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Faced with progressive warming of the Earth's surface over several decades and the increased frequency of extreme events, it is time to do more than just fight the greenhouse effect and estimate the full magnitude of climate change. It is necessary now to evaluate the consequences of these changes and anticipate adaptations that should be considered.

Within this framework, the French National Institute for Agricultural Research (INRA) has created a metaprogram called Adaptation of agriculture and forests to climate change (AAFCC).

The publication of the fifth IPCC report has provided the opportunity to present a comprehensive overview of research conducted on adaptation to climate change.

AGRICULTURE, FORESTS AND ECOSYSTEMS

Adaptation to **climate change**

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The first volume of the Fifth Assessment Report on climate change by the Intergovernmental Panel on Climate Change (IPCC) was published on September 27, 2013. It addressed the climate system and climate changes. This report confirmed the occurrence of global warming since the 1950's with temperatures rising as much as 0.6°C. Projections for 2100, dependent on human activities and uncertainties in modeling, estimate warming to vary between 1.1 and 4.8°C. A second volume issued on March 31, 2014 detailed the impacts of climate change, possible adaptive actions and the vulnerability of exposed systems and human populations. A third volume devoted to research aimed at mitigating the impacts of climate change was published on April 11, 2014. In October 2014, a final synthesis was released. The 21st Conference of Parties on Climate Change, which will take place in Paris in December 2015, will address its findings.

This exercise in collective scientific expertise and forward reasoning involved more than 800 scientists from around the world. It is based on thorough analysis of scientific publications and methodology. Each conclusion is characterized by a confidence index and an index of uncertainty. While the first report from 1990 only involved specialists in climate science, the current report highlights the interdisciplinary character of adaptation approaches. Experts in both natural and social sciences participated, indicating a common interest in informing political, economical and social choices by assessing the scientific basis of climate change and the impacts that need to be addressed, which will vary significantly depending on the region of the world.

Continental land surfaces, in all of their diverse nature and uses, whether cultivated or semi-natural environments (forests, grasslands, aquatic environments, wetlands and wilderness areas), have a particularly complex role in the context of climate change. The potential risks and impacts are huge relative to plant and animal resources, related economic activities, food safety, the functioning of ecosystems, biodiversity, water resources and health. Furthermore, these surfaces emit greenhouse gases (carbon dioxide, methane, nitrous oxide) through natural processes, but also because of human activities (agriculture, livestock, deforestation). But we will see that, at the same time, they can absorb and sequester large amounts of carbon and therefore can mitigate the importance of climate change.

The Swedish chemist Svante Arrhenius was the first to predict, in 1896, that the accumulation of carbon dioxide in the atmosphere linked to the use of fossil fuels would lead to a warming of the planet. But it was in 1958, as part of The International Geophysical Year, that geochemists Charles Keeling and Roger Revelle of the Scripps Institution of Oceanography installed at the Mauna Loa Observatory, located at the summit of the volcanic island of Hawaii, the first monitoring station for continuously measuring concentrations of atmospheric carbon dioxide. These measurements represent the longest time series available today.

