9. Recent global climate change

9.1. The rise of environmentalism in the 20th century

Human populations are profoundly affecting the environment, so much so that a new geologic epoch has been proposed in 2003: the ***Anthropocene***.
One number which perhaps reflects best the rising influence of humankind on the environment is the world's population. From 1 billion at the beginning of the 19th century, the world's population increased to 6 billions in 2000 and is expected to be between 8 to 11 billion by 2050 (projection of the Department of Economic and Social Affairs of the United Nations). We modify our landscape by constructing megacities. Our increasing energy needs still rely heavily on burning fossil fuels which releases greenhouse gases and modifies Earth's climate. A number of human activities are affecting the biosphere and causing species extinctions: the expansion of cities, deforestation for agricultural purposes, global warming, and the discharge of pollutants of all sorts in the environment. Understanding their effects on the environment is the prerequisite to taking measures to protect our environment.
Positive outcomes have emerged from our advancing knowledge of human interferences with the environment. For instance, in the 70s scientists raised public awareness on the destructive effect of chlorofluorocarbon (CFC) on the ozone layer, a layer of the atmosphere protecting the biosphere against UV radiations. The manufacturing of this compound is now strictly regulated in 197 states which have ratified the Montreal Protocol in 1987, an international treaty devised to protect the ozone layer. In parallel, ban on leaded gasoline began in the 70s after the American geochemist Clair Patterson[*] drew public attention on the abnormally high concentrations of lead in the environment.
In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations. The IPCC consists of a group of climate experts whose role is to inform the public and governments on the impact of human activities on climate, on predictions of future climate change, and on solutions to mitigate human-induced warming. They publish reports based on the work of thousands of scientists from around the world. In 1997, an international treaty called the Kyoto Protocol was designed to reduce the global emission of greenhouse gases. It has been ratified by 191 countries and the European Union. Thirty seven industrialized countries and the European Union are legally bound by the treaty to reduce their emission of greenhouse gases. The United States have not yet ratified the treaty and Canada pulled out in 2012.
Other efforts that are being made to protect the environment involve the designation of protected areas. For instance, the Great Barrier Reef Marine Park was established in 1975 by the Australian government. The park covers 344,400 km^2. Tourism is strictly regulated and fishing activities are banned in one-third of the park.

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[*] The same geochemist who determined the age of the Earth based on the age of meteorites using the uranium-lead dating technique, a technique he himself developed. He found an age of $4.55 \pm 0.07 \times 10^9$ years (published in 1956) which is still the accepted age of the Earth today.

9.2. Evidence for recent global climate change

Reliable instrumental measurements of atmospheric temperatures are available since the end of the 19th century. These measurements show that the global average temperature has increased by about 0.8°C over the past century. As we saw in chapter 10 paleoclimate indicators can be used to reconstruct the evolution of Earth's climate in the past. An important finding is that Earth has already been as warm and even warmer during the course of its history. For example, the early Eocene epoch (50 million years ago) was warmer than today with no ice at the poles and a rainforest flourishing in the arctic region! During the past 10,000 years (Holocene) the Earth's climate has been relatively stable (see fig. 89-B). The rate at which global temperature is now rising is exceptional compared with the climate record of the past 1000 years (Fig. 78).

Figure 78: Evolution of the average temperature of the northern hemisphere relative to the average temperature of the period 1961-1990. Source: IPCC 2007 Assessment Report.

The rapid increase in global temperature correlates with the rise of atmospheric greenhouse gases caused by human activities since the industrial revolution which took place during the late 18th and early 19th centuries (Fig. 79). Moreover, the geological record shows that current levels of atmospheric CO_2 and CH_4 are unprecedented during the past 650,000 years (Fig. 80). The atmospheric concentrations of CO_2 and CH_4 have increased by 40% and 250%, respectively, since pre-industrial times. Another important greenhouse gas produced by human activities is N_2O (nitrous oxide).

Figure 79: Atmospheric concentrations of CO_2 and CH_4 over the last 10,000 years. Levels prior to reliable instrumental measurements of atmospheric samples are from ice cores. Source: IPCC 2007 Assessment Report.

Figure 80: Evolution of atmospheric concentration of three greenhouse gases over the past 650,000 years measured in ice cores from Antarctica and, for recent concentrations, in atmospheric samples. Stars in the upper right corner indicate the concentrations in 2000. Source: IPCC 2007 Assessment Report.

