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Ministry of Higher Education and Scientific Research
Nour Bachir University Center
Institute of Technology
Department of Civil Engineering and Hydraulic

Course UEF 2.1.2

Title:

WATER RESOURCES AND CLIMATE CHANGE

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FOREWORD

This course handout on "Water Resources and Climate Change" has been designed as an educational support for second-year Master's students in Water Resources within the Hydraulic field. It is also of interest to learners seeking to acquire a solid theoretical foundation in this field.

Through four chapters, this handout aims to deepen the understanding of the challenges related to climate change and its impact on water resources, a crucial issue for our ecosystem and society. By closely examining various aspects of climate, greenhouse gases, and water management in a context of variability, this document provides insightful perspectives for researchers and anyone interested in the preservation of our environment.

We hope that this document will significantly contribute to raising awareness about the urgency of taking action against climate change and promoting sustainable solutions for the responsible management of our precious water resources.

OBJECTIVES

At the end of this course on water resources and climate change, students would be able to:

- Understand the concept of climate change and climate variability.
- Explain the causes of human-induced climate change and the consequences of climate change on water resources.
- Use knowledge on the general circulation of the atmosphere to understand climatic phenomena.
- Analyze the impacts of climate change on water cycles at various scales.
- Evaluate the proposed solutions to combat climate change.

CHAPTER I: UNDERSTANDING THE CLIMATE

I.1 Global Climate Change

I.1.1. Definition of Climate Change and Climate Variability

Climate change: changes that are directly or indirectly attributed to human activity that alters the composition of the global atmosphere and that add to the natural variability of the climate observed over comparable periods.

Climate Variability: An inherent characteristic of the climate that manifests as changes and deviations over time. The degree of climate variability can be described by the differences between long-term average values of climatic parameters (rainfall, temperature, humidity, length of seasons) and observed values taken at different temporal and spatial scales

The scientific history of the climate change phenomenon dates back to the 19th century and has gradually evolved over the years through new advances. In 1794, the discovery of the heat effects of solar radiation was followed by the identification of the greenhouse effect in 1824. In 1861, the identification of water vapor and carbon dioxide as greenhouse gases took place. Just in 1896, the Swedish chemist Svante Arrhenius established the quantified correlation between CO_2 concentration and atmospheric temperature. He observed that the amounts of carbon dioxide in the atmosphere increase with the increasing combustion of fossil fuels and formulated the hypothesis of global surface warming. According to Gemmene (2008), concerns about the extent of the phenomenon only emerged after a century, precisely during the sixties when the scientific community first raised alarms about anthropogenic climate change. Over the past decade, the entire scientific community, public policymakers, and the general population seem to have become aware of the environmental, economic, and health issues related to climate change.

There is, however, confusion regarding the exact definition of the term climate change. Since the establishment of the IPCC (Intergovernmental Panel on Climate Change) in 1988, climate change has been understood to mean any evolution of climate over time, whether due to natural variability or human activities. The Earth Summit and the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 define climate change as any alteration of climate directly or indirectly caused by human activities that alter the composition of the atmosphere and add to observed natural climate variability over comparable time periods. This definition differs significantly from that of the IPCC (IPCC, 2007a).

The causes of this change can be natural, resulting from natural external forcing (solar activity, volcanism, etc.), or anthropogenic (greenhouse gases, aerosols, etc.). Attributing the observed change to anthropogenic sources involves demonstrating that the detected change is consistent with a specific combination of natural and anthropogenic forcings and is not consistent with physically plausible alternative explanations.

The concept of climate change attribution requires specific scientific evidence on the role of climate change. This notion sparked a debate among scientists during the IPCC report in 2014, where each group of scientists attributed a different definition to this concept. Group (1) focuses on quantifying the connections between observed climate changes and human activity, as well as other external factors influencing the climate. On the other hand, Group (2) examines the links between the impacts on natural and human systems and the observed changes in climate conditions, regardless of their causes.

Richard (2013) highlighted that debates particularly centered around attributing anthropogenic responsibility for climate change, marked by attempts to refute the IPCC's findings by climate skeptics. Significant research efforts on methods for detecting and attributing climate change demonstrate human influence on the climate, as exemplified by ongoing studies.

Stott et al. (2001) observed that the temperature increase in the latter half of the century was caused by anthropogenic warming, with greenhouse gases likely contributing significantly to warming in the first half of the century.

Karoly et al. (2003) studied climate changes in North America during the 20th century, using large-scale surface temperature variation models. Their comparison of temperature trends in observations and model simulations indicated that North American temperature changes from 1950 to 1999 were unlikely to be solely due to natural climate variability but aligned with simulations including anthropogenic forcing from increased greenhouse gases and sulfate aerosols.

Brohan et al. (2006) confirmed that the temperature increase during the 20th century was significantly greater than their uncertainties.

Loehle and Scafetta (2011) employed empirical data decomposition to study climate change attributions, revealing an approximately linear warming trend of about 0.66°C per century from 1942 to 2010. They concluded that this warming was primarily induced by anthropogenic emissions, urbanization, and land use changes.

The term "climate change" is defined in various ways depending on the perceived causes of the phenomenon, despite the affirmed anthropogenic responsibility.

I.1.2. The current climate warming

The current climate warming is unmistakable, with a global increase in average atmospheric and ocean temperatures, significant melting of snow and ice, and a rise in the average sea level (IPCC, 2007). This finding is highlighted in the IPCC's Fourth Assessment Report on observed climate changes and their impacts, which provides valuable information to stakeholders, particularly decision-makers. Notably,

1. "eleven of the twelve warmest years on record (1995–2006) have occurred since 1850, when instrumental temperature records began" ((Figure. I.1).

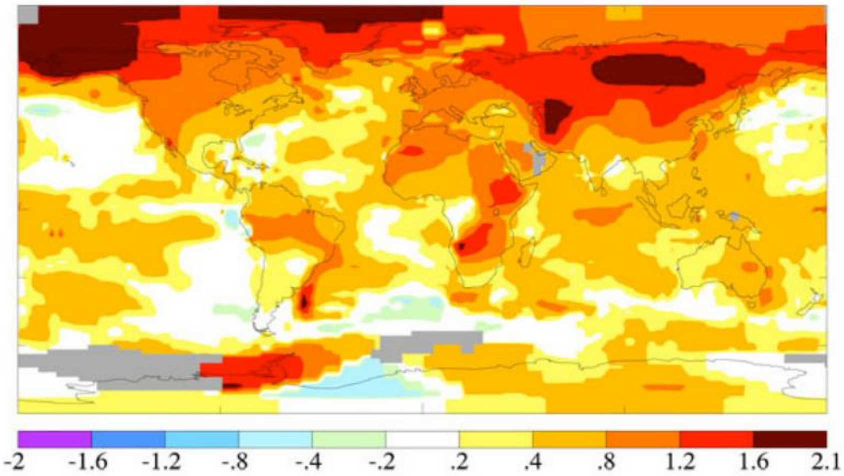


Figure I.1: Temperature Variations between 2001 and 2005 compared to the average of 1900-1955.

2. *"The rise in sea level aligns with the warming trend. Globally, the average sea level has increased by 1.8 mm/year since 1961 and by 3.1 mm/year since 1993"* ((Figure. I.2).

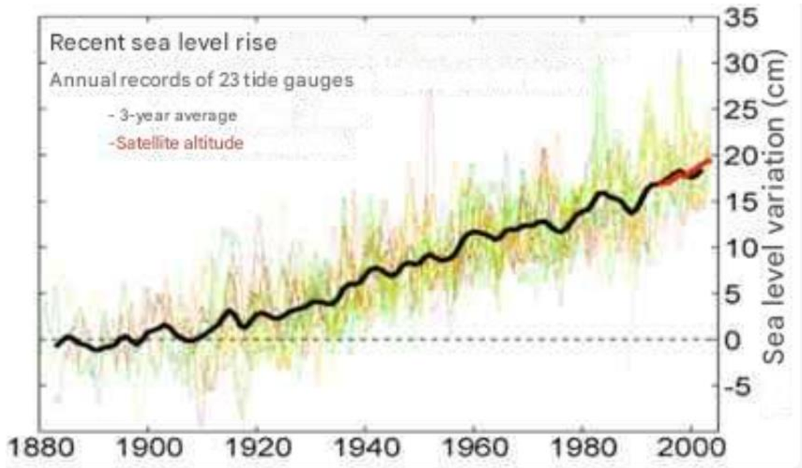


Figure I.2: Sea Level Variation compared to the average of the year 1900.

3. *'The observed decrease in the extent of snow and ice-covered areas also aligns with warming'* (Figure 1.3)

Figure I.3 on the right: a photo of the surface of the Greenland ice sheet in summer. In some areas, actual lakes form, sometimes connected by a network of streams (or "moulins"); **on the left:** a glacial river generated by the surface melting of the ice sheet; the water flowing into a "moulin" inside the ice sheet travels through subglacial and intra-glacial galleries, flowing towards lower areas of the glacier front. This process helps "lubricate" the movement of the ice over the bedrock and accelerates the iceberg calving process (http://www.jeanlouisetienne.fr).

4. *"Between 1900 and 2005, precipitation has significantly increased in the eastern parts of North and South America, northern Europe, and northern and central Asia, while decreasing in the Sahel, Mediterranean region, southern Africa, and parts of South Asia*" ((Figure. I.4 and (Figure. I.5).

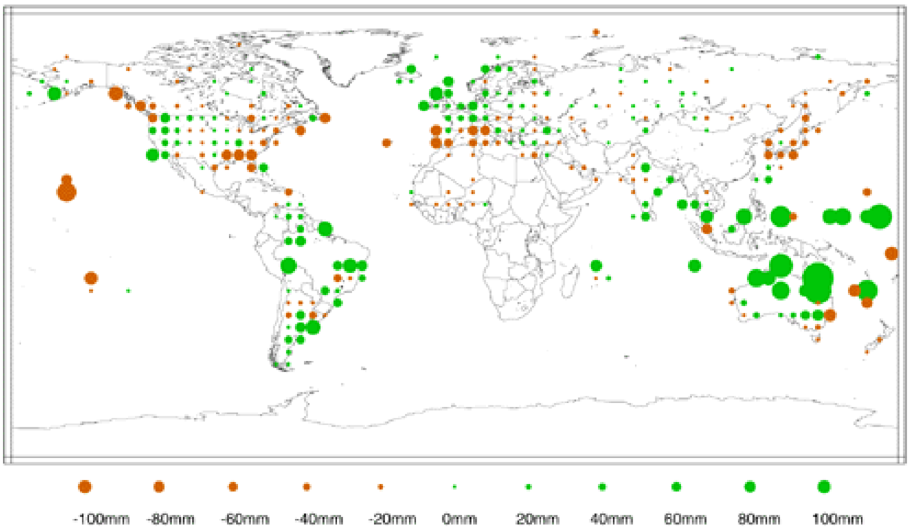


Figure 1.4 : Precipitation Anomalies (February 2000). (Relative to a base period of 1961-1990).

Source: National Climatic Data Center/NESDIS/NOAA.

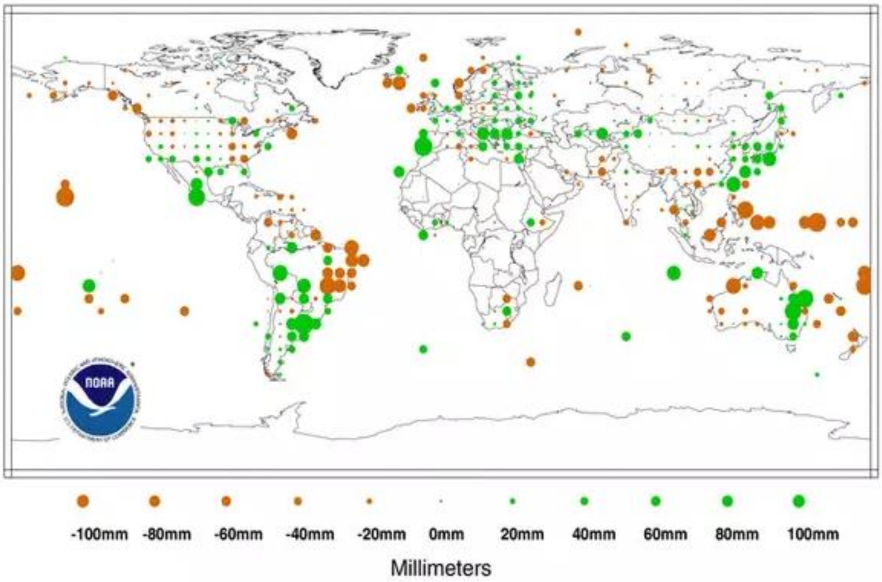


Figure I.5: Precipitation Anomalies (February 2010) relative to a base period of 1961-1990. Source: National Climatic Data Center/NESDIS/NOAA.

5. *"It is highly likely that cold days, cold nights, and frost have become less frequent over most land areas in the past fifty years, while the number of hot days and warm nights has, conversely, increased".*
6. *Observations indicate an increase in intense cyclonic activity in the North Atlantic since around 1970* ((Figure. I.6).

Figure I.6: Intense cyclonic activity in the Northern Hemisphere. Source: NASA.

I.1.3. Greenhouse Gases (GHGs)

The robust elements regarding the causes of climate change are the emissions of greenhouse gases (GHGs) and radiative forcing. The Fourth IPCC report notes : "*with very high confidence that human activities since 1750 have had a net warming effect on the climate and that global GHG emissions from human activities have increased by 70% between 1970 and 2004*" (IPCC, 2007).

Human activities result in emissions of four long-lived GHGs: CO_2, methane (CH_4), nitrous oxide (NO_2), and halogenated hydrocarbons. Atmospheric concentrations of GHGs have significantly increased due to human activities since 1750. The rise in global carbon dioxide concentrations is primarily attributed to the development of the industrial era, which began in the 19th century. In 2005, atmospheric concentrations of CO_2 (379 ppm) and CH_4 (1,774 ppb) far exceeded the natural variability range of the past 650,000 years (IPCC, 2007). This increase is mainly due to the use of fossil fuels. Kandel (2002) describes how the combustion of fossil fuels releases significant amounts of carbon into the atmosphere, disrupting natural carbon sinks, with only about half of the CO_2 emissions from fossil fuel combustion being compensated by carbon sinks like photosynthesis and the oceans. The observed increase in methane concentration is likely primarily from agriculture and fossil fuel use, while the rise in N_2O concentration mainly stems from agriculture.

The impact of GES on the warming of the planet's climate system (radiative forcing) varies based on the radiative properties of these gases and their atmospheric lifetimes. Radiative forcing is used to compare the influence of factors that warm or cool the planet's climate and to understand the impact of human activities on the climate.

With a very high level of confidence, climate change has been caused by human activities. The cumulative radiative forcing resulting from the increased concentrations of CO_2, CH_4, and N_2O is +2.3 [+2.1 to +2.5] W/m2 (IPCC, 2007). An increase of 20% in radiative forcing from carbon dioxide between 1995 and 2005 represents the most significant change in a decade for at least the past 200 years ((Figure. I.7).

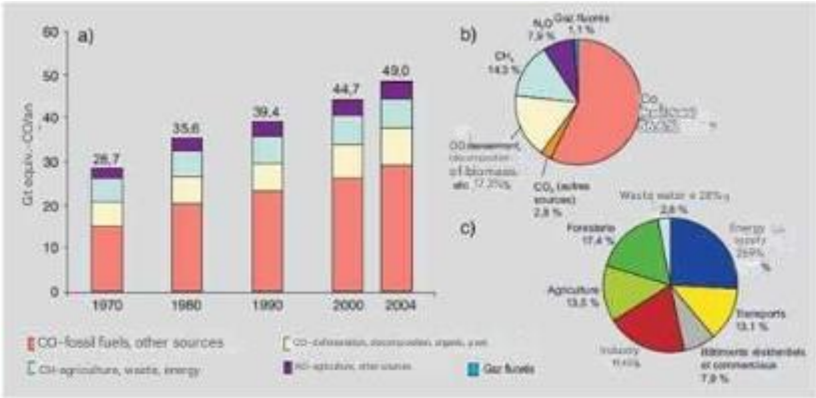


Figure I.7: a) Annual anthropogenic greenhouse gas emissions worldwide, 1970–2004 ; b) Respective shares of different anthropogenic greenhouse gases in total emissions in 2004, in CO_2 equivalent; c) Contribution of different sectors to total anthropogenic greenhouse gas emissions in 2004, in CO_2 equivalent. Source: IPCC, 2007.

I.2 The elements of climate:

I.2.1 Solar Radiation

radiation is characterized by the duration of sunshine and the intensity of global radiation. The duration of sunshine on a given day depends on the latitude of the measurement location and the day of the year. It can be reduced by topography, cloudiness, haze, fog, dense smoke, etc.

I.2.2 Cloudiness

Throughout the day, when in contact with a cloud mass, solar radiation (S) is divided into reflected radiation (R), diffuse radiation (D), and absorbed radiation (A), meaning only a portion of the solar energy reaches the Earth's surface. Thus, during the day, a cloudy sky reduces the warming of the Earth's surface ((Figure. I.8).