Changing carbon dioxide sinks and sources

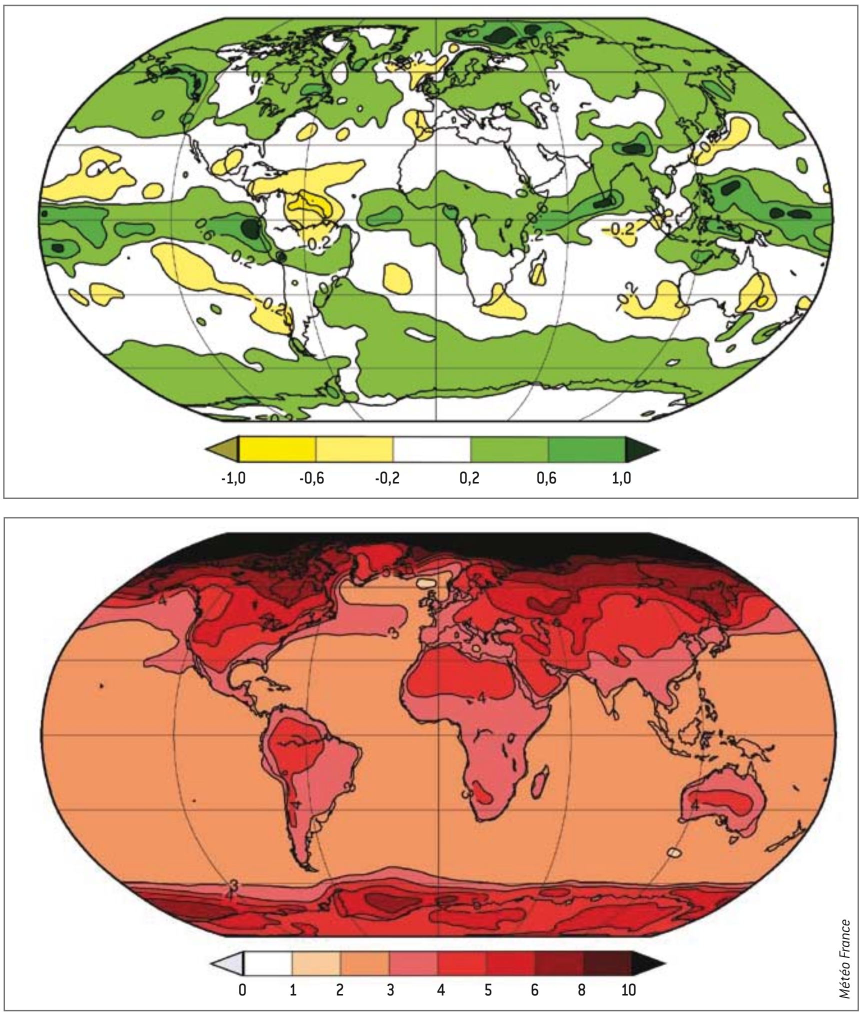
What were the main findings? The atmospheric concentration of carbon dioxide has increased dramatically since 1958. Close to 315 ppmv (parts per million by volume) in 1958, it exceeded 400 ppmv for the first time in May 2013. Values recorded in air bubbles trapped in Arctic and Antarctic polar ice before the industrial era (late 18th century), are close to 280 ppmv. The rate of increase in carbon dioxide concentration is also growing: from 0.7 ppmv per year recorded in the early 1960's, it rose to 2.0 ppmv per year between 2000 and 2010. This acceleration is similar to the rise in fossil carbon dioxide emissions, due notably to the use of fossil fuels (coal, oil, gas): these emissions reached 35 gigatons (35 billion tons) in 2011. Deforestation, another source of carbon dioxide emissions, presents a contribution from tropical forests of 4 gigatons of carbon dioxide per year.

But next to these disturbing figures, research shows that there in fact exist "shock absorbers" to limit the magnitude of these increases. As such, what we find in the atmosphere represents about half of the amount of carbon dioxide actually emitted. This phenomenon applies to assessments conducted over the last decade, but also to levels recorded since the beginning of the industrial era. It is estimated that 2,000 (± 312) gigatons of carbon dioxide were emitted into the atmosphere from 1750 to 2011 due to human activities, of which 1,340 (± 110) were attributed to the use of fossil fuels and cement production, and 660 (± 295) to deforestation and land use changes; a "mere" 800 gigatons accumulated in the atmosphere.

Progress made in evaluating carbon fluxes and assessing ocean-atmospheric and land-atmospheric interface exchanges, through measurements and process modeling, helped to clarify this phenomenon. It originates in intensive exchanges of carbon dioxide between ocean and land surfaces on one hand, and the atmosphere on the other. These exchanges occurring in both directions are estimated to be 290 gigatons of carbon dioxide per year for oceans and 400 for land surfaces. However, the assessment shows a slight imbalance resulting in a net accumulation of roughly 9 gigatons per year in oceans and about as many in terrestrial systems. Thus, these systems mitigate the increase of atmospheric carbon dioxide.