Complex computer models are used to understand how the climate system responds to various perturbations. These models show that the current global warming cannot be reproduced accurately without the contribution of anthropogenic greenhouse gases. Natural phenomena alone cannot explain the recent rise of global temperature (Fig. 81). The cooling effect of aerosols, which reflect the incoming sunlight, and solar activity, which has been relatively low in recent years, have not offset the global warming that has been detected over the past decades (fig. 82)

These models are also used to predict the future course of Earth's climate. The results greatly depend on the evolution of atmospheric greenhouse gases. The IPCC reports propose several scenarios (Fig. 83), from a pessimistic scenario with almost no reduction in emission of greenhouse gases (scenario RCP8.5) to a very optimistic scenario predicting a generalized use of non-fossil energy sources and active removal of carbon dioxide (scenario RCP2.6).

Figure 81: Comparison between observed changes in surface temperature (black line) and those simulated by climate models ("natural forcings only" models in blue and "natural forcings + anthropogenic forcings" models in pink). Source: IPCC 2013 Assessment Report.

Figure 82: Principal components of the radiative forcing of climate change. Radiative forcing is defined as the difference between the solar energy reaching the Earth (incoming sunlight) and the energy radiated back to space. A positive radiative energy (energy absorbed by Earth) causes warming, whereas a negative radiative energy (energy lost to space) causes cooling. Source: IPCC 2013 Assessment Report
(via http://www.epa.gov/climatechange/science/indicators/ghg/climate-forcing.html).

Figure 83: Evolution of the average global temperature in the future predicted by models based on different scenarios of CO_2 emissions. Source: IPCC 2013 Assessment Report.

9.3. Consequences of global climate change

I. Impact on regional weather patterns

The consequences of global warming on regional weather patterns are complex. The term global warming does not mean that all regions of the world are experiencing the same amount of warming (or even any warming at all!). The trends are not uniform. Figure 84 shows the differences between the average surface temperatures measured during the period 2000-2010 and the average temperatures of the period 1940-1980 measured in the same region.

Figure 84: Differences in annual mean temperatures measured during the period 2000-2010 and those measured during 1940-1980 in the same region. Source: NASA (http://data.giss.nasa.gov/gistemp/maps/).

The figure above clearly shows that the warming of the northern hemisphere is more pronounced than the warming in the southern hemisphere. Moreover, warming is more pronounced over the land than over the ocean. The evolution of surface temperature will therefore vary geographically.
Global warming is also disrupting precipitation patterns (Fig. 85).

Figure 85: Changes in precipitation for the period 1900-2013. Source: Mark Maslin (Climate Change, 2014).

Presumably global warming may also affect the frequency of intense climatic events such as powerful storms, cyclones/typhoons and heatwaves. Models predict that global warming will increase the number and intensity of storms and cyclones. However, no clear link between global warming and recent trends in the intensity and frequency of storms and tropical cyclones has been established. Longer-term monitoring of atmospheric and oceanographic conditions is needed to understand the influence of global warming on the life cycle of these violent climatic events.

II. Impact on the cryosphere

Global warming accelerates the melting of polar ice sheets. Whereas there is no doubt that the Greenland ice sheet is rapidly shrinking, there has been some controversy surrounding the fate of the Antarctic ice sheet. Recent satellite data confirm that both the Greenland and Antarctic ice sheets are loosing ice (Fig. 86).

Figure 86: Changes in ice mass estimated from data collected by the GRACE satellite for the Greenland ice sheet (A) and the Antarctic ice sheet (B) . Source: Velicogna (2009).

A direct consequence of the melting of the ice sheets is sea level rise (Fig. 87 on this page). Another cause of sea level rise related to global warming is the increasing volume of the oceans due to warming ocean waters, i.e. ***thermal expansion*** of the oceans. Sea level rise will increase the frequency of storm surges in low-lying coastal areas. Areas at risk include the Netherlands, Bangladesh and New York. Many low-lying South Pacific islands are also directly threatened by sea level rise, like the Maldives and Tuvalu (see Fig. 87 on page 86). The sea level is currently rising at a rate of 2-3 mm/year. Based on predictive models, the sea level is expected to rise at a rate of 2-6 mm/year during the next 100 years.

The rapid warming over high-latitude landmasses in the Northern Hemisphere may also result in a loss of permafrost that can further enhance the initial warming (see section 11.3.**IV**.).

Figure 87: On the previous page, future evolution of global mean sea level based on various scenarios of CO_2 emissions (sources: IPCC 2013 Assessment Report). Above, picture of the island of Malé, capital of the Maldives, showing how vulnerable some low-lying Pacific islands are to sea level rise (photo by Hironobu Kan, Kyushu University).

III. Impact on the biosphere

We have already mentioned the impact of ***ocean acidification*** on marine ecosystems related to the increase in atmospheric CO_2. Ocean acidification may have a detrimental effect on calcifying organisms like corals. Global warming itself may be detrimental to corals by increasing the frequency and intensity of ***coral bleaching*** events[*].