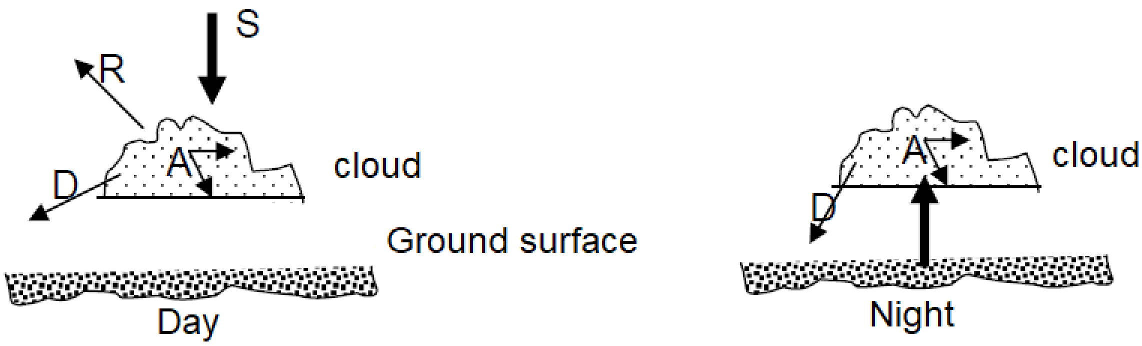


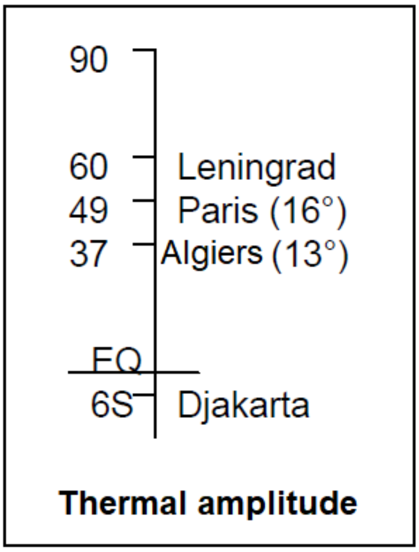
Figure 1.8: Cloudiness process

Throughout the night, a cloudy sky reduces the loss of energy from the Earth through infrared radiation, thus decreasing the cooling of the Earth.

I.2.3 Air Temperature

The usual air temperature is the temperature of the air measured in the shade, within a meteorological shelter, at an altitude of 1.5m. The choice of this altitude is due to the fact that the air warms up in direct contact with the ground. Thus, the air temperature is highest near the ground; it weakens with altitude, showing a strong gradient close to the surface. This gradient becomes negligible at around 1.5m. In the lowest layers of air above the ground, the soil temperature is higher than that of the air during the day and lower during the night.

Notes:



- If the temperature measurement (T) is taken in the sun, there is a risk of measuring the temperature of the thermometer material.
- Tmin occurs around sunrise (or shortly after sunrise [half an hour]).
- Tmax occurs two hours after noon (solar noon).
- The sheltered air temperature does not closely correspond to the heat (or cold) sensations felt by living beings (e.g., humans). This sensation is indeed related to temperature but also to humidity, wind, etc. (i.e., comfort index).
- Numerous factors influence the diurnal variation in temperature; these include cloudiness, altitude, and latitude.

- The season, the nature of the soil, the relief with all its characteristics (shape, exposure, orientation), the degree of continentality, the state of the atmosphere.
- The annual temperature range increases with latitude.

I.2.4 Precipitation

Precipitation, along with temperature, constitutes the most important elements that define the climate of a given location. It has a significant influence on the lives of humans and animals as well as on the economies of countries. According to some authors, the annual cumulative precipitation alone can classify climates as follows:

- Desert climate: RR < 120 mm
- Arid climate: 120 mm < RR < 250 mm

- Semi-arid climate: 250 mm < RR < 500 mm
- Moderately humid climate: 500 mm < RR < 1000 mm
- Humid climate: 1000 mm < RR < 2000 mm
- Extremely humid climate: RR > 2000 mm

However, precipitation is characterized not only by its quantity but also by: its physical nature (rain, snow, hail, sleet), its frequency (once a year or 100 times a year), its duration (ten minutes or 24 hours), its intensity (10 mm/hour or 100 mm/hour), and its distribution in time (e.g., successive days) and space (local or synoptic scale!). This set of characteristics influences soil absorption, drainage, river flooding, agricultural utility, human safety, etc.

- Quantities of precipitation increase as one approaches the sea (at the same latitude).
- They increase with altitude: precipitation maps coincide with hypsometric maps (altitude maps).
- In terms of relief, the "windward" slopes are wetter than the "leeward" slopes (for fairly steep slopes, of course, for winds bringing moist air).
- The distribution of precipitation across the globe is characterized by:
    - Between 20°S and 20°N: heavy precipitation (1500 mm - 3000 mm)
    - Between 20° and 30° latitude: dry zones (< 200 mm) with some rainy regions.
    - Between 30° and 40° latitude: between 400 and 800 mm
    - At high latitudes > 70°: low precipitation (< 200 mm)

I.2.5 Evaporation

Evaporation pertains to both precipitation that reaches the ground and water contained in the soil. It plays a biological role as it influences respiration and transpiration. It is related to various factors such as temperature (with the same direction of change), relative humidity, pressure, air movement (wind, turbulence), the shape and size of the evaporation surface, and the thickness of the water layer.

Evaporation can be estimated based on wind speed, solar radiation, water vapor tension, etc.

- Evaporation increases if the air is less humid and more turbulent.
- Evaporation causes the formation of fog and clouds.

I.2.6 Air Humidity

It is expressed by the water vapor tension (e) and relative humidity (U: expressed as a percentage [hygrometric degree]). The variation of U and e over time and space is very complex, but generally:

- e and U have a zonal distribution.
- e = 20 mm of mercury in equatorial zones; e < 5 mm in polar zones.
- U is around 85% in equatorial zones, very low in subtropical regions (notably in continental zones), and high in mid-latitudes, depending on the season.

I.2.7 Atmospheric Pressure

Pressure is the weight of the column of air that acts on a unit area. Its temporal variation is related to that of temperature, and its gradient generates wind (force and direction).

I.2.8 Wind

Wind results from the pressure difference between two neighboring areas. It causes the movement of air masses and thus carries climatic characteristics. For example, the Indian monsoons can be of two types: wet and rainy monsoons where air moves from the ocean to the continent, and dry monsoons where air circulates from the continent to the ocean.

- A strong wind, in contact with the surface of water or the human body, promotes the phenomenon of evaporation (kinetic energy is lost as heat).

I.2.9 Air Transparency (or horizontal visibility)

It changes according to air humidity, purity, and stability. Thus, a decrease in visibility is caused by the absorption and diffusion of light (by atmospheric

I.3 Climate Change: A Current Observation.

The World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The IPCC's mission is to: "*assess, without bias and in a systematic, clear, and objective manner, the scientific, technical, and socio-economic information needed to better understand the risks associated with human-induced climate warming, more precisely identify the potential consequences of this change, and consider potential adaptation and mitigation strategies. The assessments are primarily based on scientifically and technically recognized publications*."

Several methodological reports, special reports, technical support documents, and five assessment reports (1990, 1995, 2001, 2007, and 2014) have been published by the Intergovernmental Panel on Climate Change (IPCC) since the 1990s, becoming globally recognized reference works. The dissemination of the synthesis report of the fifth IPCC report (IPCC, 2014) took place on November 2, 2014, in Copenhagen, Denmark. This report comprises the summary of the conclusions from the contributions of the three working groups. This new comprehensive assessment is the result of a massive knowledge-sharing effort, involving the review of 30,000 studies and 800 lead authors.

The reports together form the most comprehensive assessment of climate change ever undertaken by the IPCC, including:

1. Two special reports titled Renewable Energy Sources and Climate Change Mitigation (2011) and Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2011).
2. September 2013, Climate Change: The Physical Science Basis.
3. March 2014, Climate Change: Impacts, Adaptation, and Vulnerability.
4. April 2014, Climate Change: Mitigation of Climate Change.

1. It is assessed with 95% certainty that human activities are the primary cause of current global warming.
2. The warming of the climate system is unequivocal, with many observed changes since the 1950s being unprecedented for decades or even millennia. Atmosphere and ocean warming, reduced snow and ice cover, and rising sea levels have been observed.
3. Greenhouse gas concentration measurements over 800,000 years show the largest increase in the past decade.
4. Climate changes in recent decades, regardless of their causes, have impacted all oceans and natural and human systems on all continents, demonstrating their sensitivity to climate change.
5. Changes since around 1950 have been observed in many extreme weather and climate events. Some of these changes have been linked to human activities, such as reduced cold extremes, increased heat extremes, higher sea levels, and more intense precipitation events in various regions.

Following the alarming findings, members of the IPCC issued warnings about the urgent. "*need to take action to prevent exceeding a 2°C temperature increase"*. Mr. Rajendra Kumar Pachauri, the IPCC Chairman, emphasized the limited time available to stay below this threshold.

Renowned climatologist Jean Jouzel echoed the urgency, stating that : "*at 4°C, all indicators are critical, while at 2°C, there are better chances for adaptation*".

To avoid the status quo scenario, significant reductions in greenhouse gas emissions of 40 to 70% between 2010 and 2050 are crucial to stabilize temperature increase below 2°C compared to pre-industrial levels. The scientific conclusions of the IPCC's Fifth Assessment Report served as a catalyst for policymakers during the twentieth session of the Conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC) in Paris in 2015. The report underscored the pressing need for action and the severe risks of inaction, making ignorance an unacceptable excuse for lack of intervention.

The Paris Climate Conference (COP 21) held in Paris from November 30 to December 11, 2015, marked a significant milestone in the fight against climate change. The conference concluded with the adoption of the Paris Agreement by consensus, aiming to limit temperature increase well below 2°C and striving to restrict it to 1.5°C. The agreement calls for peaking greenhouse gas emissions as soon as possible and achieving carbon neutrality in the second half of the century.

The Paris Agreement outlines key provisions for global climate action, requiring countries to update their national contributions every five years with increasingly ambitious targets. A collective assessment will occur every five years to review countries' commitments, with the first assessment scheduled for 2023. Prior to this, a meeting in 2018 will assess progress made by the states.

Regarding funding, the agreement mandates developed countries to provide and mobilize increasing financial support, recognizing the importance of public funds in climate financing. The accompanying decision extends the commitment of $100 billion annually until 2025, serving as a foundation for more ambitious financial targets. The need to rebalance funding, particularly for adaptation, is emphasized, with developing countries having the option to voluntarily contribute to assist the poorest nations.

To ensure transparency and effectiveness, a strengthened framework is established to build trust among countries and verify the agreement's efficiency. This framework applies to all countries, considering their individual capacities. Additionally, a mechanism for monitoring the agreement's implementation and compliance is set up, with procedural rules to be defined for implementation by 2020.

I.3.1 Climate and Water Cycle

The water cycle is a crucial component of the climate system, driven by the sun's heat that leads to the evaporation of water from the Earth's surfaces into the atmosphere. This water vapor moves, driven by winds, and eventually condenses to form clouds, resulting in precipitation in the form of liquid or solid water that returns to the surface. Some of the continental precipitation may be temporarily stored as snow and moisture in soils. The excess water that is not evaporated flows into lakes and rivers, eventually returning to the oceans, completing the cycle (Figure 1.9).

In the atmosphere, water has a residence time of about ten days, indicating rapid turnover. This rapid renewal of atmospheric water explains why water vapor is considered a feedback mechanism rather than a forcing agent for climate change. Groundwater, on the other hand, takes an average of 1500 years to reach the oceans, highlighting the significant time scales involved in the movement of subsurface water resources (de Marsily, 2009).

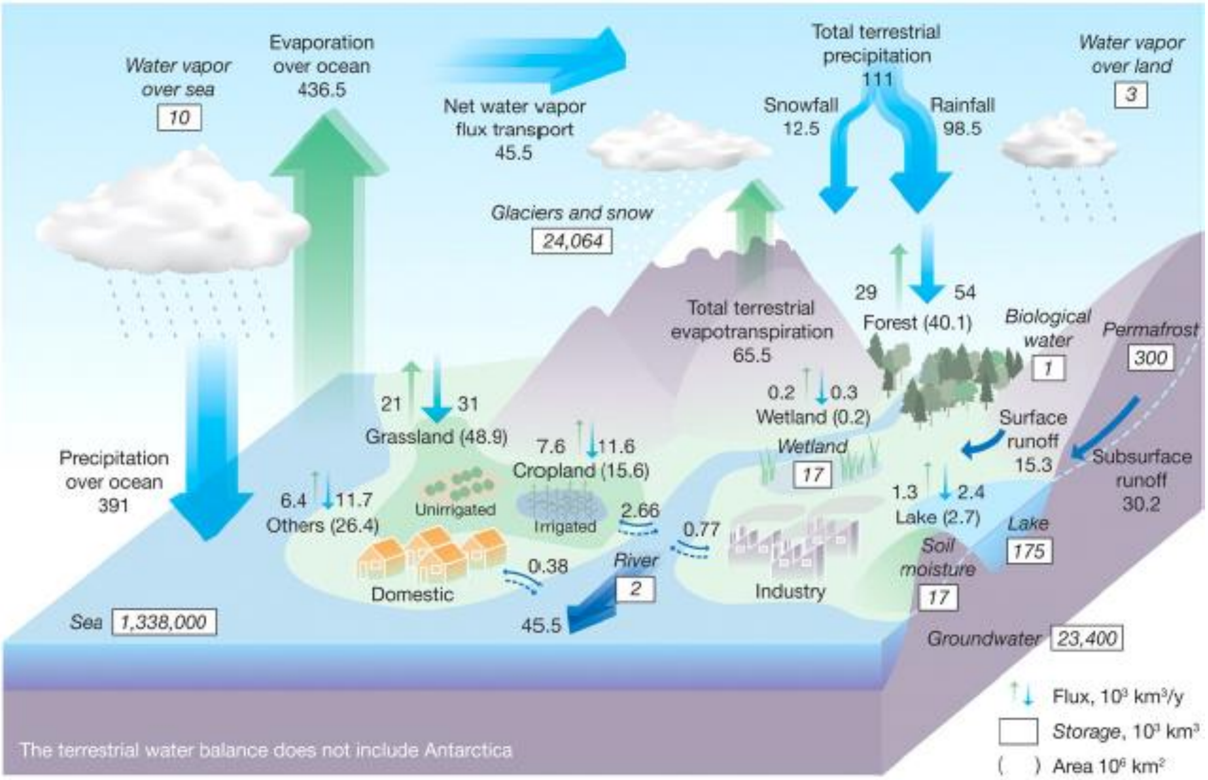


Figure 1.9: Global Terrestrial Hydrological Cycle depicting the size of each reservoir (in a box in 1000 km3) and the fluxes between these reservoirs (in 1000 km3.year-1). **Source:** Oki and Kanae (2006)

The hydrogen bonds between water molecules, created by the dipolar structure; result in a high heat capacity of water, allowing it to absorb a significant amount of heat with only a slight increase in temperature. During evaporation, the high latent heat of water enables it to absorb a large amount of energy at one point, releasing it elsewhere during condensation. Atmospheric water plays a crucial role in the radiative balance, being the most dominant greenhouse gas. Clouds formed by water vapor condensation contribute to the greenhouse effect, playing a significant and complex role in the climate system.

All climatic variables (such as wind, humidity, clouds, precipitation, snow cover) are altered when surface temperature changes. Bony and Dufresne (2007) defined the feedback loop: it involves changes in the energy balance at the top of the atmosphere due to certain climatic variations, leading to a subsequent change in the surface equilibrium temperature. If the loop amplifies the initial temperature increase, it is considered a positive feedback loop, while it is negative if it mitigates the initial increase.

The main climate feedback loops are as follows:

1. Water vapor feedback: Temperature increase raises atmospheric water vapor content, enhancing the greenhouse effect and surface temperature.
2. Cloud feedback: Clouds' optical properties, altitude, and location can lead to either warming or cooling effects. Changes in water vapor and atmospheric circulation alter cloud cover, radiative properties, solar radiation reflection, and contribution to the greenhouse effect.
3. Surface albedo feedback: Surface temperature rise can change Earth's radiative properties (due to faster melting of snow or sea ice), resulting in reduced albedo, increased solar radiation absorption, and ultimately warming.

In preparation for the 4th IPCC report, projects like the Climate Model Evaluation Project (CMEP) or the Cloud Feedback Model Intercomparison Project (CFMIP) have been launched for model intercomparison. These projects have, for the first time, quantified climate feedbacks in a large number of models and developed new analysis and evaluation methodologies (Bony et al., 2004; Forster and Collins, 2004; Bony et al., 2006; Hall and Qu, 2006; Webb et al., 2006; Winton, 2006; Williams et al., 2006). These studies have contributed to understanding the differences in climate sensitivity among models and evaluating key components in feedbacks (Bony and Dufresne, 2007).