The regional decomposition of the fluxes revealed that temperate and boreal forests in northern hemisphere represent significant carbon sinks. Indeed, these surfaces are globally expanding, increasing biomass carbon stocks. In addition, the increased concentration of carbon dioxide has a "fertilizing" effect, stimulating photosynthesis and forest productivity and therefore rendering this "trap" more efficient. In addition, atmospheric deposition of mineral nutrients from air pollution, such as nitrogen and sulfur, could strengthen this fertilizing effect. The contribution from agricultural surfaces is more variable: in Europe, grasslands would represent a carbon sink, whereas crop fields act as a source.

Will the terrestrial carbon sink continue to be as effective in the future? This is not certain. It could become increasingly less effective, or even stop working due to two given mechanisms: the first is that forest biomass and soils in the terrestrial ecosystems could become saturated, which



Modeling results (CNRM-CM5 model) indicating annual average differences in rainfall (in millimeters per day, top image) and temperature (in °C, bottom image) between the period 1970-2000 and the period 2071-2100 for the scenario RCP8.5 described in the 5th IPCC report. It would rain less in some tropical regions, including the Amazon, and temperatures could increase by 10°C in more northern regions.

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A miniature weather station in an Argentine vineyard. Climbing in altitude or changing latitude could be a way to adapt to climate change.

would reduce the capacity for carbon sequestration; the second is that future climate warming and higher frequency of droughts could affect these ecosystems turning carbon dioxide sinks into sources, as photosynthesis would be reduced and decomposition of organic matter in the soils would be stimulated. The reduction in productivity and carbon sequestration observed across Europe as a result of the drought and heat wave in 2003 may be considered as an example of what could happen.

Carbon dioxide is not the only greenhouse gas that contributes to global warming. Two additional gases, among others, are nitrous oxide (N_2O) and methane (CH_4) whose atmospheric concentrations have been measured continuously since 1976 and 1983 respectively.

Other greenhouse gases

These gases accumulate rapidly in the atmosphere and contribute substantially to global warming, despite their lower atmospheric concentrations, as their molecular capacity for trapping infrared radiation emitted from the Earth is greater than that of carbon dioxide. Methane is by nearly half (between 35 and 50 percent) natural in origin, issued from wetlands. The rest comes from agriculture (enteric fermentation of ruminants, effluents from livestock, rice paddies), from waste fermentation, and emissions related to fossil fuel and biomass combustion. Moreover, future climate warming in northern hemisphere high latitudes would lead to the disappearance of a part of the permafrost, as the thawing process would cause the release of high quantities of methane currently trapped in these permanently frozen soil surfaces. As for nitrous oxide emissions in the atmosphere, two-thirds originate from natural processes, notably the denitrification of soil and oceans, with one third being anthropogenic in origin linked directly to the use of nitrogen fertilizers, biomass burning and emissions associated with atmospheric deposition of nitrogen.

Thus, biomass and soils today are responsible for partial mitigation of the impacts of climate change because they sequester carbon. However, not only are terrestrial carbon sinks likely to be-coming less effective, but other sources of greenhouse gases might appear at the same time agriculture-related emissions continue to rise. Therefore, in addition to continuing trying to mitigate the impacts of climate change, it is also essential to look for ways to adapt.

How can we adapt to climate change?

First, by better anticipating future climate trends. Climate models have been significantly improved due to a better understanding of the whole set of greenhouse gases and of radiative forcing (or climate forcing), which is the difference between solar energy received by the Earth and the energy radiated back to space. Radiative forcing ultimately determines global warming. The increased availability of computing power, improved modeling methods, and an unprecedented mobilization in the modeling community who have committed to taking a common approach, allowed for the comparison of a set of models. Finally, spatial resolution of models has improved significantly. For example, the grid size of the Euro-CORDEX simulation system is 12 km, making representation of local phenomena and extreme events - such as heat waves and droughts - much more precise.