Global warming also affects the geographic distribution of organisms. Organisms are expected to migrate poleward or to higher altitudes to escape the heat. ***Poleward migration*** has already been observed in several groups of organisms such as corals, butterflies, and birds. The introduction of new species in areas where they were previously absent will affect species interactions. Introduction of ***new competitors*** may threaten the survival of certain species. Organisms which have a restricted climatic tolerance and cannot migrate (or not fast enough) will also be at risk of extinction. Figure 84 shows that one of the geographic areas that is the most affected by global warming is the Arctic region. Reduction in sea ice volume due to global warming leads to ***reduction of habitat*** and potential threat of extinction for organisms living on the ice, like polar bears, walruses and seals (Fig. 88A-B). On the other hand, there are also species that will benefit from global warming. A recent study reports an increase in the population of Adélie penguins on Beaufort Island due to an increase in breeding habitat related to the retreat of glaciers (Fig. 88C).

Another risk of global warming is the spread of ***contagious tropical diseases*** to high-latitudes, for example, malaria which is transmitted to humans by mosquitoes thriving in tropical to subtropical regions.

In conclusion, global warming could cause irreversible changes in the biosphere. The IPCC estimates that 20 to 30% of known species of animals and plants may face extinction if global average temperature increases by 1.5 to 2.5°C.

Figure 88: Loosers and winners of global warming. (A) Polar bear, (B) walruses (source of A and B: Greenpeace Technical Report 04-2012), (C) satellite image of Antarctica and Beaufort Island where the population of Adélie penguins has expanded (source: LaRue et al., 2013).

IV. Abrupt environmental changes

So far we have considered a steady rise in global temperature and progressive changes in weather patterns, the cryosphere and the biosphere. However, we know from the geological record that these changes are not always progressive. For instance, if we look at the sea level rise of the last deglaciation (Fig. 89), we see that there is a big jump around 14,500 years ago (MWP-1A in Fig. 89). It is called a ***melt water pulse***. The sea level rose by about 14-18 m in 350 years. The rate of sea level rise exceeded 40 mm/year which is more than 10 times faster than the current sea

[*] Corals are marine invertebrates containing photosynthetic microalgae inside their living tissue. Corals and microalgae have a symbiotic relationship, meaning that they mutually benefit from their association. Corals provide microalgae with a protected shelter. Through cellular respiration, corals also provide the CO_2 needed to perform photosynthesis. Microalgae provide corals with organic compounds produced by photosynthesis. This remarkable relationship explains why corals need light to thrive and tropical coral reefs grow in shallow waters. Corals and their symbiotic microalgae are sensitive to temperature. If the ocean water warms too much, corals loose their microalgae. Since corals get their color from their microalgae, loosing them means they loose their color and become white, hence the term coral bleaching. If the water temperature does not return to normal soon enough, corals do not regain their microalgae and perish.

level rise! Scientists relate this jump in sea level to a sudden collapse of the polar ice sheets, either in the northern or southern hemisphere. In the present context of accelerated melting of polar ice, it is important to understand the mechanism triggering these events to be able to predict future sea level jumps.

Figure 89: (A) Sea level change during the last deglaciation. Note the sea level jump (MWP-1A) around 14,500 years ago. (B) Evolution of atmospheric temperature in the Arctic during the same period. Superimposed on this curve is the evolution of average summer insolation at 65°N. Source: Montaggioni and Braithwaite (2009).

An event related to global warming that could trigger rapid and intense climatic changes is a ***slowdown of the thermohaline circulation***. As we learnt in chapter 8, the thermohaline circulation is driven by differences in water density. An important source of deep water is the North Atlantic where cold and salty —hence dense— water sinks to the bottom of the ocean. The thermohaline circulation helps redistribute heat from the tropics to higher latitudes in the North Atlantic via the Gulf Stream. The discharge of a large amount of freshwater from melting ice and increased precipitation may disrupt the thermohaline circulation by lowering the density of surface water. This could potentially affect regional weather patterns, particularly in Europe.

We have already seen that acceleration and intensification of a preexisting climatic trend, be it warming or cooling, may be caused by positive feedback mechanisms. One such positive feedback that could intensify the current warming is related to permafrost thawing (Fig. 90). Melting of the permafrost could result in a rapid decay of the organic matter it contains. The microbial decomposition of organic matter would release large amount of carbon dioxide and methane, two greenhouse gases. Methane is a particularly potent greenhouse gas. Another source of methane may come from the deep sea. A few hundreds meters beneath the sea floor, methane is sometimes present as methane hydrate (or clathrate). Methane hydrate is formed of water ice containing molecules of methane trapped in the crystal lattice of ice (Fig. 91). The methane originates from microbial activity occurring in deep-sea sediments. Methane hydrate is stable at relatively high pressure and low temperature and occurs between 200 and 400 m beneath the sea floor. Global warming could potentially destabilize methane hydrate, which would lead to a massive release of gaseous methane in the atmosphere. Release of methane in the atmosphere through ***permafrost thawing*** and/or ***destabilization of methane hydrate*** would intensify global warming. The resulting positive feedback loop may result in more methane released in the atmosphere causing a rapid and intense warming. Evidence suggests that such an event may have already happened in the geological past and even caused mass extinctions.

