D.J., Bennett, E.M. et al. 2017. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecol. Soc.* 22(4), 8.

63 Wada, Y., de Graaf, I.E.M., van Beek, L.P.H. 2016. High-resolution modeling of human and climate impacts on global water resources. *J. Adv. Mod. Earth Syst*. 8, 735–763.

Figure 15 ▪ Nine key environmental processes together regulate the functioning and stability of the earth system.



Source: From Campbell et al. (2017) modified after Steffen et al. (2015b). Campbell, B.M., Beare, D.J., Bennett, E.M. et al. 2017. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecol. Soc.* 22(4), 8. Steffen, W., Richardson, K., Rockström, J. et al. 2015b. Planetary boundaries: guiding human development on a changing planet. *Science* 347, 1259855.

the status of the climate change boundary, agriculture (including greenhouse gas emissions from land use change) contributes 'only' about 25%.

Other experts[64] took a complementary approach with a spatially detailed model assessment, asking the question how strongly current (year 2005) agriculture depends on planetary boundary violations. They found that 19% of food production would be lost if the boundaries for biosphere integrity and land-system change were respected in every biome; in other words, this share of the production depends on transgressions of either of these two boundaries in regions where forest and biodiversity actually should be protected. Restricting irrigation in areas where water withdrawals are higher than allowed by the subglobal freshwater boundary is equivalent to a further reduction by 4%, and restricting application of nitrogen fertiliser in regions where it is currently above the (local) boundary would impose another 25% reduction. In sum, thus, almost half of food production occurs at the cost of transgressing one or more of these four planetary boundaries (climate change was not analysed). Different regions are affected differently though: excess nitrogen use prevails in parts of Europe, the US and China; the tropics are hotspots of loss of biosphere integrity and land-system change; and especially the subtropics experience overuse of freshwater resources. In a number of regions, even two or more boundaries are exceeded simultaneously. Radical transformations towards more sustainable food production and consumption patterns – redistributing production areas, improving water and nutrient use efficiency, avoiding food losses, shifting diet composition toward less animal-based products – would be required to maintain all planetary boundaries while still enabling food supply for about ten billion[65].

64 Gerten, D., Heck, V., Jägermeyr, J. et al. 2020. Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nature Sust.* 3, 200–208.

65 Springmann, M., Clark, M., Mason-D'Croz, D. et al. 2018. Options for keeping the food system within environmental limits. *Nature* 562, 519–525.

How should complexity be integrated into the study of the climate system?

This chapter argues that causes and consequences of global climate change must not be viewed in isolation. The climate system is tightly interlinked with the (terrestrial) biosphere, the water cycle, the oceans, and the ice masses through numerous processes and feedbacks that may further amplify climate change, as depicted in the planetary boundaries framework. For example, warming-induced thawing of permafrost soils and associated higher microbial activity will probably lead to release of huge amounts of CO_2 and CH_4 in the boreal zone; decreases in precipitation and soil moisture, especially droughts, may weaken the natural CO_2 sink capacity of plants; and climate change-induced forest dieback in boreal and tropical regions together with the permafrost thawing may even turn the global terrestrial biosphere into a carbon source (e.g.[66]).

Such regime shifts and highly nonlinear tipping points – which may in the worst case escalate into domino and runaway effects[67]– will become the likelier the stronger the climate change boundary are transgressed[68]. But transgressions of other planetary boundaries, particularly via deforestation for food and feed production, augment the risk of such developments. Recent mega-fires in the Amazon, Australia, California and Siberia indicate a complex interplay of causes and effects of climate change on the one hand (preparing the ground for long-lasting and intense droughts and heatwaves triggering the fires, coupled to vegetation dynamics and also to anomalous ocean circulation patterns or decreasing sea ice coverage) and of more direct human interventions on the other hand (especially deforestation with associated loss of regulatory ecosystem functions and species)[69]. The vicious circle is further complicated by the fact that the carbon releases from the fires and the decrease in carbon uptake due to burnt vegetation amplify regional and global climate change.

> Radical transformations towards more sustainable food production and consumption patterns – redistributing production areas, improving water and nutrient use efficiency, avoiding food losses, shifting diet composition toward less animal-based products – would be required to maintain all planetary boundaries while still enabling food supply for about ten billion people.

The processes, their time scales and feedbacks involved in these complex and nonlinear dynamics are incompletely understood, as are interactions among planetary boundaries more generally[70]. More comprehensive and consistent studies are still a research desideratum, including systematic assessments of how transgressions of one boundary (such as different global warming

Gerten, D., Heck, V., Jägermeyr, J. et al. 2020. Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nature Sust.* 3, 200–208.

66 Schaphoff, S., Heyder, U., Ostberg, S. et al. 2013. Contribution of permafrost soils to the global carbon budget. Environ. Res. Lett. 8, 014026.
Peters, W., van der Velde, I.R., van Schaik, E. et al. 2018. Increased water-use efficiency and reduced CO_2 uptake by plants during droughts at a continental scale. *Nature Geosci.* 11, 744–748.

67 Steffen, W., Rockström, J., Richardson, K. et al. 2018. Trajectories of the Earth System in the Anthropocene. *Proc. Natl. Acad. Sci.* USA 115, 8252–8259.
Lenton, T. M., Rockström, J., Gaffney, O. et al. 2019. Climate tipping points – too risky to bet against. *Nature* 575, 592–595.

68 Schellnhuber, H. J., Rahmstorf, S., Winkelmann, R. 2016. Why the right climate target was agreed in Paris. *Nature Clim. Change* 6, 649–653.

69 Brando, P., Macedo, M., Silvério, D. et al. 2020. Amazon wildfires: scenes from a foreseeable disaster. *Flora* 268, 151609.
Nolan, R.H., Boer, M.M., Collins, L. et al. 2020. Causes and consequences of eastern Australia's 2019–20 season of mega-fires. *Global Change Biol.* 26, 1039–1041.
Zhang, W., Döscher, R., Koenigk, T. et al. 2020. The interplay of recent vegetation and sea ice dynamics – results from a regional Earth system model over the Arctic. *Geophys. Res. Lett.* 47, e2019GL085982.

70 Lade, S., Steffen, W., de Vries, W. et al. 2020. Human impacts on planetary boundaries amplified by Earth system interactions. *Nature Sust.* 3 119–128.

levels) affect the status of respective other boundaries. It is also important to examine how measures to avoid boundary transgressions come into conflict with each other – for example, biomass plantations dedicated to CO_2 removal may limit availability of freshwater and land for other purposes[71], and measures to protect the stratospheric ozone layer and to reduce air pollution may have delayed action to mitigate climate change[72]. Scenarios are needed to explore such tradeoffs, but also synergies and pathways for humanity to safely manoeuver within the multiple planetary boundaries. The need for a holistic understanding of Earth system dynamics is clear: Since collective human activities are the main cause of current climate change and other planetary boundary transgressions, warding off a dangerous destabilization of this unique planet is our civilization's responsibility.

> The need for a holistic understanding of Earth system dynamics is clear: Since collective human activities are the main cause of current climate change and other planetary boundary transgressions, warding off a dangerous destabilization of the common planet is our civilization's responsibility.

71 Heck, V., Gerten, D., Lucht, W., Popp, A. 2018. Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Clim. Change* 8, 151–155.

72 Kaniaru, D., Shende, R., Stone, S. et al. 2007. Strengthening the Montreal Protocol: insurance against abrupt climate change. *Sust. Dev. Law Pol.* 3–9, 74–76.
Ramanathan, V., Feng, Y. 2008. On avoiding dangerous anthropogenic interference with the climate system: formidable challenges ahead. *Proc. Natl. Acad.* Sci. USA 105, 14245–14250.

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2.3 What are the major uncertainties in measuring and predicting?

- How do we know that the climate is changing?
- What methods are used to measure the change?
- What type of climate models are applied?
- How is the reliability of a climate model calibrated?
- How can uncertainty be managed?
- What are the principal recommendations?

How do we know that the climate is changing?

We can estimate trends from a variety of monitoring programs and studies published in peer-reviewed literature reporting long-term series of relevant indicators about the Earth System, including atmospheric composition, temperature, ice sheets extent, etc. With that information we can estimate mean values (with their corresponding confidence interval) and anomalies from reference periods, usually over 30 years. Considering the multiple interactions and phenomena involved, it is not possible to confirm climate change from a single indicator. However, all the analysis based on independent datasets consistently point out that temperature is raising since 1900 as extensively mentioned in previous chapters. This is consistent with the increase of atmospheric concentration of long-wave radiation absorbing substances (greenhouse gases), the shrinkage of glaciers and snow cover and the raise of sea level.

One of the challenges of assessing climate change from the scientific point of view is

Considering the multiple interactions and phenomena involved, it is not possible to confirm climate change from a single indicator. However, all the analysis based on independent datasets consistently point out that temperature is raising since 1900.

the characteristic spatial and temporal scale these process are associated to. For instance, the largest fraction of the radiative forcing is related to well-mixed greenhouse gases[73], i.e. long-lived chemical species. Dealing with very long lifetimes species in the atmosphere implies a multi-decadal delay between e.g. emission abatements and the response of the climatic system. Climate change also depends on natural factors such as the modulation of solar cycles that have even longer characteristic time scales. As a result, we need to analyse climate change under a long-term perspective both backwards and forwards in time. Direct and remote observations of the climate system (atmosphere, hydrosphere, cryosphere, lithosphere and biosphere) are essential for climate science.

73 IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

However, global-scales observations became available in the mid-19th century only for temperature and other basic variables. Satellite data and other more comprehensive datasets based on indirect measurements began very recently. Therefore, models are the key tool to build our understanding of the complex dynamics of the climate systems. In addition, models are the only way we can look into the future to anticipate the outcomes of the decisions we make (or we fail to make) today. Nonetheless, we are looking into the unprecedented and the implications from a public health and economic[74] perspectives are huge. In this context, quantifying and communicating the degree of certainty in findings and future projections is a priority for the scientific community.

What methods are used to measure the change?

Putting together consistent and comparable long-term observational datasets is rather challenging. Observations used to study climate are collected from a variety of networks that, in most cases, were not designed for climate monitoring purposes. In addition, measuring technologies and experimental procedures have evolved over time. Therefore, raw data have to be processed before attempting long-term analyses. As a result, observations encompass two types of uncertainties:

- those associated with the raw data (related to instrument limitations, recording errors, location changes, methods update, etc.).
- and those related to processing stages (correction, interpolation, averaging, etc.).

Since these uncertainties are dataset and variable-specific, there is a lack of unified method to account for artefacts and thus to estimate uncertainties in observations. This hinders comparability and prevents from completely removing non-climatic influences in historic data[75].

In the absence of a unique valid method to account from potential error sources, there are a number of ways to build the necessary confidence; mainly the analysis of multiple independent datasets and the cross-comparison with other variables that are expected to show a similar trend for physical reasons. For instance, land-surface air temperature trends published in the latest IPCC assessment report (AR5)[76] are based on four independent datasets that collectively involve observations from nearly 60,000 meteorological stations throughout the globe. Each of them has their own QA/QC (Quality Assurance / Quality Control) procedures and temporal and spatial averaging methods. This variety of approaches allows IPCC to assess the structural uncertainty, derived from the overall analytical framework, more than the parametric uncertainty. For each dataset, decadal trends (typically linear) are computed by statistical methods such as least squares commonly used in regression analysis.