I.4 General Circulation of the Atmosphere

I.4.1 Origin of Atmospheric Movements

- In the "Radiation" slideshow, it was discovered that solar energy arriving at the top of the atmosphere is not evenly distributed from the poles to the equator. The red curve below indicates, for each latitude, the average power received in watts per square meter.
- The blue curve shows the power absorbed by the entire Earth/atmosphere system: the difference from the red curve corresponds to the power that is reflected back into space (reflection, backscattering).
- The green curve corresponds to the power reemitted by the Earth/atmosphere system in the infrared spectrum.At latitudes higher than 30°, the green curve is above the blue curve: more energy is lost through radiation than is absorbed. Below 30° (in the intertropical zone), the opposite is true ((Figure. I.10).

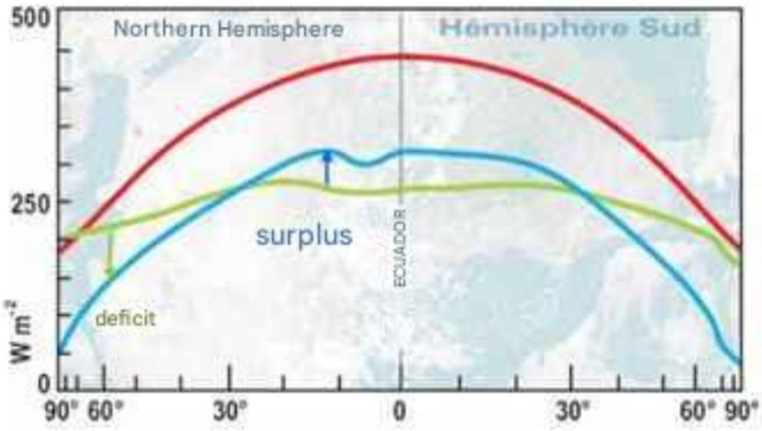


Figure I.10: Powers absorbed by the entire Earth/atmosphere system

I.4.2 Energy transport towards the poles.

- If, at each latitude in the Northern Hemisphere, we calculate the radiative balance of regions further north and south (energy deficit or surplus), we can determine the energy transport required at that latitude to balance the system (red curve below).
- At 30°N, the energy transport is most significant because the difference between the deficit in regions further north and the surplus in regions further south is maximal!
  The contribution of the atmosphere to this energy transport is known (below the blue curve), allowing for the estimation of the ocean's contribution (between the red and blue curves) ((Figure. I.11).

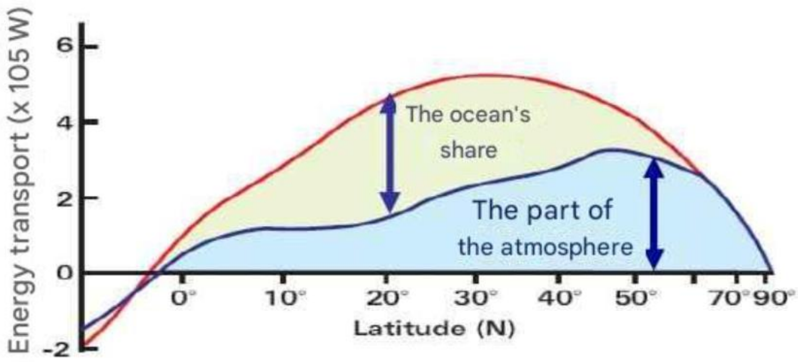


Figure I.11: Energy transport towards the poles

I.4.3 The Hadley cell: introduction

- The British scientist George Hadley, in 1735, envisioned the major atmospheric movements that facilitate this energy transfer:

In the equatorial zone, the warm air near the surface rises (as it becomes less dense): ascent.

- Once in the upper atmosphere, it would circulate towards the pole of each hemisphere, where it would descend: subsidence.

- In return, cold air would move from the pole towards the equator at low altitudes.

Hadley thus conceived a "loop" (a convection cell) for each hemisphere ((Figure. I.12).

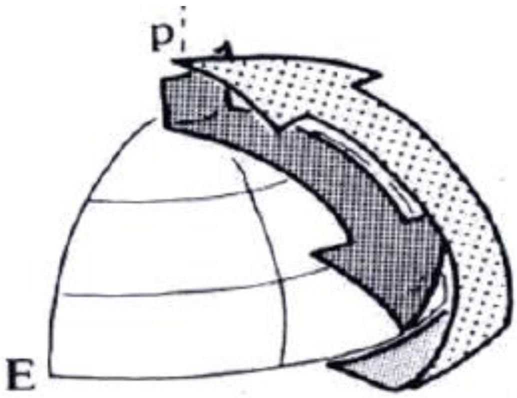


Figure I.12: Circulate of air in the upper atmosphere

Source : Joly (1992)

I.4.4 Influence of the Coriolis Force

- However, Hadley overlooked the Coriolis force. This force is an inertial force: it is not caused by material interactions but by Earth's rotation, the frame of reference in which we study atmospheric movements. This fictitious force is what prevents you from walking straight on a rotating carousel...
- This "force" applies to any moving object, hence to any air particle. Its magnitude (in the horizontal plane of the location) is proportional to the speed v of the particle and the sine of the angle φ between the meridian of the location and the Earth's rotation vector (vector ωT carried by the Earth's rotation axis). Its direction is indicated by the outstretched right arm of an observer looking in the direction of motion.
- Remember: movements are deflected to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere!
- Note that the angle φ is none other than the latitude! This means that the Coriolis force is zero at the equator and increases towards higher latitudes ((Figure. I.13).

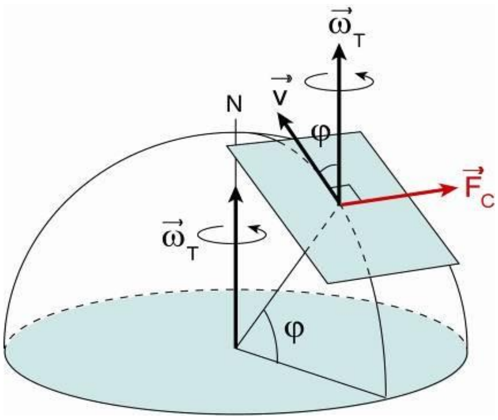


Figure I.13: Influence of the Coriolis Force

- When an air particle moves from the equator towards the North, its initial latitude is 0°. As previously mentioned, the Coriolis force is then zero (this can be intuitively understood: in this tangent plane at the equator, you neither get closer nor farther from the axis of rotation).
- As we move away from the equator and the latitude increases, the intensity of the Coriolis force grows, and the velocity vector is gradually deflected to the right. Consequently, the trajectory of the air particle is deflected towards the East.
- When the air mass reaches the latitude of 30°, the intensity of the Coriolis force becomes significant enough to halt the northward movement of the air. The return circulation of air in the lower layers begins at this latitude. A similar cell is observed in the Southern Hemisphere ((Figure. I.14).

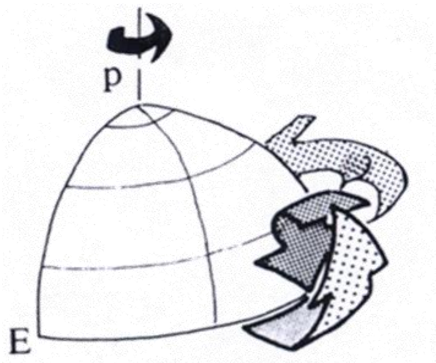
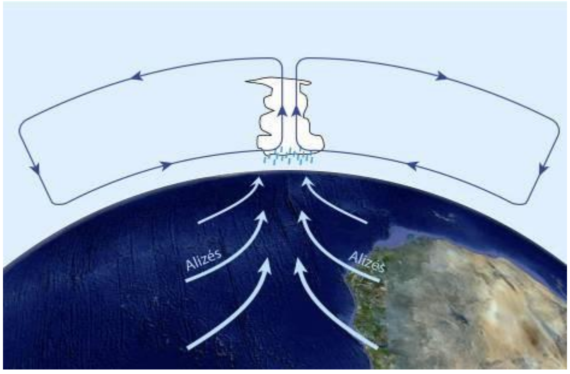


Figure I.14: The intensity of the Coriolis at the latitude of 30°,

I.4.5 The Hadley cells

- In a meridional cross-sectional view of the atmosphere, we have, on either side of the equatorial zone, two "loops," the Hadley cells, which transport energy in the form of heat from the equator towards the 30° latitudes.

- In a top-down view, for the Northern Hemisphere, the eastward deflection of the upper-level branch (red) and the westward deflection of the surface branch (blue) are depicted, corresponding to the regular winds known as trade winds (in both hemispheres, they are east winds, but Coriolis deflects them to their right in the Northern Hemisphere and to their left in the Southern Hemisphere) ((Figure. I.15).



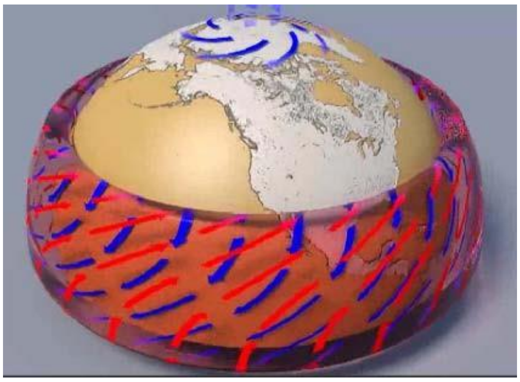


Figure I.15: top-down view, in both hemispheres

- At the equator, the air near the surface is heated by the infrared radiation from the surface and rises due to its lower density (similar to a hot air balloon principle). This air is humid because there are mainly humid forests and oceans near the equator. Additionally, warmer air can hold more water vapor (similar to a hairdryer principle).
- As the air rises, it expands and cools (refer to the "Atmosphere" sheet), reaching its dew point (saturation threshold for water): liquid water condenses. This explains the belt of large convective clouds (cumulonimbus, see "Clouds" sheet) and the intensity of rainfall in the equatorial zone.
- Evaporation absorbs heat, while condensation releases it. This process transfers more heat to the air, promoting ascent ((Figure. I.16).
- When the air begins its journey at higher altitudes towards the higher latitudes, it has lost much of its moisture (cold air can hold very little water): it becomes very dry and "potentially warm" air reaching the 30° latitudes. As it descends, it warms as its pressure increases (adiabatic warming), but its water content remains unchanged. This explains the presence of desert areas at these subtropical latitudes

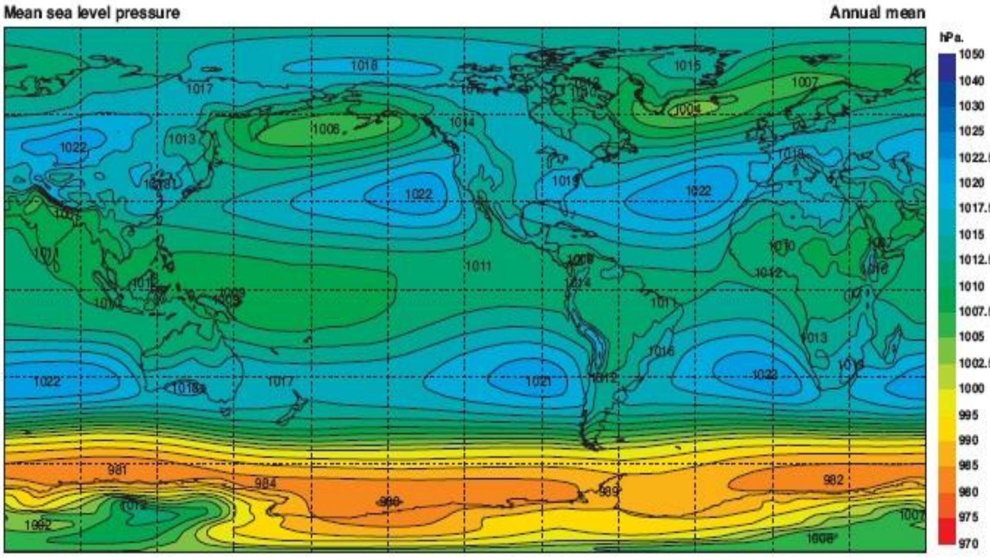


Figure I.16: Average annual sea-level pressure field

- The figure above depicts the average annual sea-level pressure field (averaged over 45 years). High-pressure zones (tropical anticyclones) are clearly visible, corresponding to the descending branch of the Hadley cells, and a less pronounced equatorial low-pressure zone corresponding to the ascending branch (where air is "drawn in"). Surface air flows from high pressure to low pressure, in the form of trade winds.
- Also noteworthy are the very low pressures in the Antarctic polar circle (ascending branch of the polar cell), much more pronounced than those in the Arctic.
- The subtropical subsidence zones, between 30° and 35° N and S, were referred to as the "horse latitudes" by the English. In these high-pressure zones, the winds are generally weak and variable. It is a calm area before encountering the trade winds further south. Legend has it that horses were sometimes thrown overboard to lighten the becalmed ships, hence the name.
- The trade winds, in English, are named "trade winds" because they facilitated transatlantic trade by providing a route southward to America. The return to Europe took advantage of the westerly winds further north.
- The zone where the trade winds converge, only a few hundred kilometers wide, is called the Intertropical Convergence Zone (ITCZ). It was called the "doldrums" by sailors because horizontal winds are weak and erratic (with mostly upward air movements), frequent thunderstorms occur, and ships often get becalmed. On average, it is located around the equator, but it shifts back and forth throughout the

year depending on maximum insolation. These variations play a role in the monsoon phenomenon ((Figure. I.17).

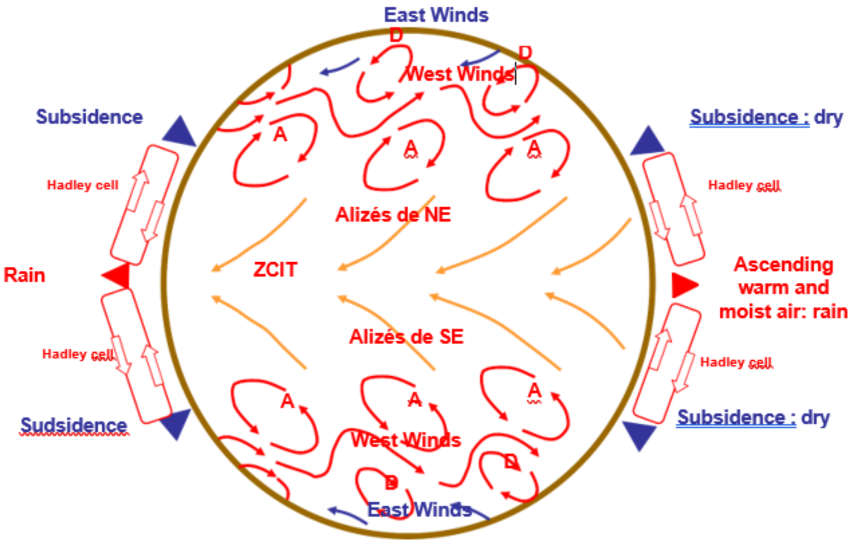


Figure I.17: Diagram of the general circulation

- Beyond 30° of latitude, regions of the globe are characterized by alternating areas of low pressure (depressions) and high pressure (anticyclones).
- The transfer of energy towards higher latitudes occurs there not through a meridional convection cell, but through disturbances associated with depressions, which mix tropical warm air with polar cold air.

I.5 Köppen-Geiger Climate Classification Category Descriptions

There are five major types of climate classification: **Equatorial**, **Arid**, **Warm Temperate**, **Snow**, and **Polar**. Each type can then be further classified by precipitation and temperature conditions. This results in 31 different climate classifications ((Figure. I.18). Here we provide a general description of each, color coded to the legend below and the Köppen-Geiger Climate Classification Google Earth kml file.

I.5.1 Equatorial rainforest, fully humid (Af)

A climate which sees all twelve months with very warm temperatures and a lot of rainfall.

I.5.2 Equatorial monsoon (Am)

Area characterized by all twelve months having a mean temperature of greater than or equal to 18°C and a mean annual accumulated precipitation greater than or equal to 25*(100-P_{min}) where P_{min} is the month with the least amount of precipitation, in mm.

I.5.3 Equatorial savannah with dry summer (As)

Area characterized by all twelve months having a mean temperature greater than or equal to 18°C and a summer month with precipitation less than 60 mm.

I.5.4 Equatorial savannah with dry winter (Aw)

Area characterized by all twelve months having a mean temperature greater than or equal to 18°C and a winter month with precipitation less than 60 mm.

I.5.5 Arid desert cold (BWk)

A climate whose mean annual temperature is less than 18°C and is too dry to support most plants.

I.5.6 Arid desert hot (BWh)

A climate whose mean annual temperature is greater than or equal to 18°C and is too dry to support most plants.

I.5.7 Arid Steppe cold (BSk)

A climate whose mean annual temperature is less than 18°C and is too dry to support a forest, but not dry enough to be a desert, usually consisting of grassland plains.

I.5.8 Arid Steppe hot (BSh)

A climate whose mean annual temperature is greater than or equal to 18°C and is too dry to support a forest, but not dry enough to be a desert, usually consisting of grassland plains.

I.5.9 Warm temperate fully humid with hot summer (Cfa)

A climate where the coldest month is warmer than -3°C but colder than +18°C and precipitation is generally the same throughout the year**.** This climate is usually found inland in the interior of continents or on their east coast, usually between 25° and 35° latitude.