Figure 90: Distribution of permafrost in the northern hemisphere. Source: International Permafrost Association

Figure 91: Left : structure of methane (source : NASA). Middle and right : methane hydrate (sources: AP images and NASA).

V. Socioeconomic impacts

The socioeconomic impact of global warming will depend on the geographic area. Some regions will be more negatively affected than others. Some may even benefit from a moderate warming, e.g. wineries in the UK. However, scientists have defined a limit of global warming beyond which the impact would be negative for most people on Earth. That limit has been set to a 2°C increase above pre-industrial temperature.

Climate change may affect human societies through its impact on a broad range of domains:

- Freshwater resources (groundwater recharge influenced by droughts)
- Food security (crop yield directly influenced by climate)
- Coastal systems (sea level rise and storms increase the rate of coastal erosion and the risk of floods in coastal areas)
- Ecosystems (e.g. the decline of coral reef ecosystems affects people for whom coral reefs are a source of food and revenue from tourism)
- Human health (heatwaves, droughts, storms, floods and contagious diseases directly affect human health)

9.4. Strategies to deal with anthropogenic global climate change

One can think of several possible strategies to deal with climate change. One of them is simply adaptation, for example, protect coastal areas against floods or switch to other types of crops requiring less water. Another solution is to reduce the emission of greenhouse gases and try to mitigate the current global warming (mitigation strategy). The Kyoto Protocol was designed for this purpose. Although some significant effort has been made, countries with fast-growing economies like China or India release more CO_2 in the atmosphere every year (Fig. 92). Efforts are being made to devise cleaner sources of energy (see next chapter). Energy-saving plans can also be adopted, for example, by improving building insulation or increasing the energy efficiency of lighting devices (e.g. LED). In addition, economic strategies to cut CO_2 emissions have also been devised: carbon taxes and carbon trading. The former consists simply of a tax that has to be paid by industries producing CO_2. The latter consists of putting a price tag on CO_2 emissions so that a country that emits more is able to purchase the right to emit to a country that emits less. The goal is to force countries to respect their engagement in cutting CO_2 emissions.

Figure 92: Evolution of anthropogenic emission of CO_2 in Japan (A), China (B), Germany (C) and India (D). Source: Carbon Dioxide Information Analysis Center.

Another set of strategies are called geoengineering strategies. Geoengineering means interfering with natural processes on a large scale with the purpose of making the environment more favorable for human populations. An example of geoengineering technique is triggering precipitation by releasing in the atmosphere chemicals which promote the formation of rain droplets or ice particles (i.e. cloud seeding). Geoengineering actions have also been devised to slow down or halt the current global warming (Fig. 93). Geoengineering techniques can be classified into two categories:

- Controlling the amount of solar radiation absorbed by Earth's surface
- Actively removing carbon dioxide from the atmosphere.

Figure 93: Examples of geoengineering strategies. Note that if carried out on a planetary scale, reforestation and carbon sequestration can also be called geoengineering. Source: Keith (2001).

Some examples of geoengineering strategies are described below:

Reforestation

Sustainable management of existing forests and planting new trees are solutions which can slow the increase of atmospheric carbon dioxide based on the ability of plants to store carbon through photosynthesis. This solution also includes the potential use of genetically modified plants that could fix carbon with a greater efficiency.

Carbon dioxide capture and storage

Another solution consists in injecting the carbon dioxide produced by industries into underground geological reservoirs. This is called ***carbon sequestration*** or carbon dioxide capture and storage (Fig. 94).

Figure 94: Carbon sequestration. Source: IPCC 2005 report "Carbon Dioxide Capture and Storage".

Iron fertilization

Iron is essential for the growth of phytoplankton (photosynthetic microaglae) which is often naturally limited by the low abundance of this element in seawater. Hence, dumping iron in the ocean can boost primary production. More primary production means more carbon fixed by photosynthesis leading to a net removal of atmospheric CO_2.

Albedo modification

The release of aerosols (tiny droplets) in the upper atmosphere and the installation of giant mirrors in space are ideas put forward by some scientists as possible strategies to block part of the incoming sunlight and induce a global cooling which would oppose the current warming trend.