The confidence interval is computed from the variance of the sample (data deviations from the trend line). This approach does not take into account the specific (parametric) uncertainty of

74 Watts, N., Adger, W.N., Agnolucci, P., Blackstock, J., Byass, P., Cai, W., Chaytor, S., Colbourn, T., Collins, M., Cooper, A., Cox, P.M., Depledge, J., Drummond, P., Ekins, P., Galaz, V., Grace, D., Graham, H., Grubb, M., Haines, A., Hamilton, I., Hunter, A., Jiang, X., Li, M., Kelman, I., Liang, L., Lott, M., Lowe, R., Luo, Y., Mace, G., Maslin, M., Nilsson, M., Oreszczyn, T., Pye, S., Quinn, T., Svensdotter, M., Venevsky, S., Warner, K., Xu, B., Yang, J., Yin, Y., Yu, C., Zhang, Q., Gong, P., Montgomery, H., Costello, A., 2015. Health and climate change: policy responses to protect public health. Lancet 386, 1861–1914. https://doi.org/10.1016/S0140-6736(15)60854-6

Van Vuuren, D.P., van der Wijst, K., Marsman, S., van den Berg, M., Hof, A.F., Jones, C.D., 2020. The costs of achieving climate targets and the sources of uncertainty. Nat Clim Chang 10, 329–334. https://doi.org/10.1038/s41558-020-0732-1

75 Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai, 2013: Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

76 IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

each datasets but it provides a common analysis framework for the trends. In this case, as shown in detail in chapter 2.2), linear temperature increase trends (and 90% confidence intervals, in brackets) for the 1979-2012 period range from 0.254 (± 0.050) ºC/decade to 0.273 (± 0.047) ºC/decade. Considering that the analysis is based on large, high-quality datasets we can conclude that there is robust evidence of temperature raise. In addition, there is high agreement of individual trends suggesting that is virtually certain that land-surface air temperature has increased in that period.

Similarly, there is very high confidence that the concentration of GHGs targeted by the Kyoto Protocol has increased from 2005 to 2011, especially CO_2 that presented a 390.5 ppm (390.3-390.7) concentration level in 2011; 40% greater than in 1750[77]. There is also strong certainty that the global abundance of Montreal Protocol regulated gases (ozone-depleting substances) is diminishing. Regarding the cryosphere, there is high or very high confidence that the sea ice in the Artic is receding.

On the other hand, limited data availability, information gaps, geographically-biased datasets or/and geographical inconsistencies in observed trends prevent from making high confidence assessments regarding other variables. According to IPCC, among others, low confidence remains in the observations and global trends of cloud variability, drought, sub-surface ocean temperatures or thickness and volume of ice in Antarctica

What types of climate models are applied?

There are many types of mathematical models involved in the study and prediction of climate that covers applications from

> In the absence of a unique valid method to account from potential error sources, there are a number of ways to build the necessary confidence; mainly the analysis of multiple independent datasets and the cross-comparison with other variables that are expected to show a similar trend for physical reasons.

paleoclimate reconstruction to near-term local climate variability prediction. From the different modelling tools climate scientist have developed, there are three types that are of particular relevance from the decision making point of view since they are able to provide answers to policy-relevant questions such as the amount of CO_2 emissions compatible with a specified climate stabilization target[78]. All of these are deterministic models based on physical principles that represent our current understanding of the highly complex climate system. In other words, they include simplified representations of the relevant dynamic processes an interactions that ultimately define the net radiative forcing in the atmosphere and thus, the evolution of climate.

Atmosphere-Ocean General Circulation Models (AOGCM) constitute the basis of climate research. They are global models (the modelling domain is the whole planet) that resolve the tightly interdependent dynamics of the atmosphere and the ocean. Earth System Models (ESM) are an evolution of AOGCM where biogeochemical cycles (e.g. carbon, ozone or Sulphur cycles) are explicitly accounted for to provide a state-of-the-science, overarching representation of the interactions of the different elements of the climate system (the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere). They typically have a spatial resolution about

77 Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai, 2013: Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

78 Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S. Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason and M. Rummukainen, 2013: Evaluation of Climate Models. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

1°x1°, i.e. dynamics equations are solved in grid points that represent a 1°x1° horizontal area. That implies that processes with smaller characteristic spatial scale (e.g. convective cloud systems) cannot be explicitly taken into account. Instead, these model use sub-grid scale parameterizations that consist in numerical approximations to unresolved processes.

Those sub-grid scale processes are very important to assess the actual evolution of climate in a particular location since regional and local features (topography, land-use, etc.) are very influential. This is also true for other local characteristics such as air quality[79]. To delve into regional or local specific features, the third type of models, Regional Climate Models (RCMs) are used. RCM are limited-area models (unlike global AOGCM or ESM, their modeling domain has boundaries) that have a similar formulation to that of AOGCM (usually neglecting the interaction of the atmosphere with the ocean and sea ice) but higher resolution (a few kilometers compared to up to 110km for the global models). RCM are often used to dynamically downscale global simulations to reflect future climate features at the local scale[80].

Although the boundary is blurred, it is generally accepted that model uncertainty can be separated into structural or ontic and epistemic. The first reflects the intrinsic limits of predictability[81] of chaotic systems (those extremely sensitive to initial conditions, typically the climatic system) and therefore, it is irreducible. The second refers to uncertainty due to limited knowledge and thus, potentially reducible by means of better science or data. There are different methodologies to attribute sources of uncertainty and to assess the overall reliability of numeric models and, from there, provide a magnitude of the uncertainty. All of them have important limitations, and complex models such us these cannot be validated in the formal sense, but rather can be shown to have predictive and diagnostic value[82].

From the different modelling tools climate scientist have developed, there are three types that are of particular relevance from the decision making point of view since they are able to provide answers to policy-relevant questions such as the amount of CO_2 emissions compatible with a specified climate stabilization target.

How is the reliability of a climate model calibrated?

The comparison of previous model projections with recent observations (CO_2 concentration, temperature anomalies, global mean sea rise, etc.) is arguably the best way to gauge model reliability. Models are not only assessed regarding average values or mean state, but also trends, variability and extreme values. In that sense, climate models used by IPCC have demonstrated to perform increasingly well over time[83]. Comparisons with observations in the 1980-2005 period yielded deviations in the

79 Fiore, A.M., Naik, V., Spracklen, D. V, Steiner, A., Unger, N., Prather, M., Bergmann, D., Cameron-smith, P.J., Cionni, I., Collins, W.J., Dalsren, S., Eyring, V., Folberth, G.A., Ginoux, P., Horowitz, L.W., Josse, B., Lamarque, J., Mackenzie, I.A., Nagashima, T., O'connor, F.M., Righi, M., Rumbold, S.T., Shindell, D.T., Skeie, R.B., Sudo, K., Szopa, S., Takemura, T., Zeng, G., 2012. Global air quality and climate. Chem. Soc. Rev. 41, 6663–6683. https://doi.org/10.1039/C2CS35095E

80 Jacob, D.J., Winner, D.A., 2009. Effect of climate change on air quality. Atmos. Environ. 43, 51–63. https://doi.org/https://doi.org/10.1016/j.atmosenv.2008.09.051

81 Held, I., 2014. Simplicity amid Complexity. Science (80) 343, 1206–1207. https://doi.org/10.1126/science.1248447

82 Dennis, R., Fox, T., Fuentes, M., Gilliland, A., Hanna, S., Hogrefe, C., Irwin, J., Rao, T., Scheffe, K., Schere, K., Steyn, D., Venkatram, A., 2010. A framework for evaluating regional-scale numerical photochemical modeling systems. Environ Fluid Mech 10, 471–489. https://doi.org/10.1007/s10652-009-9163-2

83 Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S. Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason and M. Rummukainen, 2013: Evaluation of Climate Models. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

range of ± 2ºC for the annual-mean surface air temperature in most regions while absolute errors of annual-mean precipitation rate were below 3.5 mm/day. Pattern correlations around 0.99 and 0.80 for temperature and precipitation respectively have been reported. Current global climate models have been found able to reproduce more complex phenomena, such as Arctic sea ice extent with an error below 10% all over the year.

Individual model performance assessment based on the departure between predictions and observations can inform about the skills to reproduce magnitudes of interest. However, models can provide right answers due to error compensation or other spurious reasons. In addition, past conditions may not be representative of those in the future, limiting the predictive power of the model[84].

In order to provide a systematic and informative overview of model uncertainty, IPCC assessment reports have relied on the World Climate Research Programme (WCRP) Working Group on Coupled Modelling (WGCM). They have organized a number of Coupled Model Intercomparison Project (CMIP) exercises, from CMIP3 (in support of the AR4) to the ongoing CMIP6[85]. The latest IPCC assessment report (AR5) relies on the results of CMIP5 where nearly 40 different ESM participated. More than focusing on the assessment of individual models, these intercomparison exercises provide an ensemble of climate model projections that is particularly relevant policy-wise. Instead of trying to simulate all the possible scenarios, models are set up to reproduce reference patterns or predefined scenarios (e.g. Representative Concentration Pathways[86]) of practical interest. While all climate models are based on the same physical principles, differences on parametrizations, model resolution and other implementation options lead, in some cases, to a significant spread of outcomes [87]. The ensemble average and deviation allows to derive a collective confidence interval from all simulations. This means that although models are deterministic, uncertainty assessment is of stochastic nature. Of note, this widespread ensemble approach includes the Multi-Model ensemble, where outcomes from different models are pooled together or Perturbed-Parameter Ensembles, where the same model is run several times with different input parameters. This allows to identify model sensitivity and contributes to quantify epistemic uncertainty, therefore informing about future research lines to improve model performance. The analyses of IPCC and other studies consistently point out that, despite recent model improvements, e.g. interactive representation of aerosol species and explicit consideration of anthropogenic Sulphur emissions, the uncertainties regarding aerosol-cloud interactions and the associated radiative forcing remain large[88].

84 Strobach, E., Bel, G., 2020. Learning algorithms allow for improved reliability and accuracy of global mean surface temperature projections. Nat Commun 11, 451. https://doi.org/10.1038/s41467-020-14342-9

85 Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J., Taylor, K.E., 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev. 9, 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

86 van Vuuren, D. P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C., Hurtt, T. Kram, V. Krey, J. F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S.J. Smith, Rose, S.K., 2011. The Representative Concentration Pathways: an overview. Climatic Change, 109, 5–31. https://doi.org/10.1007/s10584-011-0148-z

87 Strobach, E., Bel, G., 2020. Learning algorithms allow for improved reliability and accuracy of global mean surface temperature projections. Nat Commun 11, 451. https://doi.org/10.1038/s41467-020-14342-9

88 Fiore, A.M., Naik, V., Spracklen, D. V, Steiner, A., Unger, N., Prather, M., Bergmann, D., Cameron-smith, P.J., Cionni, I., Collins, W.J., Dalsren, S., Eyring, V., Folberth, G.A., Ginoux, P., Horowitz, L.W., Josse, B., Lamarque, J., Mackenzie, I.A., Nagashima, T., O'connor, F.M., Righi, M., Rumbold, S.T., Shindell, D.T., Skeie, R.B., Sudo, K., Szopa, S., Takemura, T., Zeng, G., 2012. Global air quality and climate. Chem. Soc. Rev. 41, 6663–6683. https://doi.org/10.1039/C2CS35095E

Held, I., 2014. Simplicity amid Complexity. Science (80) 343, 1206–1207. https://doi.org/10.1126/science.1248447

Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J., Taylor, K.E., 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev. 9, 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S.K. Satheesh, S. Sherwood, B. Stevens and X.Y. Zhang, 2013: Clouds and Aerosols. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M.

Improving the estimates of radiative forcing for relevant aerosols (secondary organic or black carbon) and GHGs has also been highlighted as a critical issue. Inconsistencies in the calculation of radiative forcing by CO_2 alone may account for half of the uncertainty of future temperature predictions, usually quoted in the 1.5°C to 4.5°C range[89].

How can uncertainty be managed?

Explicit reporting of uncertainties has become a key focus to clearly convey the scientific messages to policy makers, something that has been neglected in the past[90]. As previously illustrated with the land-surface air temperature trends example, IPCC bases its confidence assessment on two factors: evidence and agreement.

Based on that each scientific team provides a qualitative synthesis regarding the likelihood of a given finding, conclusion or claim (from virtually certain –more than 99% probability- to exceptionally unlikely –less than 1% probability)[91]. Although this provides a consistent way to communicate certainty, it stills involve qualitative judgment and may have some problems capturing IPCC actual practices to produce their assessments regarding the operative notion of agreement between scientists.

> The comparison of previous model projections with recent observations is arguably the best way to gauge model reliability. Models are not only assess regarding average values or mean state, but also trends, variability and extreme values.