I.5.10 Warm temperate fully humid with warm summer (Cfb)

A climate where the coldest month is warmer than -3°C but colder than +18°C and precipitation is generally the same throughout the year. This climate is usually found inland in the interior of continents or on their east coast, usually between 35° and 45° latitude.

I.5.11 Warm temperate fully humid with cool summer (Cfc)

A climate where the coldest month is warmer than -3°C but colder than +18°C and precipitation is generally the same throughout the year. This climate is usually found inland in the interior of continents or on their east coast, usually between 45° and 55° latitude, but may extend to 65° latitude.

I.5.12 Warm temperate with dry, hot summer (Csa)

A climate where the coldest month is warmer than -3°C but colder than +18°C and summers are dry and hot. This climate is usually found inland on western sides of continents.

I.5.13 Warm temperate with dry, warm summer (Csb)

A climate where the coldest month is warmer than -3°C but colder than +18°C and summers are dry and mild. This climate is usually found closer to the coast on western sides of continents.

I.5.14 Warm temperate with dry, cool summer (Csc)

A climate where the coldest month is warmer than -3°C but colder than +18°C and summers are dry and cool. This climate is usually found on the western coast of continents, where they are influenced by cold ocean currents.

I.5.15 Warm temperate with dry winter and hot summer (Cwa)

A climate where the coldest month is warmer than -3°C but colder than +18°C and dry winters. This climate is also characterized by hot, humid summers and is usually found on the interiors of continents or on their east coast.

I.5.16 Warm temperate with dry winter and warm summer (Cwb)

A climate where the coldest month is warmer than -3°C but colder than +18°C and a noticeable difference between the dry winters and rainy summers. This climate is usually found in the highlands of some tropical countries.

I.5.17 Warm temperate with dry winter and cool summer (Cwc)

A climate where the coldest month is warmer than -3°C but colder than +18°C and a noticeable difference between the dry winters and rainy summers. This climate is usually found in the highest altitudes of some tropical countries.

I.5.18 Snow with fully humid hot summer (Dfa)

A climate where there is at least one month colder than -3°C and precipitation is generally the same throughout the year, and summers can get very hot. This climate is usually found between 35° and 45° latitude.

I.5.19 Snow fully humid warm summer (Dfb)

A climate where there is at least one month colder than -3°C and precipitation is generally the same throughout the year. This climate is usually found between 45° and 55° latitude, but may extend up to 60° latitude.

I.5.20 Snow fully humid cool summer (Dfc)

A climate where there is at least one month colder than -3°C and precipitation is generally the same throughout the year. This climate is found even further toward the poles, usually found between 45° and 55° latitude, but may extend up to 60° latitude.

I.5.21 Snow fully humid extremely continental (Dfd)

A climate where there is at least one month colder than -3°C and precipitation is generally the same throughout the year. This climate is found only in eastern Siberia and is notable for its extreme winter cold.

I.5.22 Snow dry, hot summer (Dsa)

A climate where there is at least one month colder than - 3°C and summers are dry and hot. This climate is usually at high elevations near locations that are warm temperate with dry, hot summers

I.5.23 Snow dry, warm summer (Dsb)

A climate where there is at least one month colder than - 3°C and summers are dry and warm. This climate is usually at even higher elevations near locations that are warm temperate with dry, hot summers.

I.5.24 Snow dry, cool summer (Dsc)

A climate where there is at least one month colder than - 3°C and summers are dry and warm. This climate is usually at the highest elevations near locations that are warm temperate with dry, hot summers.

I.5.25 Snow dry summer extremely continental (Dsd)

A climate where there is at least one month colder than -3°C and winter is wetter than summer. This climate is found only in eastern Siberia and is notable for its extreme winter cold.

I.5.26 Snow dry winter hot summer (Dwa)

A climate where there is at least one month colder than -3°C with dry winters and wet summers. This climate is usually found in eastern Asia between 35° and 45° latitude.

I.5.27 Snow dry winter warm summer (Dwb)

A climate where there is at least one month colder than -3°C with dry winters and wet summers. This climate is usually found in eastern Asia between 45° and 55° latitude but may extend up to 60° latitude.

I.5.28 Snow dry winter cool summer (Dwc)

A climate where there is at least one month colder than -3°C with dry winters and wet summers. This climate is usually found in eastern Asia between 55° and 65° latitude but may extend up to 70° latitude.

I.5.29 Snow dry winter extremely continental (Dwd)

A climate where there is at least one month colder than -3°C with dry winters and wet summers. This climate is found only in eastern Siberia and is notable for its extreme winter cold.

I.5.30 Polar frost (EF)

A climate where each month is colder than 10°C, but the warmest month is still warmer than 0°C. This climate is generally found on the northern edges of Northern Hemisphere continents and surrounding islands.

I.5.31 Polar tundra (ET)

A climate where each month is colder than 0°C. This climate is generally found in Antarctica and inner Greenland.

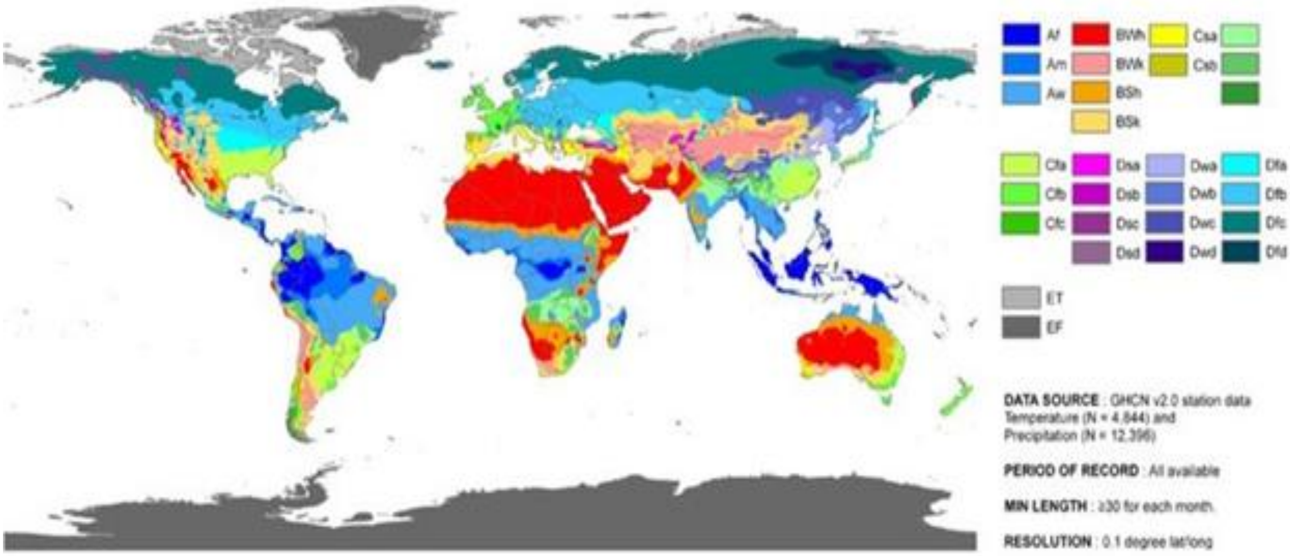


Figure 1.18: World map of Koppen Oeiger climate classification

Chapter II: Climate Change: Causes and Consequences

Humans interact with the ecosystems around them, often extracting natural resources from the planet and returning them to the environment in a non-reusable and harmful manner. Population growth, particularly over the past 50 years, has led to increased demand for resources and has exacerbated negative impacts on the planet. To meet their needs, humans require more materials and energy, and this excessive consumption contributes to resource depletion, pollution, and climate change. Issues of pollution, overexploitation of natural resources, and climate change have become major concerns for society today. It is crucial for people to become aware of the damage caused to the Earth due to human activities throughout history, especially in recent years. Simply reading daily news or listening to current events makes it clear that we are facing an urgent situation

II.1. What is causing man-made climate change?

Understanding human-induced global warming from a natural science perspective hinges on the energy balance of our planet and the physics of the greenhouse effect.

- The sun emits radiation that reaches Earth, with one-third being reflected back and the remainder being absorbed. The Earth emits long-wave thermal radiation, which balances the short-wave radiation from the sun, contributing to a stable climate.
- Water vapor, along with carbon dioxide and methane molecules in the atmosphere, hinders this radiation from escaping back into space, trapping heat and reflecting some of it back toward the Earth's surface. Without this natural greenhouse effect, the global average temperature would be around –18 °C instead of the current 14 °C, which would make life unfeasible.
- Fossil fuel combustion has increased the concentration of carbon dioxide in the atmosphere, resulting in more heat being directed back toward the Earth's surface. Consequently, temperatures at the Earth's surface and in the lower atmosphere have risen.
- The human-induced greenhouse effect has altered and continues to alter the Earth's energy balance, resulting in an excess energy flow of 0.6 watts/m^2/second.
- Concurrently, aerosols produced from fossil fuel combustion create a cooling effect in the atmosphere (Figure. II.1).

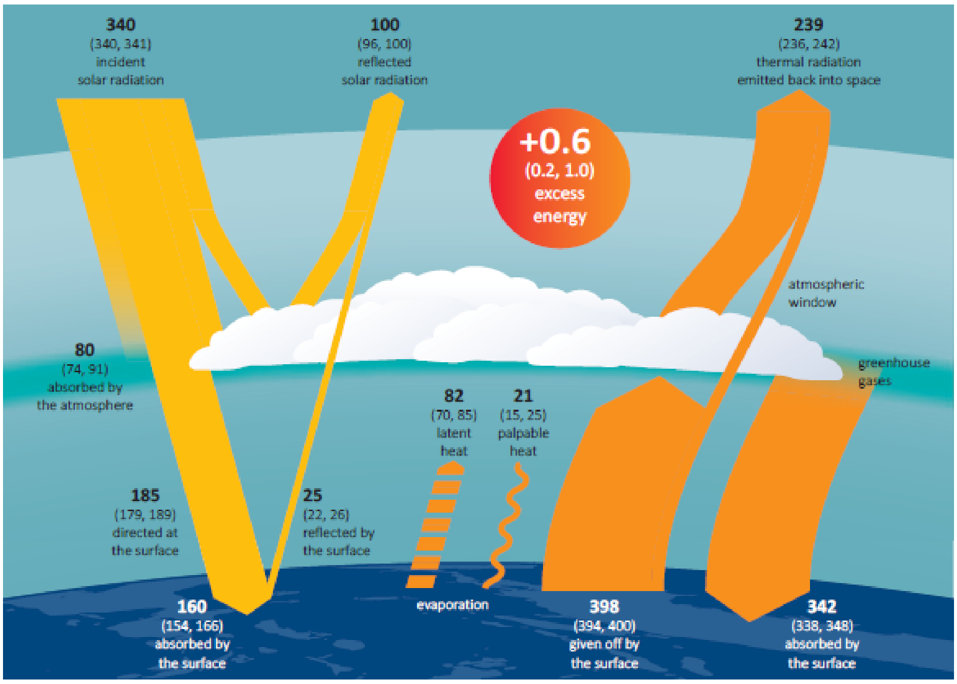


Figure II.1: Climate change upsets the Earth's energy balance

Source: Wild et al.(2015)

II.1.1. Atmospheric CO2 Concentration

- The concentration of CO2 in the atmosphere, which directly impacts the climate, has experienced significant fluctuations throughout the Earth's history.
- These climate shifts resulted from alterations in the energy balance and may have been driven by various factors, including:
  1. Variations in the sun's luminosity.
  2. Changes in the Earth's orbital parameters around the sun.
  3. Alterations in the levels of climate-relevant gases (such as CO2 and methane) and aerosols (atmospheric particulate matter, including those from volcanic eruptions).
  4. The extent of ice cover, cloud cover, and the configuration of continents, all of which affect the amount of energy reflected back into space (the Albedo effect).
- Much of the research on Earth's historical climatology relies on geological deposits from specific periods, including terrestrial and marine sediments, as well as ice cores. Isotope analyses of the calcareous shells of microplankton provide insights into past temperatures, while air bubbles trapped in ice cores reveal historical atmospheric compositions, including greenhouse gas concentrations. Findings from these sources

have led scientists to conclude that over the last 800,000 years, there has been no period in which atmospheric CO_2 concentrations have approached current levels.

- Over the past 10,000 years, CO_2 concentrations have remained relatively stable, averaging between 250 and 275 parts per million (ppm) (Figure. II.2).
- However, since the onset of the Industrial Revolution in the mid-18th century, coupled with the rise of fossil fuel use and deforestation, concentrations of CO_2 and CH_4 (methane) have surged far beyond the natural fluctuation range observed over the past 800,000 years.
- Recent research suggests that today's atmospheric CO_2 levels are likely the highest they have been in the last 3 million years.
- Such elevated concentrations of CO_2 pose a risk of destabilizing portions of the climate system in the long term, potentially resulting in severe consequences for the environment.

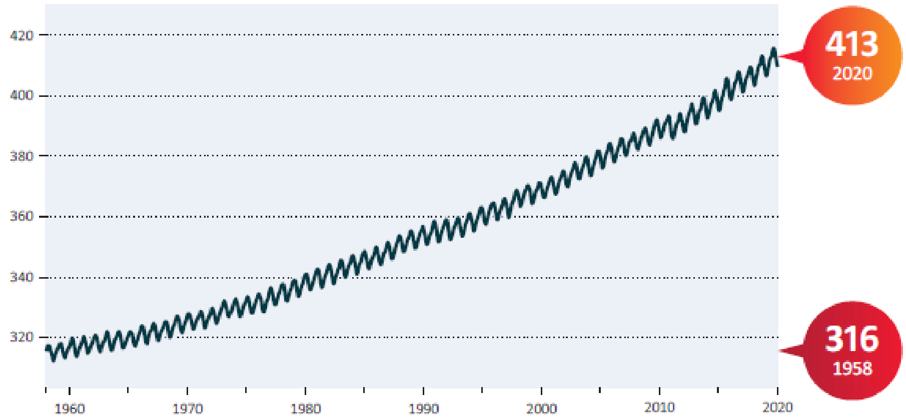


Figure II.2: Direct measurements of the atmosphere's CO_2 content began on the island of Mauna Loa since 1958

Source: NOAA (2020)

II.1.2. The global temperature

- Weather stations have been utilized since the 18th century to record temperatures on Earth, and by the 19th century, they were sufficiently widespread to produce a reliable global average. The accompanying graphic depicts three distinct phases of global temperature trends. Up until 1940, the Earth experienced a gradual warming, followed by a period of stable temperatures until the 1970s, largely attributed to an increase in cooling aerosols (air pollution). Since then, we have entered a phase of pronounced warming.

- The effects of warming are generally observed to be significantly more pronounced over land than over oceans. Between 2015 and 2019, land temperatures were approximately 1.7 °C higher than the pre-industrial averages recorded from 1850 to 1900.
- On average, the rise in greenhouse gas concentrations caused by human activity—particularly carbon dioxide and methane—has resulted in a 1.2 °C increase in surface temperatures on Earth (both land and ocean) since the 19th century.
- From 1881 to 2019, the annual average air temperature across Germany's mean surface area rose by 2 °C. Similarly, the North Sea has also warmed by 2 °C during this timeframe.
- Since 1951, fluctuations in solar radiation, volcanic eruptions, and the natural variability of the climate system have not had a measurable impact on global warming. In fact, solar luminosity has slightly decreased during this period (Figure. II.3).

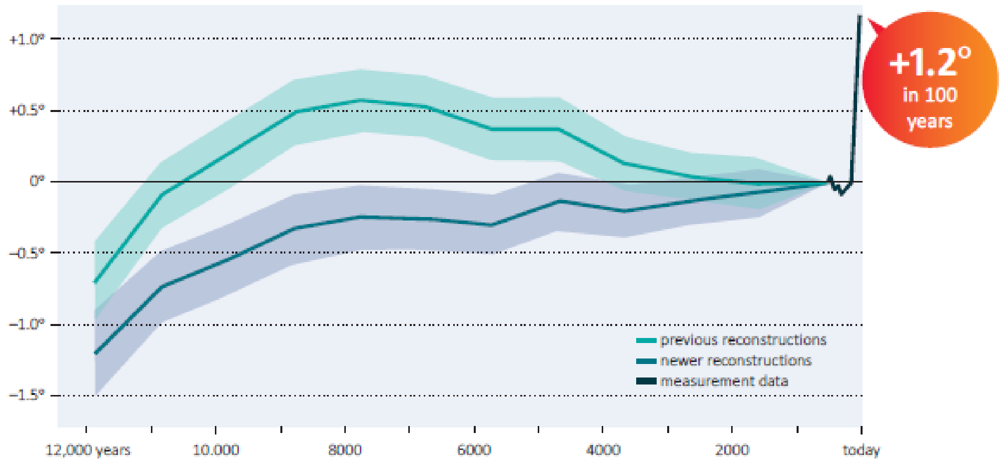


Figure II.3: Global temperature since the end of the last ice age

Source: Bova et al. (2021).

II.1.3. Human-Induced Global Warming !