Four new types of climate scenarios, or rather theoretical scenarios developed by the IPCC, are based on different radiative forcing values, linked to as many hypotheses for mitigating anthropogenic greenhouse gas emissions. Simulations using these models have shown that warming since 1950 (+0.6 °C) and the frequency of extreme events can be explained by external climate forcing (linked to human activities). According to these simulations, warming in the medium-term (2035) will remain fairly limited, regardless of the scenario; global warming in the long-term (2100) will be more significant and contrasted depending on the scenarios, but could exceed 4 °C in Europe.

Southern Europe should suffer more rapid warming than northern Europe in the summer, and warming in the winter will be more rapid in eastern and northern Europe. Rainfall should increase in northern Europe and decrease in southern Europe (including southern France). Dry periods will be more pronounced and will happen with greater frequency, and heat waves will likely occur more often.

In the short and medium-term, the increased atmospheric concentration of carbon dioxide and global warming could have positive consequences on the ecosystems and agriculture, notably for high latitude production. However, in the long term, adverse effects related to high temperatures and drought could become prevalent. They are already threatening the dry tropical zones and the Mediterranean region.

Adaptation to climate change will also require thorough understanding of responses of organisms, populations and communities, and more generally of natural and anthropized ecosystems. Essential ecological and biological processes will likely be altered, starting with production and the beginning and end of active periods, which, each year, determine species interactions within ecosystems. Furthermore, species distribution will be changed. In French latitudes, an increase by 1 °C has been associated with a displacement of thermal areas as much as 150 km northward in the plains or 150 m altitude in the mountains.

This effect will trigger a migration of the most mobile organisms (microorganisms, animals, rapidly dispersing plants and plants with short reproduction cycles), whereas less mobile organisms, such as trees or those living in closed environments like lacustrine species, will experience imbalances that will threaten their survival. In certain cases, natural responses, such as the ability of a population or a species to acclimate without genetic variation when the environment changes, or rapid genetic adaptations, could reduce these impacts. But it will be necessary to assist these responses, for example

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The impact of climate change on the frozen soils of Siberia is being carefully monitored.

by setting corridors to promote species migration, by moving species artificially via the transfer of seeds, or by assisted regeneration or forest plantations.

Progress made in modeling how cultures function or of the dynamics of forests and other ecosystems will be useful for defining options for adapting to future climate changes. As such, in the CLIMATOR project, scientists cross-referenced climate models with agronomic and forest models. Future impacts of climate change on agriculture and forestry were analyzed relative to yield, to the quality of agriculture products, cropping calendars, water requirements and plant health, without forgetting that possible crop displacement could present new opportunities.

The limited magnitude of changes expected to happen in the medium-term (2035) could be alleviated in large part by the inclusion of adaptive measures in current management practices to promote the resilience of systems to inter-annual climate fluctuations. However, the increase of extreme events may already disrupt agricultural production and have serious economic consequences. More intensive climate changes expected to occur in the second half of the 21st century will necessitate more radical adaptive measures. Production areas will need to be modified, which in turn will lead to changes in economic sectors, land management techniques and to the development of socially acceptable technical innovations.

Anticipating the changes

It will be particularly important to anticipate these changes in systems with slower dynamics (forests, permanent grasslands, lakes). Managing these adaptations will be easier for highly anthropized systems whose conditions are more controllable (annual crops, livestock systems) than for the more natural systems (permanent grasslands or non-cultivated forests, lakes, rivers and wilderness areas) for which we will only be able to consider accompanying or palliative measures.

Thus, the challenges posed by climate change to society and to scientists are considerable. It is urgent that we define appropriate ways of managing our existing resources, the environment and land (agriculture, forestry, natural environments) while at the same time anticipating the consequences of these changes. It will be particularly important to preserve all systems that contribute to climate change mitigation, which sequester carbon and limit greenhouse gas emissions.

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