Beyond epistemological considerations, it should be considered that uncertainties of the climate change phenomena are not limited to the prediction of radiative forcing or the consequences on the components of the climate system. Further considerations regarding adaptation, damage, socioeconomic issues and costs considerably expand uncertainty[92]. Nonetheless, it is important to consider co-benefits that tackling climate issues may bring about as well. In addition to contribute to global equity[93], climate change mitigation would have benefits regarding the spread of disease vectors, food insecurity and extreme weather events[94]. Air quality also support that climate action is a no-regret policy. Although, this largely depends on local conditions[95], RCM simulations suggest that increased temperatures over highly polluted regions will turn in higher peak levels of ozone and fine particles increasing significantly the burden of disease related to air pollution

Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

89 Soden, B.J., Collins, W.D., Feldman, D.R., 2018. Reducing uncertainties in climate models. Science (80) 361, 326–327. https://doi.org/10.1126/science.aau1864

90 Ha-Duong, M., Swart, R., Bernstein, L., Petersen, A., 2007. Uncertainty management in the IPCC: Agreeing to disagree. Global Environmental Change 17 (1), 8-11. https://doi.org/10.1016/j.gloenvcha.2006.12.003

91 Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe and F.W. Zwiers, 2010: Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 4 pp

92 Glanemann, N., Willner, S.N., Levermann, A., 2020. Paris Climate Agreement passes the cost-benefit test. Nat Commun 11, 110. https://doi.org/10.1038/s41467-019-13961-1

93 Diffenbaugh, N. S., Burke, M., 2019. Global warming has increased global economic inequality. Proceedings of the National Academy of Sciences of the United States of America (PNAS) 116 (20), 9808-9813. https://doi.org/10.1073/pnas.1816020116

94 Watts, N., Adger, W.N., Agnolucci, P., Blackstock, J., Byass, P., Cai, W., Chaytor, S., Colbourn, T., Collins, M., Cooper, A., Cox, P.M., Depledge, J., Drummond, P., Ekins, P., Galaz, V., Grace, D., Graham, H., Grubb, M., Haines, A., Hamilton, I., Hunter, A., Jiang, X., Li, M., Kelman, I., Liang, L., Lott, M., Lowe, R., Luo, Y., Mace, G., Maslin, M., Nilsson, M., Oreszczyn, T., Pye, S., Quinn, T., Svensdotter, M., Venevsky, S., Warner, K., Xu, B., Yang, J., Yin, Y., Yu, C., Zhang, Q., Gong, P., Montgomery, H., Costello, A., 2015. Health and climate change: policy responses to protect public health. Lancet 386, 1861–1914. https://doi.org/10.1016/S0140-6736(15)60854-6

95 Borge, R., Requia, W.J., Yagüe, C., Jhun, I., Koutrakis, P., 2019. Impact of weather changes on air quality and related mortality in Spain over a 25 year period [1993–2017]. Environ. Int. 133, 105272. https://doi.org/https://doi.org/10.1016/j.envint.2019.105272

Anthropogenic emissions are a particularly relevant input for climate projections. According to IPCC, cumulative CO_2 emissions (this GHG represents about 85% of total anthropogenic forcing in all RCP scenarios) largely dominates surface warming from late 21st century and beyond. Emissions depend on both socio-economic factors and policies and measures. Usually is unfeasible to predict the evolution of such variables and strategic analyses are based on the formulation of reference scenarios that represent policy-relevant patterns of activity level, technology and regulations.

Therefore, IPCC works with a series of scenarios that reflect alternative future behavior patterns. In the latest assessment report (AR5), most of CMIP5 experiments were based on prescribed mean CO_2 concentrations instead of anthropogenic emissions. While this is informative for policy purposes, models trend to predict larger CO_2 concentration and consequently, higher radiative forcing when forced by CO_2 emissions rather than prescribed CO_2 atmospheric concentrations. Some authors have claimed that this approach (that ignores carbon-cycle feedback) is rather uncertain under strong emission abatement scenarios since carbon-cycle feedback uncertainties can explain nearly 50% of peak warming uncertainty [96].

What are the principal recommendations?

Our understanding of the climate system is far from perfect, but current evidence provided by data and models point out that warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia[97].

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Further research is needed to fill current knowledge gaps and to keep improving our monitoring and modelling capabilities. New concepts and theoretical frameworks to conciliate observations and models are being developed in critical areas such as the aerosol-cloud interaction processes or the quantification of radiative forcing and rapid adjustments of the atmospheric system. It is important to build on recent scientific breakthroughs, enhanced computing capabilities and better targeted experiments to continue to improve our understanding of the extremely complex climate system. In addition to stronger science, improved statistical approaches, e.g. advanced ensemble methods have been suggested as valid alternatives to constrain long-standing uncertainties in climate multi-model simulations[98]. New methodologies to adapt

96 Holden, P.B., Edwards, N.R., Ridgwell, A., Wilkinson, R.D., Fraedrich, K., Lunkeit, F., Pollitt, H., Mercure, J.-F., Salas, P., Lam, A., Knobloch, F., Chewpreecha, U., Viñuales, J. E., 2018. Climate–carbon cycle uncertainties and the Paris Agreement. Nature Clim Change 8, 609–613. https://doi.org/10.1038/s41558-018-0197-7

97 IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

98 Fletcher, S., Lickley, M., Strzepek, K., 2019. Learning about climate change uncertainty enables flexible water infrastructure planning. Nat Commun 10, 1782. https://doi.org/10.1038/s41467-019-09677-x

Nowack, P., Runge, J., Eyring, V., Haigh, J.D., 2020. Causal networks for climate model evaluation and constrained projections. Nat Commun 11, 1415. https://doi.org/10.1038/s41467-020-15195-y

Shortridge, J.E., Zaitchik, B.F., 2018. Characterizing climate change risks by linking robust decision frameworks and uncertain probabilistic projections. Climatic Change 151, 525–539. https://doi.org/10.1007/s10584-018-2324-x their results for specific applications may also be beneficial[99].

Current limitations should not undermine climate policies, though. According to recent analyses, the targets of the Paris Agreement are still technically achievable and economically favorable. In addition, the co-benefits associated to a decarbonized future advocate for decided action despite current uncertainties.

In addition to contribute to global equity, climate change mitigation would have benefits regarding the spread of disease vectors, food insecurity and extreme weather events.

99 Lehner, F., Wood, A.W., Vano, J.A., Lawrence, D.M., Clark, M.P., Mankin, J.S., 2019. The potential to reduce uncertainty in regional runoff projections from climate models. Nat. Clim. Chang. 9, 926–933. https://doi.org/10.1038/s41558-019-0639-x

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Lead Author for IPCC Fifth Assessment Report (AR5) for Working Group II on Impacts, Adaptation and Vulnerability, and Business and Industry Representative in the UNFCCC Adaptation Committee TEP (from 2016-2018).
Before joining DNV GL Asun was Professor of Sociology at the University of Bergen, Norway, and Research Director of the Oslo Centre for Climate Research-CICERO.

2.4 Can we and should we adapt to climate change?

- What is adaptation to climate change?
- What is the dominant scientific position on adaptation?
- What transformative change? The two sides of climate resilience
- How important is the social and human dimension of transformation? The heart of climate change
- Are the adaptation options the same all over the planet?

What is adaptation to climate change?

Climate change impacts have been with us for a long time. Floods, forest fires, more frequent and intense hurricanes and tropical storms, heat waves, desertification or landslides are all examples of consequences of a warming planet. These impacts have substantive consequences on social and economic systems, adding pressure to existing environmental degradation, such as deforestation, and exacerbating existing socio-economic vulnerabilities such as poverty and discrimination or lack of access to natural resources, such as for example water. Climate change, even if a global phenomenon, does not impact on a vacuum but rather on specific contexts and localities. All this leads to complex sets of cascading socio-ecological risks which may trigger dangerous tipping points.

There is absolutely no doubt that we must adapt to climate change. But what exactly is adaptation, how urgent and how to go about it has no scientific consensus. Adapting to climate change is primarily a change process which can vary in its depth and speed and that often is difficult to decouple from wider social transformation processes. At the same time, many fear that too much attention to adaptation to climate change distracts our attention to the much more important task of mitigating greenhouse gas emissions.

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In this short essay I argue we need both perspectives in a balance that works both at global and local scales. I present first a brief overview of scientific work on adaptation to climate change, outline key tendencies, provide examples of successful adaptation actions and indicate potential trajectories driven by special attention to the social and human dimensions of change.

What is the dominant scientific position on adaptation?

The Intergovernmental Panel on Climate Change (IPCC) which coordinates published scientific literature relevant for understanding and solving climate change, has increasingly dedicated attention to the role of adaptation[100]. This increased attention emerges as evidence of observed climate impacts and their destructive nature shows traditional disaster risk management is insufficient to understand and prepare for unavoidable climate change risks. The focus on adaptation has also emerged as understanding of the earth system shows that there is a substantive time lag between the emission of greenhouse gasses and the visible consequences these have in disrupting the climate. This means that the actual effects of emissions emitted recently are yet to be observed, and although there are many uncertainties regarding how or when exactly these will manifest in the near future, there is robust scientific work demonstrating its potential catastrophic nature[101].

The Working Group in charge of addressing adaptation within the IPCC frames the concept, in its latest published assessment called the AR5, in relation to understanding climate change risks and the vulnerabilities of both social and biophysical systems to climate impacts. The key tasks of this IPCC WG in its last assessment cycle was to evaluate how patterns of risks and potential benefits are changing. Climate change involves "complex interactions and changing likelihoods of diverse impacts"[102]. The report assessed needs, options, opportunities, constraints, resilience, limits, and other aspects associated with adaptation. The primary focus on risk was chosen as a way to support decision making in the context of climate change; and adaptation was defined, not surprisingly, within the boundaries of a risk management framework: as "the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities.

The observed climate impacts and their destructive nature shows traditional disaster risk management is insufficient to understand and prepare for unavoidable climate change risks.

In some natural systems, human intervention may facilitate adjustment to expected climate and its effect"[103].

Although the next assessment cycle of the IPCC, the AR6, will not present its results until the end of 2021, the structure of the adaptation working group report shows more concern with the actual sustainability of systems as impacts increase in depth and extent[104].

The concept of "limits to adaption" was explored in the AR5, acknowledging that adaption is not always possible because at some point an "actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions"[105]. Amongst the solutions for adaption limits are migration, and perspectives that see the change needed not any longer as incremental, but transformational. Transformational adaptation conveys the need for speed and scale in the change of processes associated with adapting to a changing climate different from an incremental change perspective. Many authors have matured this concept of transformative adaption making direct connections to systemic change, and also addressing underlying causes that keep societies on high emissions scenarios and providing compelling accounts of the key role that social systems and social relations play in successful adaptation.

100 Para información general sobre el mandato y trabajo del IPCC, véase https://www.ipcc.ch/

101 Steffen, W. Johan Rockström, Katherine Richardson, Timothy M. Lenton, Carl Folke, Diana Liverman, Colin P., 2018.

102 IPCC, 2014: Summary for Policymakers. In: 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 [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea,T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32..

103 https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-AnnexII_FINAL.pdf

104 https://www.ipcc.ch/site/assets/uploads/2018/03/AR6_WGII_outlines_P46.pdf

105 https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-AnnexII_FINAL.pdf

What transformative change? The two sides of climate resilience

The central use of the concept of risk as the primarily lenses to understand adaptation and the overarching focus to support decision making that was put forward by the IPCC in its last assessment has become a key characteristic of a lot of adaptation to climate change research and action. I would argue that although the language of risk is fundamental to raise awareness and to integrate climate risks alongside other risks in the work of public and private actors, this has also led to define the problem space too narrowly, too focused on qualitative assessment of hazards and losses, creating blind spots for the social and human dimensions of global environmental change, which in my opinion, provide the answer to unleash the change needed.

One of the important advantages of framing adaptation as a transformative process of change is that it opens up many opportunities for seeking nonlinear processes as central elements of adaptation strategies. This also affects the types of adaptive actions considered. The tendency to see adaptation to climate change as a technological fix, be it through the building of dikes to prevent sea level rise or the use of water resistant crops, for example, tend to focus on short term actions and often devoid of a proper analysis of their long term consequences. The emergence of nature-based solutions such as restoring mangroves as means to protect livelihoods from floods and sea level rise has shown that not only is using natural ecosystems rather than brick and mortar more effective against climate related impacts, such approaches also have important side effects and co-benefits. In this case, research has shown that restoring mangroves protects culture, benefits gender relations, has a small carbon footprint, and generates additional income for local people[106].