- Modern global warming is occurring at an unprecedented rate compared to what climate research has identified regarding natural temperature increases throughout Earth's history.
- Extensive data collected from around the world now allow scientists to calculate the global average temperature over the last 20,000 years, dating back to the peak of the last ice age. These findings suggest that the current global temperature is likely warmer than it has been at any point during the Holocene, and thus throughout the history of human civilization.

- This data aligns with model predictions regarding historical temperatures.
- Additionally, significant and abrupt regional temperature shifts have been recorded in Earth's past.
- A notable example is the Paleocene-Eocene Thermal Maximum (PETM) around 55 million years ago, during which temperatures rose by approximately 6 °C over just 4,000 years. Geologically speaking, the PETM was a brief but intense warming event, yet the climate change we are witnessing today is occurring at an even faster pace (Figure. II.4).

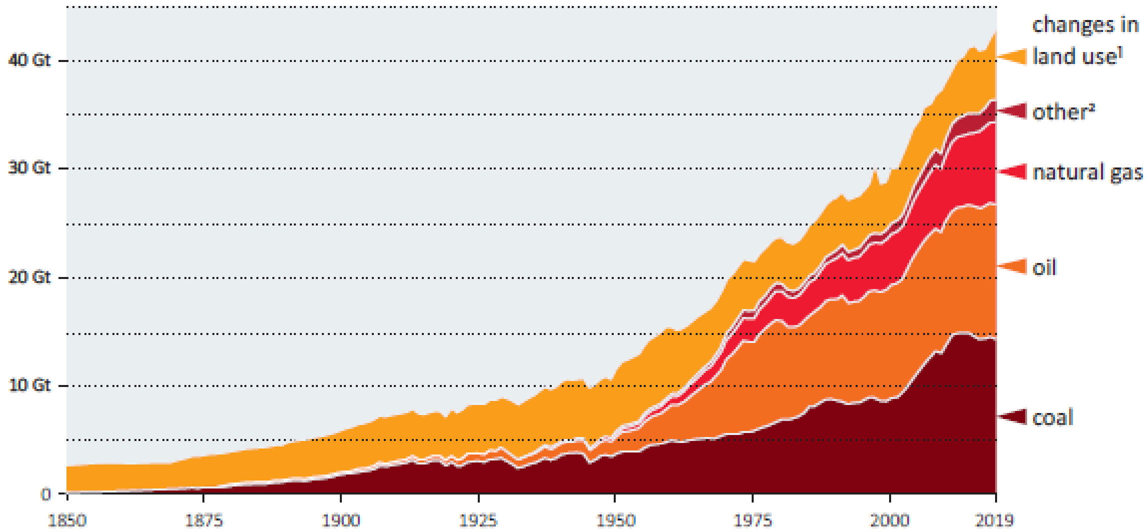


Figure II.4: Overall global CO_2 emissions, 1850–2019 in billions of tonnes of CO_2 (Gt)

Source: Global Carbon Project (2020)

II.1.4. Where Does the CO2 Released by Humans Go?

- The sources of anthropogenic CO2 and its fate are analyzed with great precision. Between 2009 and 2018, 86% of human CO2 emissions originated from fossil fuel combustion, while 14% resulted from land-use changes.
- A significant portion of these emissions—31%—is absorbed by terrestrial ecosystems, and another 23% is taken up by the oceans.
- The largest share of human-induced CO2 emissions, amounting to 46%, remains in the atmosphere (Figure. II.5).

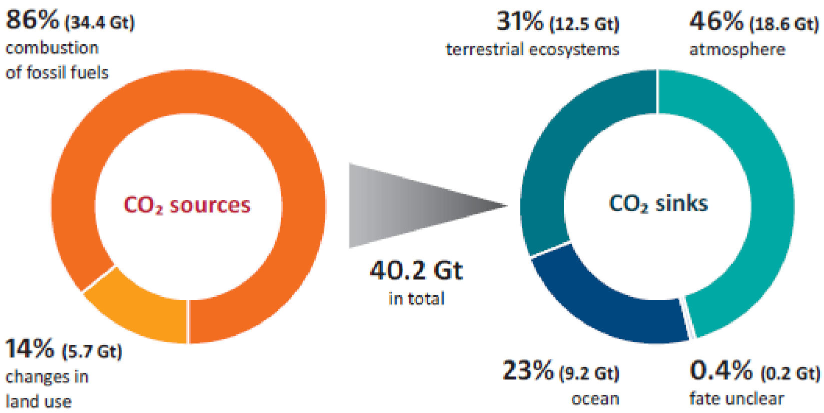


Figure II.5: CO_2 released by humans, Annual amounts as a percentage and in billions of tonnes (Gt), 2010–2019.

Source: Global Carbon Budget (2020)

II.2. Impacts of climate change on water resources

II.2.1. Climate and water cycle in the Mediterranean

The Mediterranean region is located between Europe and Africa. It is bounded by the IPCC between latitudes 30° N to 48°N and longitudes 10° W to 38°E. This region includes all the watersheds draining into the Mediterranean and non-riparian countries such as Switzerland and Bulgaria, with a population of 420 million people spread across 22 countries and territories (Figure II.6). With less than 1000m3/year/ per of renewable natural resources, the Mediterranean region comprises basins that suffer from water stress and are considered water-poor (Margat & Treyer, 2004).

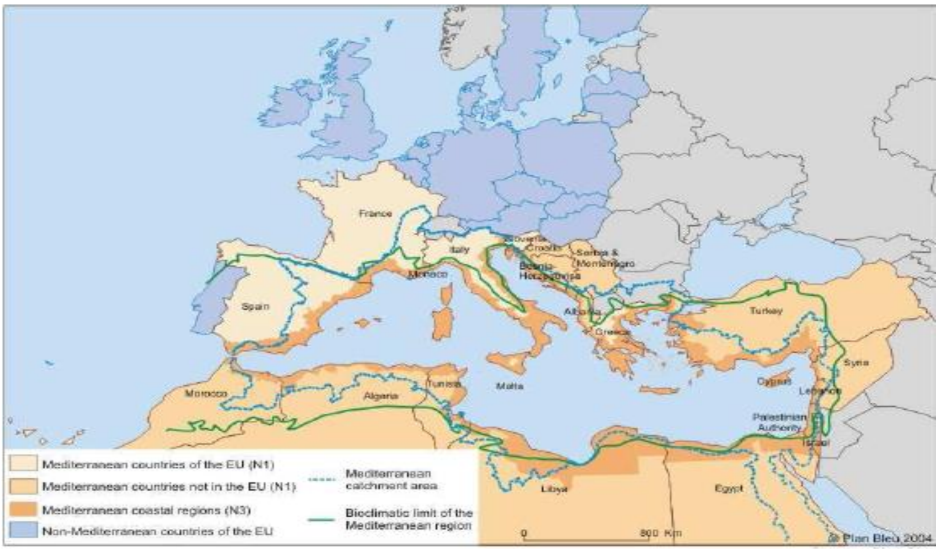


Figure II.6: The Mediterranean area, source: Benoit and Comeau (2005).

The Mediterranean climate is characterized by a seasonal alternation between two regimes, explaining the seasonal contrast between mild, rainy winters and hot, dry summers. Bolle (2003) mentioned that the Mediterranean region is influenced by the westerly wind regime in winter, while it is more under the descending branch of the Hadley cell in summer.

The spatial distribution of precipitation is uneven: two-thirds fall on Italy, France, and Turkey, with only 13% falling on the countries along the African coast. Precipitations amount to a total annual volume of 1162 km3 (UNEP, 2004), characterized by their low intensity and frequency (less than 100 days/year). Annual precipitation totals vary between 300 and 1000 mm (Figure II.7), and sometimes slightly more in certain mountains (the Alps) (Magand, 2014).

For the latter half of the 20th century, there have been decreasing trends in winter precipitation in the Mediterranean, along with a weakening of cyclonic activity in the region (Trigo et al., 2002). Numerous studies have confirmed these findings in different regions: Greece, Italy, and the Near East (Norrant & Douguédroit, 2005) for the period 1950-2000; Italy (Brunetti et al.,

2000) during the period 1951-1995; Spain (Esteban-Parra et al., 2003) over the last century; and Turkey and Cyprus (Alpert et al., 2002) between 1951 and 1995. These authors observe that this trend is a result of a decrease in the number of rainy days associated with an increase in the frequency and persistence of the subtropical anticyclone weather pattern over the Mediterranean (Lespinas, 2008).

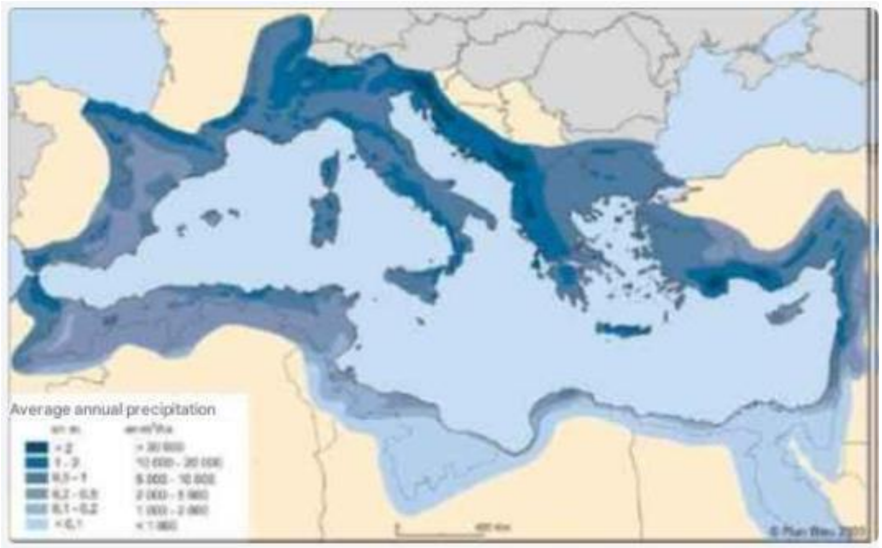


Figure II.7: Average precipitation in the Mediterranean basin, source: Benoit and Comeau [2005].

Several authors, including Xoplaki et al. (2004) and Goodess & Jones (2002), have confirmed an unprecedented trend over the past five centuries in the Mediterranean basin, showing a significant decrease in winter precipitation. The recent winter decades (the last fifty years) have been the driest and warmest. This trend is attributed to the prevalence of positive phases of the North Atlantic Oscillation (Dünkeloh & Jacobeit, 2003).

The dry season can last over four months in the South and East of the Mediterranean region, while in the North, it may last one to two months. In certain Mediterranean regions, evaporation is substantial, sometimes exceeding the total annual precipitation, reducing the efficiency of dams. For example, at the Aswan Dam, 10 km3/year is evaporated (Nassopoulos, 2012).

The average annual losses through actual evapotranspiration are estimated at 567 km3; the flow losses added to the evapotranspiration from major artificial reservoirs amount to 31.5 km3 (UNEP, 2004).

The climatic asymmetry between the southern and northern Mediterranean region is the cause of the contrasting distribution of water inputs and flows between rivers and streams. According to author Wainwright & Parsons (2010), the river regime in the Mediterranean is quite unique; predicting runoff is challenging in a basin characterized by complex topography and scattered vegetation, and the response of the basin between high and low waters can be extreme. Nassopoulos (2013) indicated that the Mediterranean Sea receives 475 km3/year, with France, Italy, the Balkans, and Turkey contributing 90%. Changes in river flow rates can serve as indicators of climate change. In Greece, according to Koutsoyiannis et al. (2007), river flows have shown a negative trend since 1920.

Hallegatte et al. (2008) highlighted that the Mediterranean region, with 7% of the global population, only possesses 3% of the world's water resources. Water resources in this region come from surface water (80%) and groundwater (20%), with distribution varying among countries. Some countries rely on groundwater resources (e.g., Libya, Malta, Palestinian territories), while others depend on surface water (e.g., Egypt). The dominance of water sources varies by sector, with surface water being the exclusive source for the energy sector and the main source for agriculture and industry, while groundwater is used for urban supply. The flow of rivers discharging into the Mediterranean has decreased by 15% due to artificial storage capacity estimated at over 200 km3 to ensure water supply in the region. Evaporation has also increased by 14% due to human interventions such as reservoir construction and irrigated areas (Nassopoulos, 2012).

II.2.2. Impacts of Climate Change on Water Resources

According to the United Nations (2003), freshwater resources are influenced by several drivers unrelated to climate, especially on a global scale. Demographic changes, food consumption (especially diet types), economic policies (particularly water pricing), technology, lifestyle, and societal perception of the value of freshwater ecosystems are the water-related drivers. Analyzing how freshwater is affected by these drivers leads to evaluating the relationship between climate change and water resources.

II.2.3. Water Stress Index of Observed Changes

Basins where water availability per capita is less than 1,000 m3/year are considered water-stressed basins. These basins are located on the west coast of South America, northeastern Brazil, Mexico, the United States, Australia, northern China, South Asia, the Near East, the Middle East, North Africa (Mediterranean region) (Figure II.8).

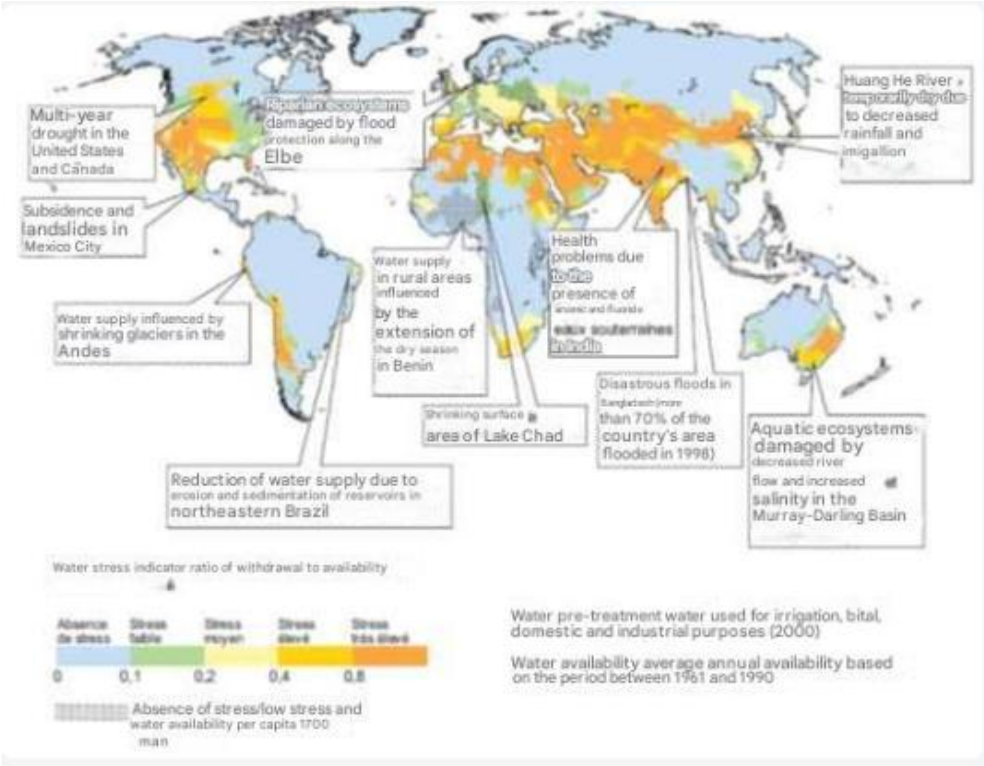


Figure II.8: Examples of Current Vulnerabilities of Freshwater Resources and Their Management

The seasonality and interannual variability of river flow influence the water availability of surface water resources or shallow groundwater. Barnett et al. (2005) stated that the decrease in water supply in summer is due to a reduction in river flow caused by increased temperatures, especially in snow-dominated basins.

Due to climate change, populations and ecosystems are vulnerable to decreased precipitation in water-stressed regions. Over the past decades in most countries, population growth, lifestyle changes, economic growth, and particularly irrigation (accounting for 70% of withdrawals and 90% of consumption worldwide) have led to increased water usage. The United Nations (2006) indicated that in recent decades, there has been a degradation in the quality of surface water and groundwater due to agricultural and industrial activities.

Regional aspects of the impact of climate change on water resources are illustrated based on current observations in the following section.

II.2.4. Observed Changes

a- In Africa:

According to Vörösmarty et al. (2005) and the World Water Forum (2000), nearly 25% of the African population is affected by water stress, with about one-third living in regions prone to drought (the Sahel, the Horn of Africa, and southern Africa). Nicholson et al. (2000) noted a negative trend in annual precipitation since the 1960s, with a decrease of 20% to 40% during the period 1968-1990 compared to the period 1931-1960.

b- In Asia:

Decreasing trends in average annual precipitation have been observed in certain regions (Russia, northeastern and northern China, coastal belts, and arid plains of Pakistan, northeastern India, Indonesia, the Philippines, and some parts of Japan), leading to water shortages in arid and semi-arid regions. Increasing trends are also noted in other regions (western China, the Yangtze River basin and southeast coast of China, the Arabian Peninsula, Bangladesh, and along the western coasts of the Philippines).