In the context of developing countries this synergetic and transformative forms of building adaptive capacity are of utmost importance. When the adaptive response to climate is transformative change, this opens up a range of novel policy options, forces us to see the systematic nature of both the causes and the solutions to a warming planet, and sheds light on the central importance that ethical, cultural, and value related aspects have as keys to drive for effective change[107].

One of the important advantages of framing adaptation as a transformative process of change is that it opens up many opportunities for seeking nonlinear processes as central elements of adaptation strategies. This also affects the types of adaptive actions considered.

Adaptive responses designed from such transformative perspective can bring cascades of positive change. This is critical in the context of countries which are already experiencing a serious deficit in their access to basic needs, conflict, or multiple forms of discrimination. It is urgent to design adaptation strategies that generate co-benefits and prevent harm. Climate is a threat multiplier, able to create poverty traps, affecting those most in need for help in a negative way. Adaptive responses can also deepen inequalities, unless care is taken to assess their social and human dimensions, ensuring they do not lead to maladaptation or generate negative consequences, in particular to those sectors of societies that are most vulnerable and have less voice.

106 Resurrección, B.P., Bee, B.A., Dankelman, I., Park, C.M.Y, Halder, M., & McMullen, C.P. (2019)."Gender-transformative climate change adaptation: advancing social equity" Background paper to the 2019 report of the Global Commission on Adaptation. Rotterdam and Washington, DC. Available online at www.gca.org.

107 Pelling, M., O'Brien, K. & Matyas, D. 2015. Adaptation and transformation. Climatic Change 133, 113–127. Trajectories of the Earth System in the Anthropocene

St.Clair, A.L. 2009. Climate Change and Poverty: The Responsibility to Protect, in O'Brien K., A. L. St. Clair, B. Kristoffersen (eds.), Climate change, Ethics and Human Security , Cambridge University Press.

How important is the social and human dimension of transformation? The heart of climate change

In order to move forward an agenda of research, innovation and action for adaptation to climate change, a key point of departure are the social and human dimensions of transformation. In a commentary we wrote for the journal Nature a few years ago, my colleagues and I argued that unless we reframe the problems related to global environmental change from a social and human perspective, the answers will be too little for the scale of the problem, too late for the huge risks we already face today, and potentially blind to negative outcomes[108].

People and societies are not external to climate change, rather, they are both the cause of increased GHG emissions as well as the solution. Yet, we seem to keep perceiving problems caused by humans and that harm humans "in terms of their biophysical nature, as matters of molecules, shifts in atmospheric dynamics or ecosystem interactions, imbalances in elemental cycles or merely as collapsing environmental systems." [109]. This seems a rather nonsensical perspective, especially because if the capacity of humans and the social and economic systems we have created are not transformed, adaptation will no longer be possible as the climate transforms us whether we like it or not.

Are the adaptation options the same all over the planet?

It is well kwon amongst climate scientists that warming from anthropogenic emissions will persist for millennia and will continue to cause further changes in the climate system. This time perspective is fundamental for understanding both the importance and the limits of adaptation. It not only tells us that adaptation would need to be sustained for a long time and maybe even become a new normal in the lives of future generations, but also that each degree matters for the amount of change to which we would need to adapt or forcibly be transformed.

The science community has established that any reduction in average temperature increase will make a difference on how humans, ecosystems and all living beings experience the impacts of climate change in the next years and decades. The IPCC Special Report published in 2018 outlined the differences between a planet heating no more than 1.5°C above preindustrial levels versus 2°C, which is the target of the Paris Agreement[110].

Summarizing it: the risks are higher and with more potential to create cascades of negative effects. This means there are many adaptation possibilities that can reduce the risks of climate change if the overall temperatures do not rise above this 2 °C threshold[111]. Clearly adaptation options are not equal across the planet, also because impacts are local and those global averages do not translate equally in different regions. For example, mountain communities, or indigenous people in the arctic already experience warming that is above 2 °C[112]. But overall every percentage of a degree does matter for the prospects of enabling resilience to shocks created by a changing climate. The feasibility of limiting the overall temperatures

108 Hackmann, H., Moser, S., and St.Clair, A.L. 2014. The Social at the Heart of Global Environmental Change; Nature Climate Change; V. 4. 1 August 2014. 665.

109 Hackmann et al., 2014: 654

110 IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)].

111 For a detailed and very informative summary of this Special Report see Carbon Brief https://www.carbonbrief.org/in-depth-qa-ipccs-special-report-on-climate-change-at-one-point-five-c

112 Wester, P., Mishra, A., Mukherji, A., and A.B. Shrestha (Eds.) 2019. The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People. Springer Open https://lib.icimod.org/record/34383

Figure 16 ▪ The different feasibility dimensions towards limiting warming to 1.5°C.

Assessing the feasibility of different adaptation and mitigation options/actions requires consideration across six dimensions

Source: FAQ 4.1, Figure 1 (Chapter 4) from de Coninck, H., A. Revi, M. Babiker, P. Bertoldi, M. Buckeridge, A. Cartwright, W. Dong, J. Ford, S. Fuss, J.-C. Hourcade, D. Ley, R. Mechler, P. Newman, A. Revokatova, S. Schultz, L. Steg, and T. Sugiyama, 2018: Strengthening and Implementing the Global Response. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [MassonDelmotte,V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter4_Low_Res.pdf

to 1,5 °C is determined by multiple and interconnected dimensions (Figure 16).

The trajectory the world economy and dominant living styles, however, are leading us way past that 2°C limit in a few decades, rising existential questions as to the potential of life in planet earth for human beings, as we have adapted for millions of years to a relatively stable climate that no longer exists. This grim outlook or discussions about the limits of adaptation, are less common in the media and in policy debates, but they are in fact critical topics to attend to. Some scientists even argue that we have already passed any possibility to prevent cascades of catastrophic impacts[113]. Others prefer to place their bets on the capacity humans have for rapid change[114]. The Covid-19 epidemic has shown the world that rapid change is possible if there are enough incentives. Clearly, the perceptions of the risks are not the same, as epidemics are immediate crisis with immediate consequences.

However, most countries could have been much better prepared to deal with the epidemic if the social and human consequences would have been better understood. Most experts warned a global epidemic will happen. The question was when it will happen. But few had foreseen the huge social and economic disruption associated with a global epidemic.

Dismissing risks, no matter how complex and distant these may be, is the most maladaptive response to the climate emergency. I would argue the field of adaptation to climate change needs, more than anything else, the cross fertilization with the human and the social sciences. Not only we need to build narratives to express what types of existential risks we face but we also need narratives of hope and agency.

113 Steffen, W. Johan Rockström, Katherine Richardson, Timothy M. Lenton, Carl Folke, Diana Liverman, Colin P. Summerhayes, Anthony D. Barnosky, Sarah E. Cornell, Michel Crucifix, Jonathan F. Donges, Ingo Fetzer, Steven J. Lade, Marten Scheffer, Ricarda Winkelmann, and Hans Joachim Schellnhuber. Trajectories of the Earth System in the Anthropocene Proceedings of the National Academy of Sciences Aug 2018, 115 (33) 8252-8259; DOI: 10.1073/pnas.1810141115.

114 Véase, por ejemplo, la obra de cChange que aboga por la transformación personal como forma importante de provocar otros tipos de cambio transformativo: https://cchange.no/about/the-three-spheres-of-transformation/

OPTIMAL ADAPTATION TRAJECTORIES FOR THE WARMING WE CAN NO LONGER PREVENT.

The reflective nature of human beings in terms of understanding the problems and the solutions has been a key characteristic across history and a major driver for rapid and sustained change. No matter the race, culture, religion or geographical location, all societies have histories of agency, debate, and self-reflection.

When facing a challenge that has no clear answers, is full of pitfalls, trade-offs, and unintended negative consequences, the right types of adaptation strategies –including what is perhaps the most important adaptation: drastically changing our ways of life to prevent further emissions– are not only those emerging from science. Individual self-reflection on how we contribute to solutions, and deliberative democracy to sort out challenges and trade-offs, are urgently needed. I believe we need both self-reflection and deliberative democracy to carve narratives of hope and to devise optimal adaptation trajectories for the warming we can no longer prevent.

Kirsten Dunlop

Ph.D. in cultural history, Dr. Dunlop's career spans across academia, consulting, banking, insurance, strategy, design, innovation and leadership, and across three continents. Chief Executive Officer at EIT Climate-KIC since February 2017, where she joined from Australian financial services conglomerate, Suncorp. One of 16 experts at the Economic and Societal Impact of Research and Innovation (ESIR) expert group, providing independent advice on how future EU research and innovation policy can best support sustainable development and the Von Der Leyen Commission's priorities. Her vision for EIT Climate-KIC is to offer a capability in systems transformation, resilience and renewal to achieve a zero-carbon economy and a climate resilient society through innovation. In her role at Suncorp, Dr. Dunlop founded and led a bespoke division focused on managing and responding to strategic risk through innovation, transforming core business and industry models from within. Led the Generali Group Innovation Academy for Assicurazioni Generali, pioneering proprietary thinking in the areas of strategic risk management, strategic innovation, strategic leadership development and cultural change.

2.5 And what about climate change mitigation transforming our socio-economic model?

- What are the most complex systemic challenges humanity faces with climate change?
- What kinds of strategies does this systemic challenge of climate change require?
- What structural changes do we have to promote? Time for green economy
- How do we identify with the natural environment? Towards a new manifesto for human identity

What are the most complex systemic challenges humanity faces with climate change?

Towards the end of 2019, over 11,000 scientists published a blunt warning of a climate emergency in Bioscience. The signatories stated, "The climate crisis has arrived and is accelerating faster than most scientists expected... It is more severe than anticipated, threatening natural ecosystems and the fate of humanity... climate chain reactions could cause significant disruptions to ecosystems, society, and economies, potentially making large areas of Earth uninhabitable.... *we need bold and drastic transformations regarding economic and population policies*"[115].

Climate change is on track to have catastrophic effects on human life on Earth because the actions we are taking to address it are too little, too late, and most critically of all, ill-suited to the complex systemic nature of the challenge. A system can be defined as a set of connected things that operate together. A complex system is one in which there are multiple interactions between many different components. The complexity of a system is a function of the elements that are present, of their interactions and of the relational and evolutionary outcomes they induce. A complex system will exhibit emergent properties characterised by non-projectable directions[116]. On account of these properties, complex systems fundamentally challenge our capability to take decisions and they exponentially increase our uncertainty. Climate change and biodiversity collapse are the most complex, systemic challenges humanity faces, occurring at the limits of our capacity to understand, let alone respond, even though our actions have caused and accelerated both[117]. For us to tackle either and both effectively, calls for a significant difference in how we design and take actions.

The limitations of our progress so far can be ascribed to multiple intersecting factors, but three of the most structural elements stand out:

- We have been tackling an incredibly complex systemic problem with linear, mechanistic solutions and approaches.
- We continue to accept and perpetuate root cause issues.

115 https://academic.oup.com/bioscience/advance-article/doi/10.1093/biosci/biz088/5610806.

116 "Complex systems are composed of interconnected parts that, as a whole, exhibit properties that are not present in the individual parts alone and are characterised by features that include: unpredictability, emergence, simultaneous order and disorder, heterogeneity, chaos, non-linearity, feedback loops and hysteresis." Snyder, Carolyn W., et.al., "The Complex Dynamics of our Climate System: Constraints on our Knowledge, Policy Implications and the Necessity of Systems Thinking", *Handbook of the Philosophy of Science*, Elsevier BV, 2011, Volumen 10, pp. 467-505.

117 W.Steffen, P.J. Crutzen & J.R.McNeill, *Ambio* 36, 614-621 (2007).

THE MAIN EFFECTS OF CLIMATE CHANGE ON THE PLANET

According to the IPCC Special Report (see previous note) to limit warming to 1.5°C we need to slash global emissions by 45% by 2030 and remove 1,000 gigatons of CO_2 from the atmosphere by 2100, through terrestrial carbon sinks, bioenergy coupled to carbon capture and sequestration, and direct air capture. The IPCC points out that nothing on this scale has been done to date, and exceptional innovation and commitment will be required. Even if we succeed in achieving that, climate-related risks to growth, livelihoods, health, food security, and water supply will rise from those we experience now. But if we fail to limit warming to 1.5°C, even if it reaches only 2°C:

- The decline in marine fisheries with 2°C of warming will be double what we'll experience at 1.5°C.
- Maize harvests will fall by over twice as much.
- Insect ranges, including those of pollinators, will decline threefold.
- Sea levels will rise by a further five cm, putting another 10 million people at risk.
- The number of people experiencing extreme heat with 2°C warming will be double that of a rise of 1.5°C.

Pandemics such as the current COVID-19 crisis will continue to emerge with accelerated frequency and impact on already fragile social and economic systems.

- We are dealing with climate change as an exogenous not endogenous problem: we are avoiding changing ourselves.

In other words, in the global fight against climate change we have left all the hardest problems to last. We have tackled the essentially linear problems of energy substitution and transition to renewable energy first, a movement that is well under way. We have left the wicked problems to last – transitioning or rather transforming the complex systems that represent epicentres of emissions and environmental degradation, in which extraordinary innovation is required because truly transformational solutions are not obvious. Such systems can be found by viewing whole cities, industrial value chains, regional agricultural economies, capital markets and financial systems as complex "climate problems". Viewed through the lens of systems thinking, we observe that emissions behaviours within these domains respond to emergent properties of complex nonlinear relationships, confounding historic problem solving approaches based on linear paradigms. The challenges of making such systems carbon neutral and ecologically benign are enormous, especially at a pace that pulls away from the inherently marginal impacts of our efforts over the last three decades. Simply put: we do not know what the required interventions are. And by extension, we also do not know the capital expenditure requirements.

What we *do* know is that continuing to work through gradual, incremental changes will not be enough. What is needed now is a fundamental transformation of economic, social and financial systems that will trigger exponential change in decarbonisation rates and strength climate resilience – what the IPCC report calls, "rapid, far-reaching and unprecedented changes in all aspects of society." If we are to avert the catastrophic effects of climate change as it is currently unfolding, we require a major paradigm shift in the socio-economic model of the developed, industrialised world, and in the globalized dynamics of the developing world. We need our human system (made up of many nested and diverse subsystems) to change its sense of self.

For a new identity of our socio-economic model to emerge, change needs to be of an order that would alter the fabric of what makes that model currently exist functionally. This would mean genuine saltations – sudden, large scale mutations – in the constituent elements of the systems make it up, and in their relations, so as to induce discontinuities in time and space. Innovation is the key – across all scales and dimensions but in the context of growing climate emergency, the focus of innovation and of design must be to change the way humans conceive of themselves in relation to the environment and to one another. This is a significant challenge and at the same time an opportunity for policy and governance innovation, as Joanna Boehnert observes: "Humankind already has the knowledge to make sustainable and socially just ways of living on this planet possible. What we do not yet have is the ability to make these transitions possible in the current political context. New types of design and economics could be the basis for systemic transitions"[118].

What follows proposes three critical paradigm shifts in our approach to climate change to allow us to survive, build an endogenous capability for resilience, and transform our socio-economic model profoundly enough to allow us to live together peacefully, equitably, safely and sustainably.

What kinds of strategies does this systemic challenge of climate change require?

Despite large investments, climate change mitigation activities remain too fragmented and too incremental to unlock the exponential changes needed[119]. Many sectors, countries and cities are simply not able to set targets ambitious enough to ensure a 1.5 degree world, because the pathways for getting there through incremental approaches do not exist. The issue lies in our expectation setting and our tools for thinking about and responding to those expectations. We are focusing climate action on our projections of an ordered system's response to anthropogenic forcing, i.e. too many cars producing CO_2 emissions, too many buildings with a high carbon footprint, cows that produce too much methane, exponential growth in aviation which relies on fossil fuels, too many coal-fired power stations and too much coal used in steel manufacturing, for example. Our responses have followed suit. They have been predominantly substitutional, ultimately geared to permitting human life and developed world aspirations to carry on as normal. We have sought, for example, technology solutions to change the sources of energy towards something renewable or less polluting; innovation to create animal feed that reduces methane emissions in livestock, implementing processing and design improvements in aviation and manufacturing, introducing waste management technologies to recycle and reuse.

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These actions are also largely characterised by 'single-point', fragmented approaches, generated within the frames of industry sectors and assumptions, based on calculations of aggregate emissions rather than comparing different emission paths and interdependencies, often solving for one problem in a relatively linear and mechanistic way rather than a multitude of factors[120]. These actions are also largely characterised by 'single-point', fragmented approaches, generated within the frames of industry sectors and assumptions, based on calculations of aggregate emissions rather than comparing different emission paths and interdependencies, often solving for one problem in a relatively linear and mechanistic way rather than a multitude of factors. Siloed

118 https://theconversation.com/survivng-climate-change-means-transforming-both-economics-and-design-109164

119 In recent years €25-30 billions of climate-relevant funding per year in the EU has achieved emissions reductions of 22% with largest cuts from energy industries, construction and manufacturing. See Eurostat 2018 (p.71-2)
https://ec.europa.eu/eurostat/documents/3217494/9087772/KS-02-18-728-EN-N.pdf/3f01e3c4-1c01-4036-bd6a-814dec66c58c
EC strategy 2050, 2019 (p. 15-16)
https://publications.europa.eu/en/publication-detail/-/publication/92f6d5bc-76bc-11e9-9f05-01aa75ed71a1/language-en

120 Snyder, Carolyn W., et.al., "The Complex Dynamics of our Climate System: Constraints on our Knowledge, Policy Implications and the Necessity of Systems Thinking", *Handbook of the Philosophy of Science*, Elsevier BV, 2011, Volumen 10, pp. 467-505.

programming, funding and success metrics seek predictable, dependable and therefore investable gains. The net result is a proliferation of stand-alone initiatives, incremental solutions and process improvements that have made too small a dent in the problem and, worse, generated a set of established expectations, habits and practices associated with sustainability that are now hindering us from tackling climate change as the complex, systemic, world-redefining challenge it is.

In the last 15 to 20 years, innovation in the energy sector for example, was focused on single-point solutions and commercial scale-up. The traditional paradigm of innovation policy was about supporting research and development and engineering projects, and there was a certain confidence that the world was going to be able to innovate itself out of the climate crisis and eventually find a way to decouple economic growth from environmental growth. Today, many of the easier wins – partial energy substitution, efficiency gains – have been activated. The energy sector accounts for approximately two thirds of global CO_2 emissions, and we realise that technology advances alone will not solve the climate crisis: the two decades of technology-focused innovation policy need to be followed by a different innovation paradigm. Innovation support in the energy sector must be coupled with social, political, economic, financial and institutional innovations as well. Furthermore, while there may be a pathway emerging for energy systems transition, the other challenges that remain are far more difficult, including land management (and all related systems) and industrial processes and products (along with the consumer behaviour that drives it), which together account for 45% of GHG emissions globally.

The systemic nature of the transformation that is needed also bears important consequences for public policy: we need to direct innovation and policy change at systems, not at their isolated parts, acknowledging the fundamental

> We are focusing climate action on our projections of an ordered system's response to anthropogenic forcing, i.e. too many cars producing CO_2, too many buildings with a high carbon footprint, , exponential growth in aviation which relies on fossil fuels... Our responses have followed suit. They have been predominantly substitutional, ultimately geared to permitting human life and developed world aspirations to carry on as normal.

uncertainty that comes from engaging in interventions in complex systems dynamics. In this case that uncertainty is all the greater for the fact that the systems requiring the greatest and fastest change are social, political and cultural.

Innovation has an invaluable role to play in the face of such uncertainty. It offers a mechanism to hedge the risk of the status quo through systematic learning. And it furnishes a means of mobilising participation and a sense of possibility through experiences that identify relevant combinations of interventions together with the reference narratives needed for transformation[121]. But the paradigm of innovation itself needs to change to embrace a strategic and systemic approach [122].

Innovation deployed with the objective of socio-economic transformation starts from specific needs and contexts and uses a portfolio approach to activate real economy interventions. Instead of creating the usual competitive funnel for ideas that gradually selects down to winning solutions optimised for capital investment, a systems innovation portfolio selects and activates a spread of diverse possibilities simultaneously – connecting them up to learn from one another through sensemaking. Aspiring to catalyse systemic change means thinking in terms of more or less effective intervention points, drivers of change, moveable levers or leverage points, to use Donella Meadows' language,

121 See Kay, John and King, Mervyn, *Radical Uncertainty: decision making for an unknowable future*, Londres 2020.

122 See the work of Chôra Foundation (https://www.chora.foundation/) y EIT Climate-KIC (www.climate-kic.org).

acknowledging, in other words, that systems have dynamic properties[123]. This is particularly important to nudge and catalyse civil society engagement and behavioural change rather than engineer it. One of the biggest obstacles to transformation is a problem of empirical belief – seeing is believing. Decision makers need options. Innovation can generate options through the experience of experimentation and demonstration in local places and contexts, with everyday agents of change.

What structural changes do we have to promote? Time for green economy

If mitigation of climate change is to be effective and timely as we need it to be, we urgently need to address the dominant economic ideas, structures and systems that industrialised nations and increasingly developing nations adhere to, the social values, social systems and design imperatives that these economic ideas produce, together with some of the core tenets of human civilisation that create norms around the notion of human dominance over and exploitation of natural resources.

In particular we need to make a definitive shift beyond traditional neoclassical economic ideas and contemporary neoliberal economics which are root causes of anthropogenic climate change and of humanity's paralysis in acting to effect structural change. Both make virtues out of consumerism and economic materialism – the notion that human beings live by goods and service as the foundation of individual wellbeing and prosperity – along with belief in the social value of self-interest, maximisation of profit and accumulation of capital in the shortest possible time, and above all exploitation of natural and social resources without a need to compensate the ecological or indeed social cost.

Neoliberalism has become so pervasive that we accept the proposition as if it were a neutral force, a kind of biological law like Darwin's theory of evolution[124]. As a result, competition has become the defining characteristic of human relations and citizens are defined as consumers whose democratic choices are best exercised by buying and selling, thus rewarding merit and punishing inefficiency. This perpetuates the drive for producing more than we can consume, planning obsolescence into design and production, and wasting materials and resources on a vast scale despite the knowledge that we have reached planetary limits on almost every life-sustaining resource. As Dr. Jorge Majfud comments, "Trying to reduce environmental pollution without reducing consumerism is like combatting drug trafficking without reducing the drug addiction"[125].

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These ideas are extremely deep-seated and, worse, are anchored in vast range of powerful vested interests, as well as being normalised across social and political systems on a global scale as a function of convenience, habit, practice and individual responses to social norms – how to act and who to be. We are further hampered by the fact that we have either centralised or decentralised the decision making that governs our processes. The big divide that governs our policies is concerned with whether one or the other governs our progress, which

123 Meadows, Donella H., *Thinking in Systems: A Primer*, Vermont, 2008.

124 Monbiot, George, "Neoliberalism – the ideology at the root of all our problems", *The Guardian*, viernes, 15 de abril de 2016.

125 Majfud, Jorge, "The Pandemic of Consumerism". UN Chronicle, 2009. Archivado el 19 de Julio de 2013.

blinds us to faultline between protecting and enabling the welfare state and providing a mandate to act to the entrepreneurial state[126].

It is time to apply ourselves to institutionalising hope and care in our systems – as equally powerful components of human nature to the fear and greed we have been feeding. Human wellbeing depends on empowerment: our ability to shape our destiny and our means – and on care for others as part of a socially connected context. Success of social and economic policy should be measured by more than GDP and material productivity. We need to redraw company law so that we do not measure the success of business by shareholder value but rather on social and ecological contribution[127]. Creating this new paradigm requires systemic change through reform of our institutions, our norms and our values. Key to the transition is ecologically literate education in both design and economics to facilitate sustainable transitions and make another world not only possible but desirable[128].

In order to do so, we need a managed form of cultural evolution for human society towards forms of governance and community better suited to the world environment as an ecosystem. Humans are a highly cooperative species primarily at small scales. We did not evolve to function as individuals. We are biologically wired for living in small cooperative groups. We need to rebuild small groups of all kinds so that humans can get much more purposeful and work more effectively through collaboration and trust building across boundaries, taking inspiration, for example from the work of Elinor Ostrom on polycentric governance[129].