Trenberth and Hoar (1997) stated that over the past two decades, there has been an increase in the frequency of extreme weather events associated with the El Niño phenomenon. In many regions of Asia, several researchers such as Izrael and Anokhin (2001), Mirza (2002) and Lal (2003), Min et al. (2003), Ruosteenoja et al. (2003), and Gruza and Rankova (2004) have observed that the frequencies of intense rainfall events have increased, leading to floods, landslides, while the number of rainy days and the total annual precipitation have decreased.

c- Australia and New Zealand

Since the mid-20th century, a severe multi-year drought has persisted in the eastern regions and other southern regions of Australia, following significant decreases in winter rainfall. These reductions have impacted natural runoff (The total inflow of the Murray River was the highest recorded from 2001 for five years). A portion of the drying is attributed to the greenhouse effect (IOCI, 2002).

d- Europe

According to Scaife et al. (2024), changes in winter North Atlantic Oscillation (NAO) have contributed to the increase in average winter precipitation in most of Atlantic and Nordic Europe during the period 1946-1999. From 1950 to 2000, as noted by Norrant and Douguédroit (2006), negative trends were observed in eastern areas within the Mediterranean region. These changes, along with alterations in hydrological and thermal regimes, have had notable impacts in other sectors (Auer et al., 2007).

d- Latin America

Between 2000 and 2005, the frequency of climate-related disasters in Latin America increased by 2.4 times compared to the period from 1970 to 1999. These events were documented in various regions of Latin America, including floods in Argentina (2000 and 2005), Amazonian drought in Brazil (2005), destructive hailstorms in Bolivia (2002) and Buenos Aires (2006), Cyclone Catarina in the southern Atlantic (2004), and the hurricane season in the Caribbean regions (2005). The cost of damages from just 19% of the observed events during the period 2000-2005 is estimated to be 20 billion US dollars.

e- North America

In North America, over the past century, several trends indicate significant regional variability in the impacts of climate change on water resources. According to Hunt (2005), increasing trends have been observed in:

- Increasing trends:

1. Annual precipitation (North America)
2. Frequency of heavy rainfall events (United States)
3. Lake water temperatures (0.1 to 1.5 °C) (North America)
4. River flow (eastern United States)
5. Drought periods (Western United States, southern Canada)

- Decreasing trends:

1. Duration and extent of snow cover (North America)
2. Snow water equivalent in mountainous regions (Western North America)
3. Annual precipitation (Central Rocky Mountains, southwest United States, Canadian prairies, and eastern Arctic)
4. Ice cover (Great Lakes, Gulf of St. Lawrence)

It is likely that variations in wealth and geographical nature have influenced the unequal distribution of impacts, vulnerabilities, and adaptive capacity in the United States and Canada. However, the most significant impacts of climate change (both societal and ecological) are undoubtedly related to changes in surface and groundwater resources.

II.2.5. Impact of Climate Change in Algeria

Algeria is the largest country in Africa, covering an area of 2,381,741 square kilometers. It is bordered to the north by the Mediterranean Sea with 1200 km of coastline, to the east by Tunisia and Libya, to the south by Niger and Mali, to the southwest by Mauritania and Western Sahara, and to the west by Morocco. The country is situated between the parallels 18°58' and 37°05' North and the meridians 08°40' West and 11°58' East.

Algeria's geographical location gives it a unique climate and ecological diversity. Letreuch-Belarouci (1995) noted that the Algerian territory is highly diversified in terms of climate, topography, soils, and natural vegetation, encompassing three main structural units: the Tellian system, the high steppe plains, and the Sahara ((Figure. II.9).

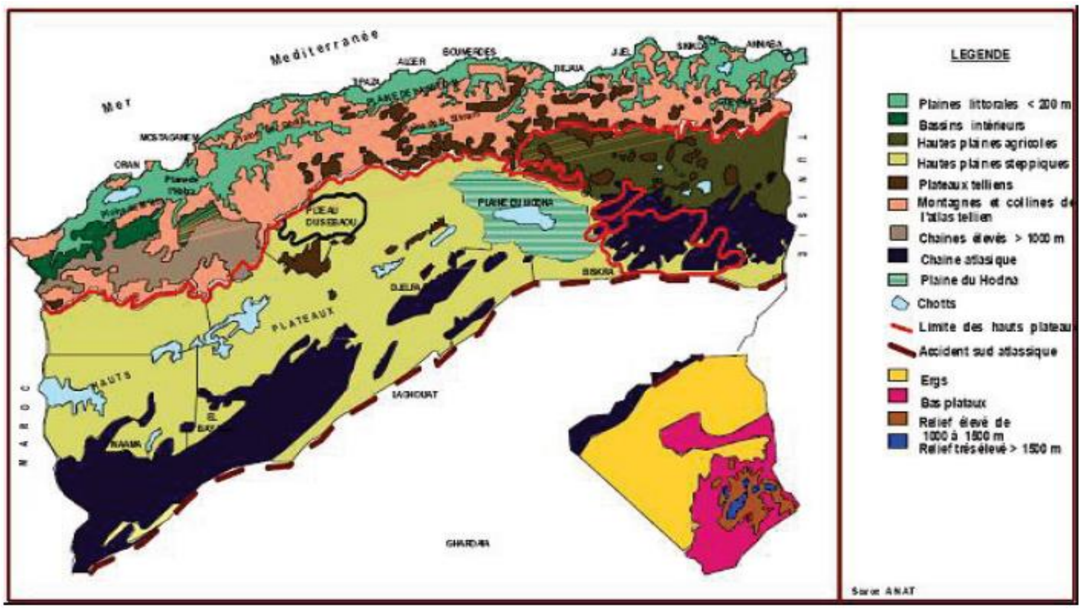


Figure II.9: Natural Zones in Algeria.

The climate of Algeria falls under the Mediterranean regime with two distinct seasons, the rainy season and the dry season (Kadik, 1986), comprising three bioclimatic zones

1. A subhumid bioclimatic zone along the coast and in the Tellian Atlas.
2. An arid bioclimatic zone in the High Plains and the Saharan Atlas.
3. A desert bioclimatic zone (hyper-arid) in the Saharan region.

II.2.6. Observed Climate Changes

a. Temperature

The positive trend in temperatures has been confirmed by several authors across various regions of the country. In Eastern Algeria, Khoualdia et al. (2014) affirmed this trend through the increased heatwaves in the Medjerda watershed during the period 1980-1990. Farah (2014) supported this trend since 1977, while Laala and Alatou (2016) highlighted that the warming experienced during the period 1982-2011 was due to temperature rise.

In the west, the presence of potential thermal changes was confirmed by Amara (2014), showing an increase in average annual temperatures for the stations of Ghazaouet, Zenata, Oueld Mimoun, and Maghnia during the period 1980-2013. El-Mahi et al. mentioned that the average temperature increased by 0.9°C in Mascara, Saida, and Ghriss during the period 1985-2006. Conversely, Haouchine et al. (2015) reported a temperature increase of 1°C to 2°C from 1926 to 2006 (Es-Senia station) with a positive trend since the late seventies.

There has been a decrease in the frequency of cold days, cold nights, and frost, while there is an increase in the trend of hot days, warm nights, and heatwaves (Abderrahmani, 2015).

b. Precipitation

Since the 1970s, Algeria has experienced a significant rainfall deficit of about 30% across the country (MRE, 2008). Several research studies have confirmed this trend. In the north, according to Hassini et al. (2008), around a hundred meteorological stations in coastal and inland areas have experienced alternating episodes of above-normal and below-normal rainfall during the periods 1951-1980 and 1961-1990. There was an increase in precipitation between 1930 and 1950 following a relatively dry phase, followed by a decrease in rainfall from the 1970s onwards. The reduction in rainfall exceeds 36% in the Mascara region (West) and 20% in Mitidja (Central) (Meddi & Meddi, 2009; Medejerab & Henia, 2011; Nezzal & Iftini-Belaid, 2013; Khoualdia et al., 2014).

In the southeast, in the Chott Melghir basin, annual precipitation decreased by 66% during the period 1965 to 1994 (Benkhaled A., 2011).

c. Potential Evapotranspiration

Karsili (2013) highlighted the impact of recent temperature increase on the water cycle, stating that evapotranspiration also contributes to water stress. Since the late seventies, Algeria has experienced a significant rainfall deficit of 30%, a positive temperature trend, and a considerable increase in potential evapotranspiration. This combination has affected agricultural yields, especially during the years 2002 to 2005 (Medejerab, 2009). The distribution of potential evapotranspiration varies from region to region, with annual averages of 858 mm in Oran, 865 mm in Mostaganem, 880 mm in Mascara, 1009 mm in Ain-Defla, 840 mm in Annaba, and 810 mm in Tébessa, while monthly averages are equal to or greater than 100 mm (MATE, 2010).

d. Drought

Between 1967 and 1991, drought events affected approximately 1.4 billion individuals according to the World Meteorological Organization (WMO) (Obassi, 1994). The recent IPCC report (2014) emphasized that atmospheric system instability has led to an increase in the intensity and frequency of extreme weather events, including more heatwaves and expanded areas of droughts and floods. A connection has been established between the ENSO phenomenon and drought in Algeria (Matari et al., 1999). Droughts in the 1940s were due to reduced spring rains, while the drought in the 1980s resulted from decreased winter rainfall, findings supported by principal component analysis (Matari & Douguerdoit, 1995). The latter drought persisted for over thirty years due to a rainfall deficit, particularly in the western region.

The chronic and adverse impacts of this rainfall deficit lead to desertification, soil salinization, increased water pollution (Benslimane et al., 2008), not to mention the growing pressure on water resources. These detrimental consequences have economic and social implications (Meddi & Humbert, 2000).

e. Flood

According to Maury et al. (2005), floods result in nearly 20,000 deaths annually, representing 60% of the natural disaster toll. They cause more fatalities and damages compared to other disasters worldwide (UN, 1994). Grabs et al. (1997) cautioned that the flood issue will worsen due to climate change and the increasing global population. Climate change challenges the stationarity of rainfall series and the validity of hydrological analyses based on statistics. The IPCC (2014) highlighted floods as among the impacts of recent extreme weather events. These high-impact events underscore the significant vulnerability leading to ecosystem degradation and numerous human systems being affected (disruption of food production, water supply, damage to infrastructure and human settlements, morbidity and mortality, mental health consequences, and individual well-being). Algeria has experienced numerous floods over the past 40 years. Touaïbia (2000) mentioned that both northern and southern regions are threatened by these hydrological disasters. Their origins and environmental impacts depend on the geographical, climatic, and land-use conditions that characterize them. Yahiaoui (2012) identified factors that cause and contribute to the intensification and exacerbation of flood effects, classifying them into three types.

Floods occur in regions with unfavorable topographical environments, such as cities crossed by rivers (Bordj Bou Arreridj, Oued R'Hiou, Sidi Bel Abbès, El Bayadh) or located at the foot of a mountain (Ain Defla, Batna, Médéa).

Floods are linked to exceptional weather situations characterized by heavy rainfall (intense rain, severe thunderstorms). Examples include the floods in March 1974 in the Algiers and Sebaou basins, the floods in December 1984 across eastern Algeria, etc.

Floods are triggered by factors associated with human activities: failures in sanitation and stormwater drainage systems, raising of riverbeds due to debris and waste, and other human actions that contribute to damage during seasonal downpours. Instances include the recurring winter flooding in the city of Tiaret and floods occurring every 2 to 3 years in the M'Zab plain, highlighting the influence of these factors.

Floods in large river basins constitute one type of flooding, characterized by massive, slow-rising waters resulting from significant widespread rainfall over large areas for an extended period (10 to 15 days). Another type involves floods affecting smaller watersheds (a few tens of square kilometers) caused by intense, localized rainfalls resulting from convective storms, known as flash floods. These floods are sudden, dangerous, and rapid. Examples include:

1. Oued R'Hiou, on October 20, 1993, recorded significant damage within 20 minutes of rainfall, with 23 fatalities, 20 injuries, and several missing individuals.
2. El Bayadh, on October 1, 2011, experienced 10 fatalities and over 400 displaced families within an hour of rainfall. The estimated damage reached 600 million euros.

An inventory compiled over the past 40 years asserts that no region is immune to such potential events (Lahlah, 2004), extracting significant events from a national disaster. For instance, notable floods include:

1. February 3, 1984, focused on the Constantine Mountains (120 mm in 3 days) and Medjerda Mountains (80 mm in 3 days), affecting the entire eastern region of Algeria (Jijel, Constantine, Skikda, Guelma, Khenchella, Oum El Bouaghi).
2. December 29, 1984, to January 1, 1985 (over 250 mm in 4 days and 195 mm in a single day) severely impacted the eastern region of Algeria, causing catastrophic flooding in the provinces of Jijel, Constantine, Skikda, Guelma, Annaba, and El-Tarf.
3. January 26 and 27, 1992, resulted in catastrophic flooding in the provinces of Algiers, Blida, Tipaza, Chlef, Ain Defla, and Médéa.
4. November 9 and 10, 2001: a catastrophic flood hit Bab El Oued in Algiers (750 fatalities, 115 missing persons, and material losses of 30 million dinars) (Figure II.10).
5. October 1, 2008, saw Ghardaïa experiencing torrential rains (150 mm in an hour) accompanied by severe thunderstorms (Figure. II.11et Figure. II.12) .

Figure II.10 : The catastrophic flooding in Bab El Oued, Algiers,

Source: (Yahiaoui, 2012).

Figure II.11: The M'zab River in flood reaching 10m

Figure II.12: shows the water in palm grove

Source: (Medejerab, 2009)

f. Heatwaves:

According to the Magicc model focused on the Maghreb region, which estimates a temperature increase of 1°C between 2000 and 2020, this could reach 3°C by 2050 and exceed 5°C by 2100. Climate change projections for Algeria suggest significant impacts on resources and the population. Algeria is projected to be the most affected, experiencing a temperature increase ranging from 3.5 to 4.5°C across 90% of its territory. By the end of the 21st century, the Maghreb region is expected to see heatwaves occur ten times more frequently. Heatwaves, due to their duration and intensity, can lead to damage or serious incidents, with their frequency influenced by topoclimatic and anthropogenic factors.

Abderrahmani et al. (2009) conducted a study in the northwest of Algeria, particularly focusing on the wilayas of Oran, Tiaret, and Sidi Bel-Abbes, analyzing the recorded minimum and maximum temperatures at the localities' stations during the period of 1997-2006. They observed that heatwaves, impacting sectors such as health, agriculture, and others, pose a threat to the elderly. In the period from June 1 to August 31, 2003, maximum temperatures were recorded in Annaba (41°C), Algiers (41.8°C), El Kala (40°C), among others. This temperature peak was a result of a heatwave affecting the Maghreb countries and a large part of Europe. An investigation by Sabri et al. (2009) aimed to uncover the cause of this heatwave, one of the hottest in the past fifty years, confirming that it was due to the recent climate warming. Other studies by Beniston et al. (2007) suggest that the increasing temperatures combined with the overall warming trend would lead to more frequent heatwaves, surpassing or equaling the intensity of the 2003 heatwave.

g- Water resources:

The overall water capacity, as estimated by MRE (2009), is 19.4 billion m3/year, with 2 billion m3/year constituting water resources from the northern aquifers of the country (renewable resources), and 12 billion m3/year being surface water resources. The potential of the Continental Intercalary and Terminal Complex aquifers (non-renewable resources) is estimated at 60,000 billion m3, with 40,000 billion m3 located in Algeria (Figure. II.13).

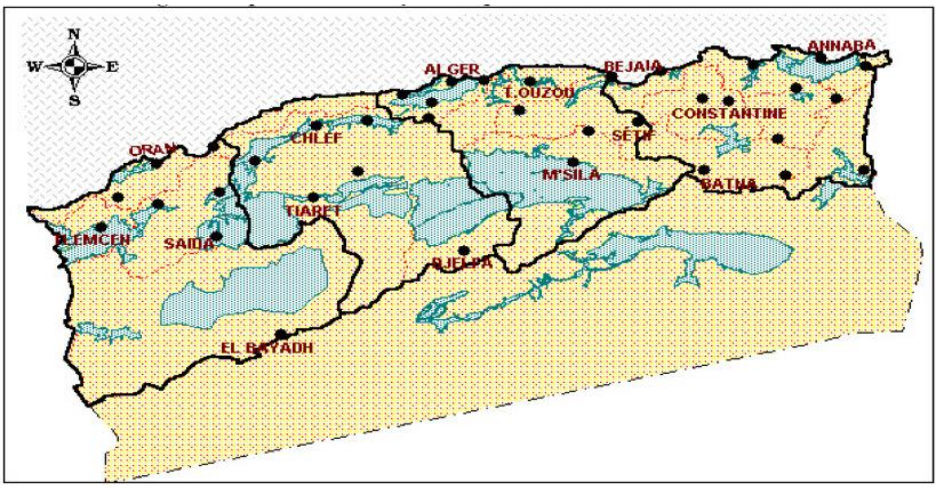


Figure II.13: Map of the 5 regions of hydraulic planning.