In particular we need to make a definitive shift beyond traditional neoclassical economic ideas and contemporary neoliberal economics which are root causes of anthropogenic climate change and of humanity's paralysis in acting to effect structural change. Both make virtues out of consumerism and economic materialism.

How do we identify with the natural environment? Towards a new manifesto for human identity

Finally, the central and most fundamental 'problem space' of climate action is the human perception of self and identity in relation to the natural environment. The word 'citizen' derives from the notion of (human) civilization which in turn carries within it the defining moment of settlement into the walls and laws of a city (civis) with the objective of maximising self-preservation and prosperity through organisation of relationships and above all cultivation and management of resources through notions of property or rights over land[130]. The rise of agrarian and ultimately urban societies associated with civilisation across the planet has embedded a meta-narrative of human identity, justified by superior intelligence and/or divine mandate, as one as that has the right to dominate nature, make use of natural resources and harness the lives and capabilities of other species to support human life and the expansion of human ambitions. That reference narrative has all but tuned out the uncomfortable truth of interdependency with the natural world, so central to indigenous communities. Even more than our attachment to consumerism, anthropocentrism is the ultimate root cause issue requiring systemic change.

To address this, we need to reclaim the concept and purpose of 'innovation' as a transitive verb:

126 Mazzucato, Mariana, *The Entrepreneurial State: Debunking Private vs Public Sector Myths*, Nueva York, 2015.

127 See B-Corporation as an example of an effort to take company law in this direction in multiple jurisdictions: https://bcorporation.net/

128 Boehnert, https://theconversation.com/survivng-climate-change-means-transforming-both-economics-and-design-109164

129 Ostrom, Elinor, *Governing the Commons: The Evolution of Institutions for Collective Action*, Cambridge, RU, 1990.

130 Cicero, De Oratore, I, viii, 33-34.

not the intransitive act of creating new things for the sake of it, but the transitive imperative of an 'in-novation' of the self – a shift of identity and self-conceptualisation to enable coherence with an emerging, future context that demands profound differences. Changing human beliefs and notions of identity on a global scale – across different cultures and societies – especially under pressure of time, is an immensely complex task for which we do not have ready-made solutions. The changes needed are not clearly defined, and the limits of our imagination are all too clear, therefore we must use innovation to explore radically uncharted approaches and seek to catalyse unexpected cross-pollination by bringing different disciplines and communities together. We need to identify new and different assumptions, values, practices, standards and behaviours across all industrial, social and economic fields to enable the scale and pace of transformation we need. We need multiple acts of imagination and for that we need to bring art and science back together – to intuit, represent, narrate our way forward just as much as we calculate and engineer: "We have become comfortable with the idea that constant movement and incremental change is a sign of impact and progress and that that is enough. We have all but given up on the idea of solving the most complex problems. We aren't using our imagination. There is a gap between what we think about, the kind of impact we try to have and what we could conceivably achieve" Brian Reich[131].

When it comes to human systems, above all, we should recognise that they are formed by, and ultimately represent, narratives of identity: human systems create meaning, and they are structured by it. These narratives are the function of social conversations over time. Their coherence with the contexts we need to address is the source of our resilience and our capability to change. We need to supply those narratives with a richness of new elements, with a constant supply of difference, with images of the possibility of alternative ways of living and

Creating greater resilience by design, not by disaster should be at the core of our response to climate change. In 2020, in the midst of a global health emergency and imminent economic recession, a concerted investment in innovation-led transformation working along the lines of an integrated "people, planet and prosperity" model might enable us to emerge with a capability for continual renewal through dynamic learning.

of being, so that we can create the new forms in which our systems and ourselves can be transformed.

Creating greater resilience by design, not by disaster should be at the core of our response to climate change. In 2020, in the midst of a global health emergency and imminent economic recession, a concerted investment in innovation-led transformation working along the lines of an integrated "people, planet and prosperity" model[132] might enable us to emerge with a capability for continual renewal through dynamic learning. We need to reframe our intent and actions constantly, living in a permanent state of learning, discovery, reforming. Our innovation efforts will help us if they are designed in such a ways as to explore the possibility of things, discover the means to a 'difference', and imagine and commit to a new image of 'us' that will be consistently coherent with a climate changed and changing context.

131 Reich, Brian, *The Imagination Gap: Stop Thinking the Way You Should and Start Making Extraordinary Things Happen*, Bingley 2018, p. xi. See also Nowotny, Helga: *Insatiable Curiosity: Innovation in a Fragile Future*, Londres, 2010.

132 See The Club of Rome, https://clubofrome.org/publication/the-planetary-emergency-plan/ y https://clubofrome.org/impact-hubs/climate-emergency/emerging-from-the-emergency-key-policy-recommendations-to-g20-leaders/

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2.6 Is CO_2 capture and storage needed?

What to do with the CO_2, once captured?

Carbon Dioxide Capture and Storage (CCS) involves capturing CO_2 generated by burning fossil fuels before it is released to the atmosphere. In addition, there has been considerable interest recently in using CCS technologies to remove CO_2 from the atmosphere. Whether from the flue-gas stream of a power plant, or from direct air capture, the question then arises: What to do with the captured CO_2?

While some opportunities for using it as a feedstock exist, they are very limited in the amount and rate that can be economically deployed. As a result, most current CCS strategies call for the injection of CO_2 as a supercritical fluid in deep geologic formations for long-term storage. In the case of fossil fuel combustion, this forms a closed loop, where the carbon is extracted from the Earth in the form of fossil fuels and then the carbon is returned to the Earth in the form of CO_2. In the case of CO_2 capture from the atmosphere, it generates "negative emissions"[133].

A critical aspect in any discussion of climate-change mitigation technologies is the scale of the problem[134]. A critical aspect in any discussion of climate-change mitigation technologies is the scale of the problem . Current anthropogenic emissions are on the order of 40 gigatonnes of CO_2 per year ($GtCO_2$/year). At a typical density of supercritical CO_2 in subsurface reservoir of 500 kg/m^3, this corresponds to a volumetric rate of about 1,400 million barrels of compressed supercritical CO_2 per day –about 20 times larger than the volume of oil that consumed worldwide daily. Even if CCS were to accommodate the mitigation of a fraction of the emissions (say, 5 to 10%), it would still have to operate at the gigatonne-per-year scale– a phenomenal challenge that is shared by all climate-change mitigation technologies.

What CO_2 capture technologies exist today?

Chemical scrubbing is the principal process in use today for CO_2 capture. This process has two main steps, absorption and stripping. In the absorption process, the CO_2 in the exhaust gas from a power plant or industrial process is captured through a chemical reaction with a liquid solvent. Stripping, which occurs at

133 Herzog, H.J. (2018) *Carbon Capture,* an MIT Press Essential Knowledge Series Book https://mitpress.mit.edu/books/carbon-capture

134 Pacala S., Socolow R. (2004) Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. Science 305, 968–972.

International Energy Agency (2020) *Energy Technologies Perspectives 2020 (ETP2020) – Special Report on Clean Energy Innovation.* https://www.iea.org/reports/clean-energy-innovation elevated temperatures, then strips (i.e., releases) the CO_2 from the solvent, which is then cooled and sent back to the absorber. Amines are the solvent of choice today. It is a "goldilocks" solution, forming chemical bonds with the CO_2 that are not too strong and not too weak. The attraction is strong enough to capture the CO_2 from the exhaust gases, but weak enough that the reaction can easily be reversed at elevated temperatures.

The capture of CO_2 from exhaust gases has a price in terms of both capital costs and energy use. As a result, there is quite a bit of research underway to develop improved capture processes. These approaches include separation of CO_2 from the exhaust gas by solid adsorbents, membranes, or cryogenics (i.e., freezing out the CO_2). Another approach, termed "oxy-combustion", combusts the fossil fuel in high purity oxygen instead of air. This creates an exhaust gas that has a high concentration of CO_2 along with some water vapor, which is easily separated out through condensation.

Thirty years ago, a primary focus for CCS was coal-fired power plants. However, energy systems have changed significantly since then. CCS is now being considered for natural gas-fired and biomass-fired power plants, industrial plants like cement and steel, hydrogen production, and even from the air. These sources differ in the concentration of CO_2 in their exhaust gas: almost 100% pure CO_2 from ammonia or ethanol production, ~60% from hydrogen production, ~20% from cement plants, 12-15% from coal-fired boilers, 3-5% from natural gas turbines, and 0.04% in the air. In general, the lower the concentration, the more difficult and costlier to capture. While most of these gas streams are at atmospheric pressure, there are some cases of having a gas stream at pressure, for example from gasification processes, that make CO_2 capture easier and less costly. A final consideration is the amount of impurities in the gas stream. The more impurities, generally the more the cost.

There has been much interest lately in removing CO_2 from the atmosphere. Two options under consideration require the use of CCS technologies. The first option is bioenergy with CCS (BECCS), where biomass in the form of wood or grasses, remove CO_2 from the air through photosynthesis. The biomass is then harvested and burned in a power plant, with the CO_2 being captured and stored in geologic formations. This generates "negative emissions" because it removes CO_2 from the atmosphere and securely stores it in geologic formations. The second option is called direct air capture (DAC), where CO_2 is removed from the air using chemical scrubbing processes. Due to the very low concentration of CO_2 in the air, about 300 times more dilute than in exhaust gases from power plants or industrial plants, DAC is very expensive today.

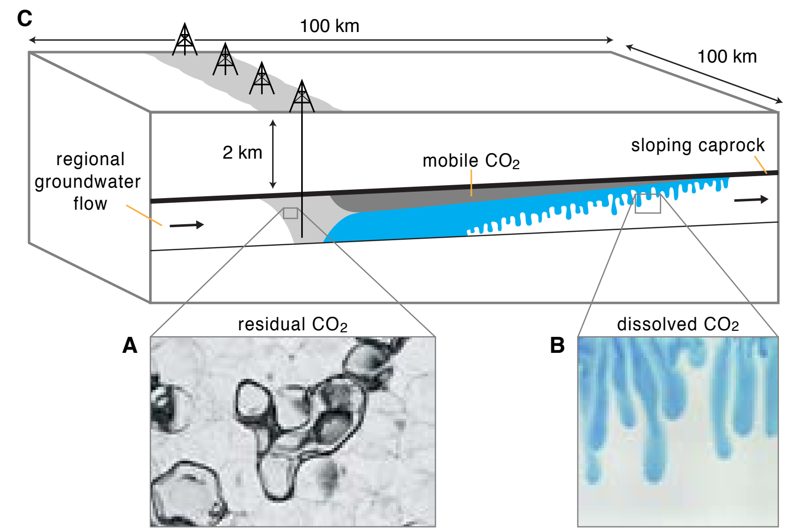
The capture of CO_2 from exhaust gases has a price in terms of both capital costs and energy use. As a result, there is quite a bit of research underway to develop improved capture processes.

Once the CO_2 is captured, it must be transported to the storage site. The transport is generally done by pipeline. This requires the captured CO_2 to be compressed to pressures in the range of 100-150 bar, so it becomes liquid-like. Pipeline transport shows great economies of scale, with pipeline capacities of ten million tonnes per year or greater being desired. Since this is much larger than most individual CO_2 sources, it is envisioned to create transport hubs where CO_2 from multiple sources are combined. Ship transport is also possible, but is generally more expensive than using pipelines. The CO_2 is shipped as a pressurized cryogenic liquid (e.g., 20 bar, -20ºC), similar to transport of LPG (liquefied petroleum gas) today. Ship transport schemes are being actively developed today for the North Sea region in Europe and in Japan.

What is geological storage?

The storage of compressed CO_2 in the subsurface is realized by means of injection wells to a depth of 1 to 3 km, where the CO_2 is in supercritical form (liquid-like density, but gas-like viscosity). Different geologic environments

Figure 17 ▪ Residual and solubility trapping are the key trapping mechanisms that contribute to CO_2 storage capacity.



A) Shows blobs of gas immobilized by residual trapping in an experimental analog system: a glass-bead pack saturated with water.

(B) Shows solubility trapping in a different analog system: a Hele-Shaw cell. The brine with dissolved CO_2 is denser than the ambient brine, dissolution occurs via finger-like protrusions of dense fluid.

(C) At the large scales relevant to gigatonne CO_2 storage, trapping occurs primarily after injection, when the CO_2 migrates due to the aquifer slope and regional groundwater flow. As the buoyant plume of mobile CO_2 (dark gray) rises and spreads away from the well array, residual trapping immobilizes blobs of CO_2 in its wake (light gray), and solubility trapping shrinks the plume from below (blue).

Source: Szulczewski, M.L., MacMinn, C.W., Herzog, H.J., Juanes, R. (2012) Lifetime of carbon capture and storage as a climate-change mitigation technology. *Proc. Natl. Acad. Sci. U.S.A.* 109(14), 5185-5189, doi:10.1073/pnas.1115347109.

are in principle possible to hold the CO_2 over millennia. One option is injection into depleted oil and gas reservoirs. The advantages of this option are that these geologic structures have been well characterized, and the CO_2 can be used to enhance oil recovery (EOR), thus offsetting some of the costs associated with CCS (a fraction of the CO_2 would be produced with the oil/gas, and this CO_2 would be separated and reinjected into the reservoir). While this option is attractive, and the industry has decades of experience in CO_2 EOR, depleted oil and gas reservoirs ultimately would have limited capacity and geographic availability. Another option for CO_2 storage is injection into deep saline aquifers. These are permeable geologic strata, deeper than 1 km and with pore-water salinity much higher than seawater, generally confined between strata of very low permeability (caprock). Deep saline aquifers constitute the most promising option for large-scale CO_2 storage, given that they are widespread and offer a potentially huge storage capacity[135].

It seems likely that CCS is a viable climate-change mitigation from the standpoint of widespread storage capacity at the gigatonne scale.

The physical mechanisms at play during injection and storage of CO_2 are by now fairly well understood. Injection of supercritical CO_2 creates a plume of buoyant fluid that tends to rise up and migrate laterally within the reservoir layer, confined by the caprock –thus, initially it is the geologic structure that prevents upward migration and leakage of CO_2. Over time, other mechanisms like residual trapping and solubility trapping contribute to the long-term storage of CO_2 (Figure 17). Two physical constraints must be accounted for when estimating the storage capacity of a geologic formation[136]: (1) the migration of CO_2 must be limited to ensure that the mobile CO_2 becomes fully trapped before traveling to leakage pathways such as outcrops, large faults, or high-permeability zones in the

135 IPCC (2005) Special Report on Carbon Dioxide Capture and Storage, eds. Metz B., et al. (Cambridge University Press, Cambridge, Reino Unido). https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/

136 Szulczewski, M.L., MacMinn, C.W., Herzog, H.J., Juanes, R. (2012) Lifetime of carbon capture and storage as a climate-change mitigation technology. *Proc. Natl. Acad. Sci. U.S.A.* 109(14), 5185-5189, doi:10.1073/pnas.1115347109.

caprock; (2) the pressurization of the pore fluid as a result of CO_2 injection does not compromise the integrity of the caprock.

Indeed, pressurization of the formation is an important consideration, since fluid injection is known to modify the state of stress of the geologic faults, and be responsible for inducing earthquakes in a number of subsurface energy technologies[137]. While the concern for seismicity risk and potential CO_2 leakage through faults is legitimate[138], its relevance to CCS must be understood in the proper context: geologic reservoirs of buoyant fluids (hydrocarbons, but also carbon dioxide and other gases) have existed for millions of years in areas of intense seismic activity. In particular, proper site selection in geologies dominated by "soft" sedimentary rocks that behave aseismically and without establishing leaking pathways faults[139]. Thus, it seems likely that CCS is a viable climate-change mitigation from the standpoint of widespread storage capacity at the gigatonne scale. Indeed, the study of Szulczewski et al. (2012) suggests that deep saline aquifers exist throughout the United States that can accommodate the CO_2 migration and pressure increases associated with large-scale injection at the century time scale (Figure 18).

What are the prospects for the future? Outlook

Today, CCS projects are successfully storing over 30 million tons of CO_2 every year. Two of these projects are at coal-fired power plants, Boundary Dam in Saskatchewan, Canada and Petra Nova near Houston, Texas. However, in May 2020, CCS operations were suspended at the Petra Nova plant because of low oil prices adversely affecting the economics of the EOR operations. Capture from industrial sites include natural gas processing, fertilizer plants, hydrogen production, ethanol production, and steel

> Since it is almost always cheaper to emit the CO_2 into the atmosphere rather than capture and store it, policy is required to create markets for CCS. Some of these policies can be general, like an economy wide carbon tax. Others can be specifically targeted to CCS, like the tax credits.

manufacture. Most of these projects store the CO_2 as part of EOR operations, but several use deep saline formations.

Using CCS for negative emissions is just starting. The DRAX power plant in the UK is the world's largest biomass-fired power plant (2.6 GW). They have recently started up a one tonne per day BECCS pilot plant. Climeworks, a Swiss company, is selling operating DAC units. These units are cumulatively capturing thousands of tonnes of CO_2 per year. Other DAC companies include Carbon Engineering and Global Thermostat.

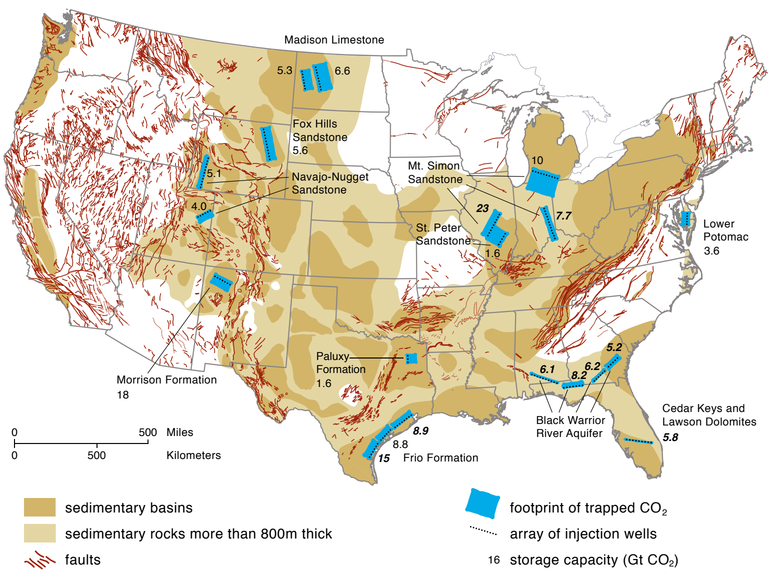
It is very hard to give exact costs for CCS because it is a new technology and supply chains are not fully developed. That makes the first-of-a-kind costs today higher than the nth-of-a-kind costs we can expect in the future. Also, there are significant geographic variations in capital costs, energy costs, and regulatory requirements. Estimates for nth-of-a-kind costs in dollars per metric ton CO_2 are: <\$50/tCO_2 for high pressure sources like natural gas processing or for high purity sources like ethanol or ammonia production; \$50-100/tCO_2 for most power plant or industrial processes; and \$200-250/tCO_2 for BECCS. Despite some really low estimates for DAC costs (\$100-200/tCO_2), \$500-1000/tCO_2 is a more realistic range. Note that the above costs are based on the "net" amount of CO_2 captured (i.e., the gross amount captured minus any emissions attributed to the CCS processes).

137 National Research Council (2012) *Induced Seismicity Potential in Energy Technologies* (National Academy Press, Washington, DC).

138 Zoback M.D., Gorelick S.M. (2012) Earthquake triggering and large-scale geologic storage of carbon dioxide. *Proc. Natl. Acad. Sci. U.S.A.* 109(26), 10164–10168.

139 Juanes, R., Hager, B.H., Herzog, H.J. (2012) No geologic evidence that seismicity causes fault leakage that would render large-scale carbon capture and storage unsuccessful. *Proc. Natl. Acad. Sci. U.S.A.* 109(52), E3623, doi:10.1073/pnas.1215026109.

Figure 18 ▪ Estimation of the United States' nationwide storage capacity from 20 arrays of injection wells in 11 aquifers.



These aquifers were selected because they are large, exhibit few basin-scale faults, and have been relatively well characterized. This map shows the locations of the aquifers and their storage capacities for an injection period of 100 years. Capacities in boldface italics are constrained by pressure; otherwise, they are constrained by migration. The map also shows the ultimate CO_2 footprints for those capacities, which correspond to the areas infiltrated by migrating, free-phase CO_2 before it becomes completely trapped.

Source: Szulczewski, M.L., MacMinn, C.W., Herzog, H.J., Juanes, R. (2012) Lifetime of carbon capture and storage as a climate-change mitigation technology. *Proc. Natl. Acad. Sci. U.S.A.* 109(14), 5185-5189, doi:10.1073/pnas.1115347109.

Since it is almost always cheaper to emit the CO_2 into the atmosphere rather than capture and store it, policy is required to create markets for CCS[140]. Some of these policies can be general, like an economy wide carbon tax. Others can be specifically targeted to CCS, like the 45Q tax credits in the United States, worth about $50 for every tonne of CO_2 stored in geologic formations. In addition, policies are needed to regulate the industry, such as defining permit requirements for CO_2 injection wells and CO_2 pipelines. For negative emissions, policies must be developed so those emissions can be monetized. How these policies develop will greatly impact how CCS does or does not grow in the future.

140 National Petroleum Council (2019) *Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage.* https://dualchallenge.npc.org/

Glossary

Glossary

Developed from information available at:
https://meteoglosario.aemet.es
https://www.ipcc.ch
https://www.iberdrola.com/medio-ambiente/consecuencias-efecto-invernadero
https://es.wikipedia.org
https://espanol.epa.gov/la-energia-y-el-medioambiente/descripcion-general-de-los-gases-de-efecto-invernadero
https://www.miteco.gob.es/es/cambio-climatico
https://dle.rae.es

Aerosol. A suspension of tiny solid or liquid particles in air or some other gas.

Albedo of the Earth. The fraction of solar radiation that is reflected by the Earth's surfaces: land, sea, snow and ice.

Anthropocene. The Anthropocene (from the Greek anthropos, meaning human being, and kainos, new) is the geological epoch proposed by the scientific community to succeed or replace the so-called Holocene, the current epoch of the Quaternary period in terrestrial history, due to the significant global impact that human activity has had on terrestrial ecosystems. There is no common agreement on the precise date of its beginning, some consider it to coincide with the commencement of the Industrial Revolution (mid-18th century), while other researchers trace its origins to the start of agriculture, thereby entirely overlapping with the Holocene.

Anthropogenic. Originating in human activity and, in particular, affecting nature.

Biodiversity. The broadest definition is provided by the 1992 Convention on Biological Diversity. Biodiversity is the variability of living organisms from any source, including, but not limited to, terrestrial and marine ecosystems and other aquatic systems, and the ecological complexes they form part of; it comprises the diversity within each species, between species and of ecosystems. Biodiversity therefore encompasses the enormous variety of ways in which life is organised. It includes each and every one of the species that live on the Earth with us, whether they are animals, plants, viruses or bacteria, the spaces or ecosystems they are part of and the genes that make each species, and within them each individual, different from the rest.

Biomass power plant. Industrial facility that produces electrical energy through the combustion of any type of biomass.

Black carbon. Forming part of the atmospheric aerosols (tiny solid and liquid particles in suspension in the atmosphere), black carbon consists of pure carbon which is typically formed through the incomplete combustion of fossil fuels and wood, and is sometimes also referred to simply as soot. It is black in colour which means that, as opposed to the case of other aerosols, it is a net absorber of heat in the atmosphere. Precisely calculating its net radiative forcing is extremely complicated as it is a short-lived species (4-12 days) and therefore its effect varies greatly from one place to another. It is estimated that its heating capacity (per unit mass) is of the order of 460-1500 times greater than that of CO_2. Furthermore, it has negative effects on human health and accelerates thawing when it forms deposits on glaciers or snow.

Capital costs. The costs a company incurs to finance its investment projects using its own financial resources.

Carbon budget. Amount of carbon that a national economy or some part of it can emit over a given period of time, thereby encouraging the introduction of the appropriate mechanisms to ensure compliance with reduction targets.

Carbon capture. Separation of carbon dioxide from the other gases that are produced during combustion in industrial activities.