Source: (MRE, 2009)

Water resources in Algeria are utilized through various means:

1. Dams (79 dams - 7.40 billion m3)
2. Groundwater exploitation (wells - 1.6 billion m3)
3. Foggaras (85 million m3)
4. Desalination of seawater (23 stations - 347,000 m3/day)
5. Recycling of treated wastewater (65 stations - 365 million m3/year)

National intermenstrual dialogues on climate change, as well as national and international seminars, are conducted, and reports are generated to assess the sensitivity of water resources to climate change. In Algeria, water resources are notably responsive to these changes. The high vulnerability of watersheds to slight variations in hydro-climatic parameters affects the mobilizable volume, leading to a flow deficit and reduction in surface water flows and groundwater levels (Arrus & Rousset, 2007).

Besides climate change, other factors such as economic, demographic, consumer behavior, and management mechanisms contribute to defining the vulnerability of water resources.

Climate change in recent decades has had a negative impact on water resources, leading to a decrease in flows of up to 70% (Meddi & Hubert, 2003). In 2020, potential changes result in the Middle Cheliff basin facing a very severe hydro-climatic regime characterized by heavy rainfall, floods, droughts, water resource scarcity, and reduced crop yields.

This vulnerability was confirmed in the Chellif-Zahrez basin, where even aquifers were affected by the drought in northern Algeria. In the Mactaa watershed, the decrease in precipitation from 1976 to 2002, as noted by Laborde (1995), has implications for average annual water flow, with a 28 to 36% reduction compared to the period of 1946-1976 (Meddi et al., 2009).

The decrease in rainfall, estimated at 27%, has significantly impacted the Tafna basin due to the drought affecting the region since the 1970s. This has led to a 69% decrease in river runoff (Ghenim et al., 2010).

h- Soil and ecosystems:

Tabet-Aoul's research (2008) examining temperature data from the Oran station during 1926-2006 reveals a 2°C rise, affirming a precipitation deficit in northern Algeria since 1973. This deficit enhances soil vulnerability to water and wind erosion, along with salinization due to increased evapotranspiration resulting from rising temperatures. These factors contribute to the loss of fertile lands and forest degradation in natural and pastoral regions. Ecosystem dynamics are disrupted by human activities and climate changes, impacting agro-systems, biodiversity, species distribution, and natural habitat balance.

Kadik (1986) supported the northward migration of Mediterranean bioclimatic zones due to climate changes, leading to the expansion of arid and desert areas, causing land degradation, vegetation cover deterioration, loss of biological potential, and reduced soil fertility. Climate parameter variability (temperature, precipitation) causes a shift and reduction in growth periods in dry regions, directly affecting plant metabolism.

I- Health

The World Health Organization (WHO) reports from 2000 stated that climate change was accountable for approximately 2.4% of global diarrheal cases and 6% of malaria cases in certain middle-income nations, resulting in approximately 150,000 deaths. Furthermore, the latest Intergovernmental Panel on Climate Change (IPCC) report in 2007 confirmed that climate change has impacts on human health, leading to deaths and illnesses from extreme weather events like heatwaves, floods, and droughts.

Moreover, analyses of the global warming impact are projected to affect the epidemiology of numerous diseases and conditions. Climate changes may hasten the spread of vector-borne diseases (such as malaria, cutaneous leishmaniasis), worsen mental health issues (stress) due to population displacement during floods, increase the impact on nutrition-related diseases leading to famines (due to droughts), elevate endemic diseases (trachoma, schistosomiasis, leptospirosis), and foster the emergence of new diseases (Lyme disease, Rift Valley fever).

In Algeria, the substantial rise in temperatures, significant decrease in precipitation, and increased evaporation will worsen the vulnerability of populations in terms of health risks. The ability of healthcare systems to adapt to these climate changes varies from one region to another due to the country's vast geographical extent. It is imperative to readjust measures in case of a pronounced intensification or acceleration of climate changes.

II.3. How to Combat Climate Change?

After analyzing the effects of climate change related to water, it is important to examine the strategies implemented to combat climate change. Efforts in the fight against climate change are distinguished in two areas: *mitigation*, which includes all strategies and policies aimed at addressing the causes of climate change, particularly by limiting the emission of greenhouse gases into the atmosphere, and *adaptation*, which encompasses all strategies and policies that seek to address the consequences of climate change. These two approaches complement each other and are essential.

II.3.1. Mitigation

II.3.1.1. Mitigation: Definition and Issues

Mitigation refers to activities aimed at reducing greenhouse gas (GHGs) emissions, either directly or indirectly, by avoiding the production of GHGs or capturing them before release into the atmosphere, or by trapping GHGs already present in the atmosphere by increasing natural carbon "sinks" like forests. These activities may involve changes in behavior, technological advancements, and the dissemination of new techniques (IPCC, 2001).

Global GHG emissions have increased since the pre-industrial era, with a 70% rise between 1970 and 2004. This increase is primarily attributed to the energy sector, followed by transportation, industry, and land use. To keep global warming below 2°C by 2100, GHG emissions would need to be reduced by a factor of 3 before 2050, as stated by Hervé Le Treut, a contributor to the IPCC (Sciences Po, 2013).

The issue of mitigation and limiting GHG emissions has historically been at the core of climate negotiations, especially during various Conference of the Parties of the UNFCCC. It is based on the principle of common but differentiated responsibilities among countries. This principle recognizes that developed countries are historically the main emitters of GHGs and, therefore, they should bear the major burden of reducing GHG emissions.

II.3.1.2. Key Mitigation Measures

According to the IPCC, reducing greenhouse gas emissions involves changes in the global energy system and land use: improving energy efficiency and reducing energy demand, quadrupling the share of renewable and other low-carbon energies, developing carbon capture and storage methods, promoting biofuels and reforestation, and limiting deforestation. These solutions vary in their environmental risks and potential conflicts with sustainable development principles. It is essential to assess the risks associated with these decarbonized energies, as they may not fully address the challenge of sustainable energy production and consumption. For instance, nuclear energy raises concerns about nuclear waste storage and facility safety.

Biofuels can negatively impact food security by reducing available land for food production and contributing to price fluctuations in commodity markets. Carbon storage involves capturing, compressing, and burying carbon underground. While these techniques are still experimental, they face various limitations such as cost, energy-intensive technology, and the risk of leakage.
Mitigation measures extend beyond the energy sector to various key sectors contributing significantly to current greenhouse gas emissions. These sectors include transportation, construction, industry, agriculture, forestry, and land use.
Table II.1 : Mitigation measures

	Key Mitigation Measures:
Transport	Changes in usage patterns and evolutions technologiques
Construction	Construction of buildings with low energy consumption.
Industry	Technological advancements, recycling development, and waste management
Agriculture, Forestry, land use	Management of forests and agricultural lands, as well as soil restoration.

II.3.1.3. Water and Mitigation

The relationship between water and mitigation is reciprocal; different mitigation measures can impact water availability, and conversely, the water sector can contribute to mitigation efforts. Various examples can be cited:

- Carbon capture and storage techniques may deteriorate groundwater quality in case of CO_2 leakage.
- The use of biofuels to meet energy demand is also highly controversial and raises questions about land allocation for food and biofuel production. Bioenergy crops increase water demand, leading to risks of overexploitation of available reserves and potential conflicts over usage.
- Hydropower contributes to securing energy supply. The construction of dams and water reservoirs has low greenhouse gas emissions and also has a positive effect on flood control. However, uncertainties persist regarding these large-scale projects and their environmental impact, in addition to their economic and social implications. That is

why the Executive Board of the United Nations Framework Convention on Climate Change decided to exclude large hydroelectric projects with significant water storage from the Clean Development Mechanism (CDM). More efficient irrigation methods can lead to better.

- Carbon storage in the soil, thereby avoiding its release into the atmosphere.
- Land use change and management of cultivated land can have positive or negative impacts on water resources depending on the options chosen for their management. Restoration of wetlands, fallow practice have positive effects on water conservation and quality. Afforestation or reforestation helps reduce flood risks and improve water conservation in water-rich areas. However, in dry areas, excessive reforestation can have negative effects on groundwater levels by contributing to increased plant water demand.

   Wastewater emits a significant amount of methane and nitrous oxide. It is expected that methane emissions from wastewater will increase by nearly 50% between 1990 and 2020 due to the rapid development of certain regions. The widespread implementation of wastewater treatment and sanitation systems is therefore essential to limit greenhouse gas emissions related to wastewater.

II.3.2. Adaptation

The issue of adaptation is the main concern for developing countries and the least developed countries that will be most affected by the impacts of climate change. Adaptation is increasingly gaining importance in climate negotiations but remains the poor relative. It is crucial to better define this concept and the stakes involved: how is adaptation done? What are the links between adaptation and development? Where do we place the distinction between development and adaptation? Can we work on this issue in a sectoral manner, even though the connections between energy, water, and food security are so strong that actions in one sector will have repercussions on others, increasing the risks of maladaptation? What are the limits of the adaptation concept? What is the course of action when adaptation is no longer feasible?

II.3.2.1.Definition of the concepts of adaptation, risk, vulnerability, and resilience

The definition and delineation of the concept of adaptation are complex issues. It is a recent concept that fits into the framework of discussions on climate change, considering that the effects of this change are already underway and that societies need to respond to these changes. The definition provided by the IPCC for adaptation is as follows: "*adaptation is the adjustment of natural or human systems in response to actual or expected climate stimuli or their effects, in order to reduce the disadvantages or exploit the benefits.*" The impacts of climate change hit harder on countries and populations that are the poorest because they have fewer technological, financial, or institutional resources to adapt to these changes. In reality, climate change makes it more challenging to achieve development goals that would enable the most vulnerable countries to adapt.

Adaptation involves the concepts of resilience, risk, and vulnerability, which need to be better understood to grasp the challenges related to adaptation. Risk in the face of climate change can be defined as the interaction of three elements (Figure. II.14).:

a) **Climate hazard** (such as drought, flooding, etc.): The hazard describes the possibility of a natural event occurring, and climate change increases the likelihood of these events happening.

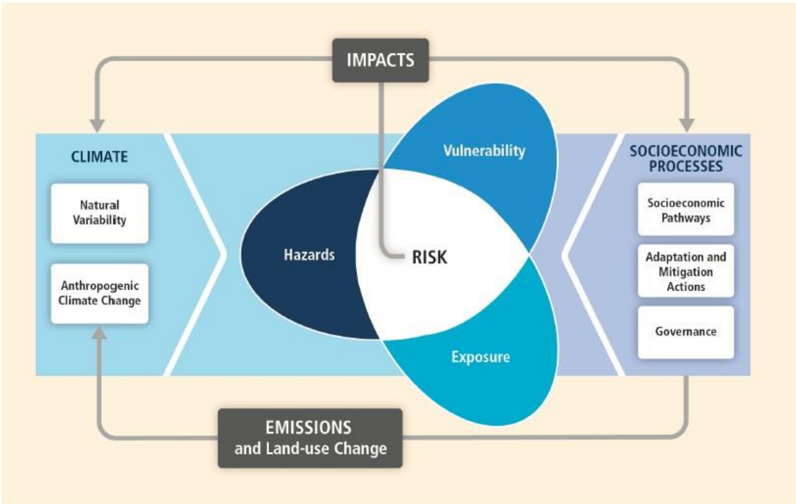


Figure SPM.1.

Figure **II.14:** Map Risk as a function of hazards, vulnerability and exposure..

b) **Exposure** : meaning a stake (whether human, economic, or environmental). The higher the stake, the higher the risk as well. For instance, the occurrence of a hazard in a densely populated area poses a greater risk than in a sparsely populated area.

c) **Vulnerability** : defined as the fragility of the system as a whole, its capacity to resist hazards, and its resilience. For example, during a natural disaster, children, women, and marginalized populations are the most affected due to existing vulnerabilities. In general, lack of basic development such as access to essential services, as well as lack of preparedness or warning systems, are factors contributing to vulnerability.

Resilience is defined by the IPCC in a report published in 2012 as "*the capacity of a system and its components to anticipate, absorb [shocks], adapt, or recover from the effects of a hazardous* *event in an effective and timely manner, particularly through protection, restoration, or enhancement of its essential basic functions and structures.*"

The adaptive capacity of institutions, ecosystems, or individuals is defined as their general ability to adapt to potential damages, take advantage of opportunities, or cope with the consequences of climate change. This capacity is significantly influenced by socio-economic factors such as the ability to earn a living, access credit, access natural resources like land, water, and seeds, or education.

Adaptation therefore incorporates concepts of risk management in the face of natural disasters, challenges related to improving societal resilience, as well as notions of human development, with poverty and lack of access to natural, economic, financial, and institutional resources being the main factors of vulnerability for individuals and societies.

The IPCC outlines various types of adaptation:

- **Preventive adaptation**: implemented before the impacts of climate change.
- **Autonomous adaptation:** unconscious response to climate stimuli triggered by climate change.
- **Planned adaptation:** the result of strategies and policy decisions made to address the effects of climate change.
- **Private adaptation:** carried out by individuals, families, communities, or private groups.
- **Public adaptation:** initiated at all levels of government.

Chapter III:

Climate projections

III.1. Emission Scenarios

The implications of climate change for the environment and society will depend not only on the Earth system's response to changes in radiative forcing but also on how socio-economic changes (economy, technology, lifestyle, public policies) will evolve. In order to analyze the future climate evolution, the Intergovernmental Panel on Climate Change (IPCC) quickly recognized the need to rely on socio-economic scenarios of greenhouse gas emissions.

Socio-economic scenarios involve making various assumptions about future economic development and its impacts on the environment. These scenarios are provided by integrated impact models that consider the evolution of factors, including population, economy, industrial and agricultural development, and, in a simplified manner, atmospheric chemistry and climate change.

For the first and second IPCC reports, the so-called IS92 scenarios were used. The second generation of scenarios, known *as Special Report on Emissions Scenario* (SRES), was then utilized until the IPCC Fourth Assessment Report (AR4) in the early 2000s.

Due to the evolving nature of these factors, the IPCC tools were updated to account for them. Thus, for the latest IPCC report (AR5), the so-called *Representative Concentration Pathway* (RCP) scenarios were developed and have been used since then to generate climate projections. You will find in the following sections a description of these two major families of scenarios:

- The SRES scenarios
- The RCP scenarios

III.1.1. The SRES Scenarios (Special Report on Emissions Scenarios)

III.1.1.1. Reference Scenarios

Reference scenarios correspond to observed concentrations of greenhouse gases and aerosols. They are used as initial conditions for numerical models to simulate the recent climate evolution covering the period from 1860 to 2000.

The objectives of these simulations are threefold:

- Compare the simulated climate evolution by models with observed data over the past 140 years.
- Compare the characteristics of the simulated climate with those observed in recent years.
- Establish an initial state for future climate change simulations under different socio-economic scenarios.

The latter objective presents specific challenges. Indeed, to accurately simulate the recent climate evolution, all forcings, both natural (volcanic eruptions, solar constant variations) and

human-induced (greenhouse gas emissions, aerosols, etc.), need to be considered. However, as these forcings are unpredictable, it is uncertain how to account for them in future projections.
The volcanic forcing is random and always negative: part of the dust emitted during very large volcanic eruptions remains in the lower stratosphere for several months. They reflect solar radiation, which tends to cool the surface. Therefore, considering volcanic forcing for the 20th century but not for the 21st introduces a bias, a systematic error.
There are two possible solutions: either consider the observed natural forcings in the 20th century and generate them more or less randomly for the 21st century, or, conversely, not consider them in either the 20th or 21st centuries.
The second solution was chosen. The simulations from 1860 to 2000 are performed considering only forcings due to human activities: increased greenhouse gases and sulfate aerosols. The evolution of greenhouse gas concentrations distributed homogeneously in the atmosphere, such as CO2 or CH4, is well-known. It has been directly measured in the air for a few decades (since 1958 for CO2) and in air bubbles trapped in glaciers for earlier periods.
Unlike gases well-distributed in the atmosphere, the concentration of sulfate aerosols is highly variable in space and time. Based on measurements from various sites, it is not possible to directly estimate the geographical distribution of aerosols and their temporal evolution. A chemistry-transport model must be used. The sulfate aerosol concentrations calculated by Boucher and Pham (2002) and recommended by the IPCC were utilized.

III.1.1.2. Socio-Economic Scenarios

Socio-economic scenarios involve making various assumptions about future economic development and its impacts on the environment. These scenarios are provided by integrated impact models that consider the evolution of population, economy, industrial and agricultural development, and, in a simplified manner, atmospheric chemistry and climate change. These integrated impact models offer scenarios of greenhouse gas and aerosol evolution, which are introduced as forcings in coupled ocean-atmosphere simulations.
We are currently in the second generation of scenarios known as SRES (Second Report on Emission Scenario). Previously, for the first and second reports, the 6 IS92 scenarios (for IPCC Scenarios) were used. The different scenarios from the fourth IPCC report are described in the summary for policymakers of Working Group I.