Carbon cycle. Term that describes the exchange of carbon (for example, in the form of carbon dioxide: CO_2) between the atmosphere, the oceans, the terrestrial and marine biosphere and the lithosphere. The reference unit for the global carbon cycle in IPCC reports is $GtCO_2$ or GtC (a gigaton of carbon = 1 GtC = 1015 grams of carbon, which is equivalent to 3.667 $GtCO_2$).

Carbon neutral (net zero carbon footprint). Property of a system in which the net emissions of GHGs are zero, including absorption in carbon sinks and compensating via other actions, such as buying carbon offsets.

Carbon offsets. Reductions in CO_2 or other GHG emissions made in order to compensate for emissions made elsewhere.

Carbon tax. Fiscal measure that taxes fossil fuels in proportion to their carbon content, since this determines the amount of CO_2 emissions derived from their combustion.

Climate change. Change in the climate attributed directly or indirectly to human activity that alters the composition of the Earth's atmosphere and is in addition to the natural variability of climate observed over comparable periods of time.

Climate change adaptation. Measures aimed at limiting the effects of, reducing vulnerabilities to and increasing resilience to the changing climate for human and natural systems, including biodiversity, forests, coasts, cities, the agricultural sector, industry, etc.

Climate change mitigation. Set of measures designed to minimise the destructive and disruptive impact of global warming.

Climate system. The extremely complex system comprising the atmosphere, hydrosphere, biosphere cryosphere and lithosphere in their entirety, together with their interactions. The climate system evolves over time under the influence of its own internal dynamics and the effects of natural external forcings, such as volcanic eruptions or solar variations, and of anthropogenic forcings, such as changes in the composition of the atmosphere or changes in land use.

Coal-fired power station. Industrial facility that produces electricity by burning coal.

Collective intelligence. A form of intelligence that emerges from the collaboration of different individuals, generally of the same species, in relation to a particular topic.

Conference of the UNFCCC Parties (COP). International convention of the Parties to the UNFCCC at which decisions are adopted. A COP has been held once a year since 1995 (a year after the entry into force of the UNFCCC), with the exception of 2020 due to the Covid-19 pandemic. At a COP, the Parties have the mandate to review implementation of the Convention and can negotiate new commitments.

Confidence interval. A pair of values that limit a range which has a certain probability, from a statistical point of view—-given by the desired confidence level, such as 90% for example—of containing the true or underlying value. Alternatively it can be expressed as ± a value with respect to the mean or centre of the confidence interval. However it is expressed, it always indicates that according to a given statistical distribution, typically the normal distribution, there is a probability—such as 90%, for example—that the real value is contained within the estimated interval. The smaller the confidence interval, the more robust the estimate.

Cryogenic liquid. Liquids with a boiling point below 183 K (-90ºC).

Decarbonisation. Elimination of GHG emissions from a system, economy or product.

Ecosystem. A biological system made up of a community of living organisms (biocenosis) and the physical environment in which they relate to each other (biotope). Ecosystems usually form a series of chains which reflect the interdependence of the organisms within the system. Abiotic and biotic factors are considered to be linked by trophic chains: flows of energy and nutrients within the ecosystem.

Emission trading scheme (ETS). A market-based approach through which an economic incentive or disincentive is created to achieve an environmentally beneficial goal: that a group of industrial plants collectively reduce the emissions of polluting gases released into the atmosphere.

Empowerment. The action and effect of giving someone the authority, influence or knowledge necessary to do something.

Ensemble. A set of model simulations that characterise a climate prediction or projection. Differences in the initial conditions and the model formulation give rise to varying evolution of the model systems. This can provide information on the uncertainty associated with the model error and with the error in the initial conditions, in the case of climate forecasts; or on the uncertainty associated with model error and internally generated climate variability, in the case of climate projections.

Feedback. The return of part of the output energy or information from a circuit or system to its input.

Fragmentary approximation. Approaching a problem by solving it in parts, without taking into account the interdependencies of the system.

Geological formation. The formal lithostratigraphic unit that defines rock bodies that are characterised by shared lithological properties (composition and structure) which differentiate them from adjacent units.

Global warming potential (GWP). This is a measure that compares the potential climate impact of emissions of different GHGs. The global warming potential of a substance compares the radiative forcing integrated over a specific period of time (for example, 100 years) with the impact of the emission of one mass unit of CO_2 over the same period. Thus, the warming potential of CO_2 is equal to 1 and that of other GHGs is compared with CO_2 over the selected period of time.

Good governance. The art or way of governing that aims to achieve lasting economic, social and institutional development, promoting a healthy balance between the state, civil society and economic markets. It also refers to the form of interaction of public administrations with the market and private organisations or the so-called civil society (companies, employers, unions and others), which have no hierarchical subordination, but rather function as an integrated network, in what has been called "public-private-civil interaction networks along the local/global axis."

Greenhouse effect. The natural phenomenon by which certain gases present in the atmosphere retain part of the thermal radiation emitted by the Earth's surface after it has been heated by the Sun, thereby maintaining the planet's temperature at a suitable level for the development of life.

Greenhouse gas (GHG). Gaseous components of the atmosphere, both natural and anthropogenic, that absorb and re-emit infrared radiation from the Earth, producing the greenhouse effect and increasing the temperature. The main GHGs are: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N2O) and fluorinated gases (hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6) and nitrogen trifluoride (NF3): synthetic gases that are emitted in various industrial processes). Each of these gases can remain in the atmosphere for different periods of time, from a few years to thousands of years. All of these gases remain in the atmosphere long enough to mix well; that means that the amount measured in the atmosphere is roughly the same worldwide, regardless of the source of the emissions.

Holistic. Approach based on total and global integration of a concept or situation.

Incremental solution. The resolution of a problem via the addition of limited improvements without implementing a substantial modification of the system.

Innovation. A change that introduces new features, and can refer to the modification of existing elements in order to improve them, or it may also refer to the implementation of totally new elements.

Interdependence. Reciprocal dependence.

Intergovernmental Panel on Climate Change (IPCC). International scientific organisation for the evaluation of climate change. It was created by the United Nations Environment Programme (UNEP) and the World Meteorological Organisation (WMO) in 1988 to provide a scientific overview of the state of knowledge on climate change and its potential environmental and socioeconomic effects.

Mangrove swamp. A biotic area or biome formed by trees that have high salt tolerances and which exists in the intertidal zone near the mouth of fresh watercourses at tropical and subtropical latitudes. Thus, mangrove swamps include both estuaries and coastal areas. They are very productive and contain considerable biodiversity, including many species of both birds and fish, as well as crustaceans and molluscs.

Mass units. t=1,000 kg; kt=1,000 t; Mt=1,000,000 t; Gt=1,000,000,000 t

Palaeoclimate. The climate that existed in periods before the development of measuring equipment, which includes historical and geological time, and for which we only have indirect records.

Paradigm. A generalised worldview which provides the basis and model for solving problems and advancing knowledge within a particular branch of science. Also, a typical example or model of something.

Parts per billion (109) (ppb). Means of reporting concentration that reflects the number of units of a substance present in every billion (109) units of the total mixture. In the case of atmospheric gases, we talk of ppb by volume, which refers to the number of m^3 of a gas that are present in 109 m^3 of the atmosphere.

Parts per million (ppm). Means of reporting concentration that reflects the number of units of a substance present in every million units of the total mixture. In the case of atmospheric gases, we talk of ppm by volume, which refers to the number of m^3 of a gas that are present in 106 m^3 of the atmosphere.

Permafrost. A permanently frozen layer of soil, though not permanently covered by ice or snow, in very cold or periglacial regions, such as the tundra. It can be found in areas near the poles in Canada, Alaska, Siberia, Norway and on several islands in the South Atlantic Ocean, as well as in Tibet.

Permeability. The quality of allowing water or some other fluid to pass through or penetrate a material.

Planetary boundaries. A conceptual framework that evaluates the state of 9 fundamental processes related to the stability of the Earth system and suggests a series of thresholds for these processes that, if exceeded, could place the habitability of the planet in danger. The concept was proposed in 2009 by a group of 28 international scientists led by Johan Rockström from the Stockholm Resilience Centre and Will Steffen from the Australian National University. Their objective was to define a “safe operating space for humanity” that could be used by governments at all levels, international organisations, civil society, the private sector and the scientific community.

Point of inflexion. The point in a path at which a change in the direction of curvature occurs.

Portfolio. A set of projects, pieces of work or initiatives.

Precautionary Principle. Concept that supports the adoption of protective measures when suspicions arise that certain products or technologies represent a serious risk to public health or the environment, but without yet having definitive scientific proof.

Radiative forcing. The capacity to trap or lose heat—depending on the sign—that results from each of the changes we make on the Earth's surface or in the atmosphere. According to the IPCC, it is a measure of the influence of a factor on modifying the balance of incoming and outgoing energy in the Earth's atmospheric system and represents an index of the importance of the factor as a potential mechanism of climate change. Positive forcing tends to heat up the Earth's surface while negative forcing tends to cool it. It can also be defined as the variation, expressed in W/m^2, of the net (descending minus ascending) radiative flux at the tropopause or top of the atmosphere, due to a change in the external driver of climate change (for example, a variation in the concentration of carbon dioxide or solar radiation). Sometimes internal drivers are still treated as forcings even though they result from the alteration in climate, for example, such aerosol or GHG changes in palaeoclimates. For IPCC reporting purposes, radiative forcing is specifically defined as the change since 1750 and, unless otherwise noted, denotes an annual global average.

Reservoir. One or more components of the climate system in which a GHG or a GHG precursor is stored.

Resilience. The capacity of a material, mechanism or system to recover quickly from a perturbation or difficulty.

Scrubbing (gas absorption). Unit operation consisting of the separation of one or more components of a gaseous mixture with the help of a liquid solvent with which it forms, or they form, a solution.

Secondary organic particles. Part of the atmospheric aerosol (tiny solid or liquid particles suspended in the atmosphere) that is formed from organic substances, typically volatile organic compounds (VOCs), that can be biogenic or anthropogenic. The physical and chemical processes that govern the evolution of this fraction are extremely complex; our understanding of them and also their representation in our models are still imperfect.

Sensibility (of models). Within the context of evaluating numerical models of the climate, sensitivity refers to the change in the response of the model when some input variable is changed. Sensitivity analysis consists of quantifying the changes in the result of the simulation for a specific variable when the initial parameters of the model or the input data are modified to some degree (one by one).

Sink. Any process, activity or mechanism that absorbs a GHG, an aerosol or a GHG precursor from the atmosphere.

Source. Any process or activity that releases a GHG, an aerosol, or a GHG precursor into the atmosphere.

Supercritical CO_2. Carbon dioxide that is under conditions of pressure and temperature that exceed its critical point (30.95ºC and 72.8 atm), which means it behaves like a hybrid between a liquid and a gas: it can diffuse as a gas does and dissolve substances like liquids do. Above critical conditions, small changes in pressure and temperature produce large changes in density.

Synergy. (From the Greek sunergos meaning working together; from sun- "together" + ergon "work.") The interaction of two or more causes whose result is greater than the sum of the individual effects.

System dynamics. Method for analysing and modelling temporal behaviour in complex environments. It is based on the identification of feedback loops between different elements, and also on the time-delays in information and materials within the system.

Systemic. Affecting or relative to an entire system; general, as opposed to local.

Uncertainty. The degree to which knowledge is incomplete, which may be due to a lack of information or disagreement regarding what is known or even knowable. It can be due to different circumstances, from imprecision in data to an ambiguous definition of a concept or term, or an uncertain projection of human behaviour. Therefore, uncertainty can be represented by quantitative magnitudes (such as a probability density function), or by qualitative assertions (which reflect, for example, the evaluation of a panel experts).

United Nations Framework Convention on Climate Change (UNFCCC). International climate change treaty under the auspices of the United Nations, adopted in 1992 and which came into effect in 1994, which has been ratified by 195 countries (the Parties to the Convention). The Convention recognises the existence of the climate change problem, and establishes an ultimate objective: stabilisation of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic (human-caused) interference in the climate system. In addition, such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Wavelength. Distance over which a periodic disturbance that propagates through a medium in a cycle repeats itself. It is the inverse of the frequency. Wavelength is usually represented by the Greek letter λ.

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