Table III.1: SRES projection scenarios

Scenarios \ Forces		Energy Technologies	World population	Environment	Economic Situation
A1		Rapid integration of non-technologic more efficiently	Reaches its maximum in the middle of the century and then declines	Essentially technological solutions to protect the environment	Very rapid growth Reduction of regional differences in income
	A1T	Exploitation of non-fossil energy sources			
	A1B	Balanced exploitation of resources			
	AIFI	Heavy exploitation of fossil energy sources			
A2 (Heterogeneous scenario)		Technological progress is heterogeneous and slow	Augmentation constant	Divergence in solutions	Per capita growth fragmented and slow. Regionally oriented development
B1 (Convergent scenario)		Rapid development of clean technologies based on efficient use of resources	Reaches its maximum in the middle of the century and then decreases	Global Solutions	Very fast growth Economy oriented towards the valorization of services and information
B2 (Local scenario)		Slow --- differentiated according to regions	Steady increase	Regional solutions	Several levels of economic growth, oriented towards local solutions

The A1 scenario family describes a future world where economic growth will be rapid, the global population will peak in the middle of the century before declining, and new more efficient technologies will be rapidly introduced. The key underlying themes include convergence between regions, enhanced capabilities, increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.

a) The A1 scenario family is divided into three groups that describe possible directions of technological evolution in the energy system. The three A1 groups are distinguished by their technological focus:

- High fossil fuel intensity (A1FI),
- Non-fossil energy sources (A1T),
- Balance between sources (A1B) ("balance" meaning not overly relying on a particular energy source, assuming similar rates of improvement apply to all energy supply and end-use technologies).
- b) **The A2 scenario family** describes a highly heterogeneous world. The underlying theme is self-sufficiency and the preservation of local identities. Fertility patterns between regions converge very slowly, resulting in a continuous increase in the global population. Economic development is primarily regionally oriented, and per capita economic growth and technological evolution are more fragmented and slower than in other frameworks.

- c) **The B1 scenario family** depicts a convergent world with the same global population peaking in the middle of the century and declining thereafter, as in the A1 framework, but with rapid changes in economic structures towards a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The focus is on global solutions oriented towards economic, social, and environmental sustainability, including greater equity, but without additional initiatives to manage the climate.
- d) **The B2 scenario family** portrays a world where the emphasis is on local solutions in terms of economic, social, and environmental sustainability. The global population continues to grow but at a slower pace than in A2, there are intermediate levels of economic development, and technological evolution is slower and more diverse than in the B1 and A1 frameworks and scenario families. The scenarios are also geared towards environmental protection and social equity but are focused on local and regional levels.

In summary:

- A1: Reduction of North-South inequalities with economic development following the current pattern.
- B1: Reduction of North-South inequalities with environmentally conscious and sustainable development.
- A2: Heterogeneous development with economic growth following the current pattern.
- B2: Heterogeneous development with environmentally conscious and sustainable development.

The diagram below, which combines the approaches of the IPCC and that of the Millennium Project, illustrates the different scenarios (Figure. III.1).:

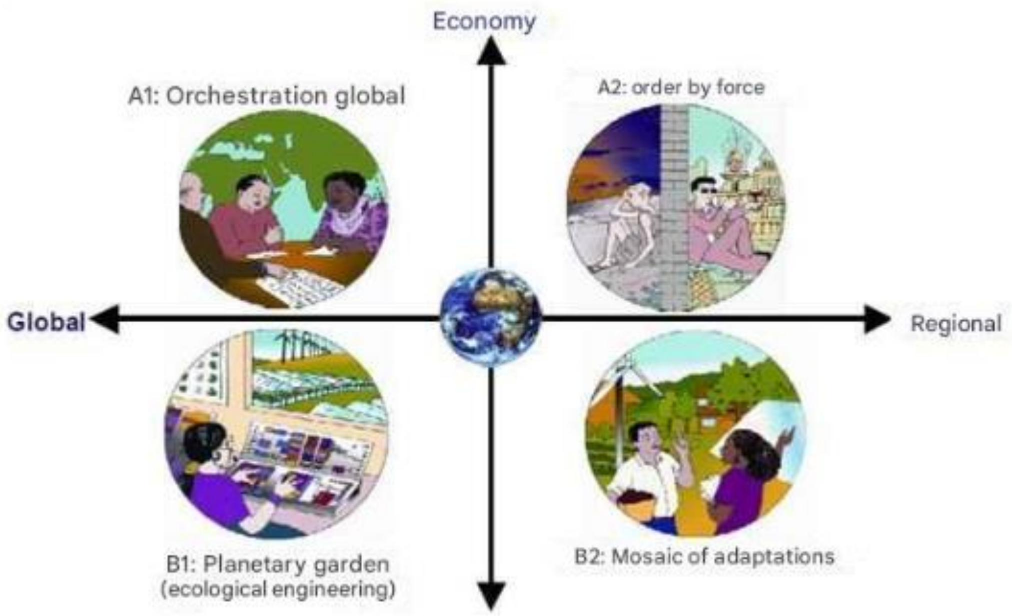


Figure III.1: The SRES Scenarios

Source: White Paper ESCRIME & Internal Note RETIC Météo-France

III.1.1.3. The new scenarios of the IPCC

During the preparation of the 5th Report, a different approach was adopted to expedite the evaluation process. In order to analyze the future of climate change, IPCC experts this time predefined four trajectories of greenhouse gas emissions and concentrations, ozone, aerosols, and land use called RCPs ("Representative Concentration Pathways"). These RCPs are used by different teams of experts (climatologists, hydrologists, agronomists, economists, etc.) who are working in parallel for the first time. Climatologists derive global or regional climate projections from these RCPs. Economists develop scenarios exploring all possible technological and socio-economic developments compatible with the RCPs.

III.1.1.3.1. What do the RCPs correspond to?

The four profiles of greenhouse gas concentration evolution (RCPs) selected by the IPCC experts for the 5th Report have been translated into terms of radiative forcing, which denotes the modification of the planet's radiative balance. The radiative balance represents the difference between the received solar radiation and the infrared radiation emitted by the planet. It is calculated at the top of the troposphere (between 10 and 16 km altitude). Due to climate change factors, such as greenhouse gas concentration, this balance is altered, known as radiative forcing. The 4 RCP profiles each correspond to a different evolution of this forcing by the year 2300. They are identified by a number, expressed in W/m^2 (power per unit area), indicating the value of the considered forcing. The higher this value, the more energy the Earth-atmosphere system gains, leading to warming (Figure. III.2).

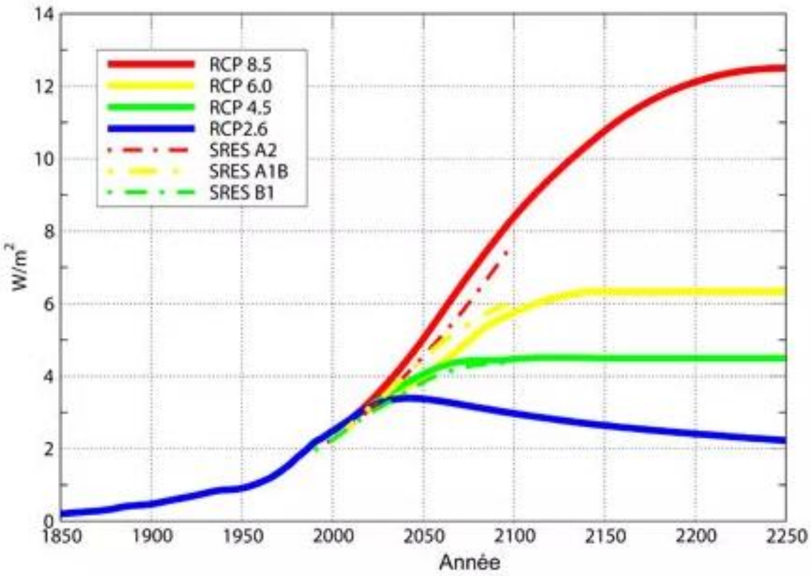


Figure III.2. Evolution of Earth's radiative balance or "radiative forcing" in W/m² over the period 1850-2250 according to different scenarios.

After 2006, the solid lines represent the new scenarios known as RCPs (Representative Concentration Pathways), and the dashed lines represent scenarios from the IPCC reports of 2001 and 2007.

III.1.1.3.2. Comparison between RCPs and old scenarios

The RCPs and scenarios used in the 2001 and 2007 Reports overlap partially. However, the RCPs cover a longer period: up to 2300 (2100 for the old scenarios).

- The RCP 8.5 profile is the most extreme (pessimistic). It is slightly stronger than the most pronounced scenario used in the simulations of the IPCC 2007 report (A2).
- The RCP 6.0 and RCP 4.5 profiles correspond closely and respectively to scenarios A1B and B1.

Lastly, the RCP 2.6 profile has no equivalent in the previous IPCC proposals. Its realization involves, and this is a significant novelty, the integration of emission reduction policy effects capable of limiting global warming to 2°C.

III.2. Global and Regional Climate Models

Predicting climate change based on greenhouse gas emission scenarios relies on the use of climate models. These models can be described as mathematical representations of the climate system, grounded in physical, chemical, and sometimes biological laws. The equations derived from these laws are so intricate that they necessitate numerical solutions. To solve them, the submerged and emerged surfaces, as well as the atmosphere, are modeled using a three-dimensional grid covering the globe.

Vertical and horizontal exchanges are simulated at each grid point. Therefore, climate models provide a discrete solution in time and space, with the results representing averages at a specific time scale and regional level, whose size depends on the resolution of the model grid cells (ranging from 150 to 300 km). Among these models, the most effective tool appears to be the coupled atmosphere-ocean general circulation model (AOGCM) (Giorgi & Mearns, 2002). The atmospheric component of an AOGCM (the atmospheric GCM) is linked with a land use scheme and utilized to predict changes in representative land surface state variables (such as soil moisture).

Global Circulation Models (GCMs) calculate future climate changes under anthropogenic influence, that is, the present and future emissions of greenhouse gases (IPCC, 2001a). Their use is widespread in studies assessing the impacts of climate change (IPCC, 2001b; Reilly et al., 2001). These models provide internal consistency in climate by solving, on a global scale, the relevant and explanatory equations of the physical processes related to climate (Figure. III.3).

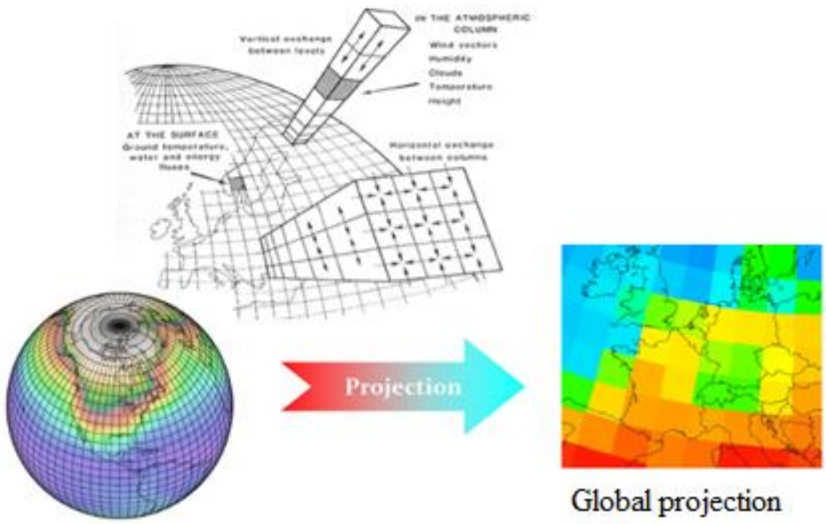


Figure III.3: Depicts a three-dimensional and discretized representation of the climate system along with a typical grid structure used in climate models (adapted from Pag et al., 2010).

The climate projections from Global Circulation Models (GCMs) are subject to significant uncertainties due to their low spatial resolution and our still limited understanding (epistemic error) of key climate dynamics (IPCC, 2001a). Even among GCMs predicting similar temperature changes, forecasts of regional precipitation can vary considerably due to the inherently chaotic nature of the climate and the different approaches used to resolve local to regional atmospheric dynamics. For instance, GCM projections of the extent and location of changes in soil moisture are often conflicting and challenging to compare due to significant variations in land use patterns used by AOGCMs, casting doubt on their accuracy (Cornwell & Harvey, 2007).

This scenario presents a challenge when assessing the impacts of climate change on grasslands and crops. Many studies have based their impact projections on a single GCM, thus overlooking a major source of uncertainty (IPCC, 2007a). Additionally, the low spatial resolution of GCMs greatly limits the accuracy of local projections of climate changes, especially in areas with complex terrains. To enhance the accuracy of describing climate at a regional scale, the use of Regional Climate Models (RCMs) forced by GCMs is widely employed in studies on regional impacts (Giorgi & Mearns, 1999; IPCC, 2007a).

III.2.1. Simulations of Climate at Regional Scale in Europe

a) Introduction and Presentation of the Concepts of "Dynamic Downscaling" of Climate Evolution Scenarios

The warming of the climate system in recent decades is evident from observations, primarily attributed to the increase in anthropogenic greenhouse gas (GES) concentrations (IPCC, 2013). Consequently, the precipitation rate will also be altered, partly because a warmer atmosphere will contain more water vapor, leading to heavier rainfall. Moreover, these processes will result in increased droughts in certain areas, partly due to greater water absorption from the soil and vegetation.

The primary tool for understanding and predicting possible future climate changes is climate modeling. Climate models are software tools that simulate the behavior of Earth systems based on fundamental laws of physics.

Specifically, General Circulation Models (GCMs) that simulate climatic dynamics at a planetary scale are powerful instruments for simulating the global climate system's response to external forces (Giorgi, 2005).

However, in general, GCMs are not suitable for simulating local climates since they currently feature resolutions typically around 100 km or coarser, while many important phenomena occur at spatial scales below 10 km. Additionally, GCMs do not adequately account for variations in vegetation, complex topographies, and coastal zones, which are significant aspects of the physical response governing the signal of regional/local climate changes. As a result, downscaling techniques have been developed that utilize the large-scale predictions provided by a GCM and implement methods to extract implicit information on climate changes at more regional/local scales (Figure. III.4).

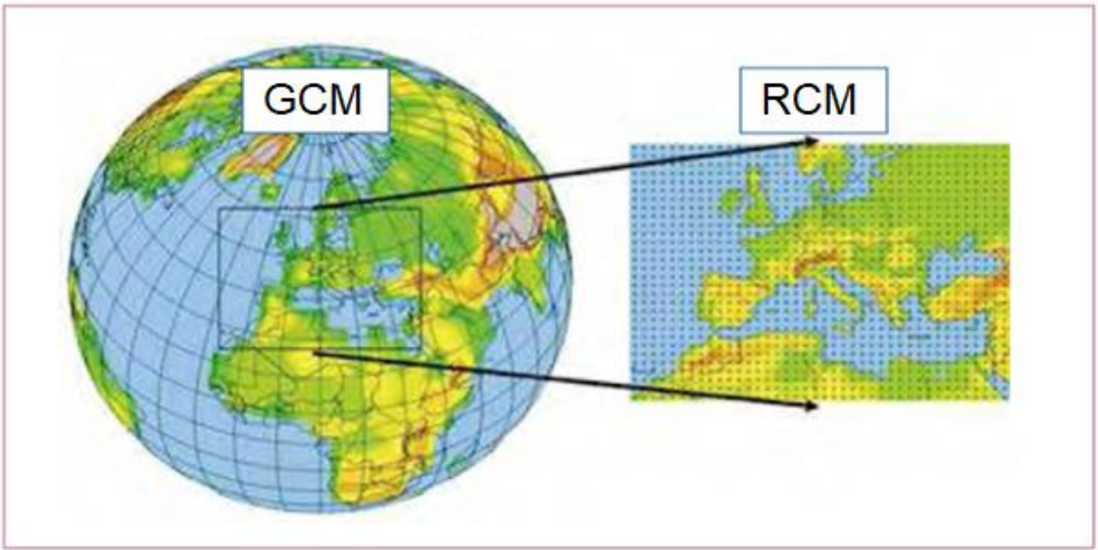


Figure III.4: Illustrates a schematic representation of the dynamic downscaling technique.

Downscaling methods can be broadly categorized into two main types: statistical methods, which apply transformations to the output data of GCMs based on relationships calculated from high-resolution observations, and dynamic methods, which explicitly resolve the physical dynamics based on processes of the regional climatic system at high spatial resolution when driven by the large-scale and low-resolution forcing of GCMs. One of the most effective tools for providing high-resolution climate analysis through dynamic downscaling is the Regional Climate Model (RCM) (Giorgi & Mearns, 1991). RCMs often have the capability to offer precise descriptions of climate variability at the local scale. Additionally, RCMs can provide detailed descriptions of extreme weather conditions, including statistical data on extreme meteorological events (Rummukainen, 2010).

The capabilities of the current generation of RCMs have been assessed in various international projects. In recent years, the establishment of the experimental project for regional climate simulation by the PRUDENCE Model Regional Climate (CORDEXLI2) (Giorgi et al., 2009) aims to globally coordinate the regional downscaling of climate data to improve policies for adapting to the effects of climate change and impact studies. Naturally, dynamic downscaling also has some drawbacks: it is a computationally expensive method that relies on large-scale computing facilities and is highly dependent on the boundary conditions provided by GCMs. If a large-scale simulation produced by a GCM contains errors, they may propagate to the downscaled results.

Errors in large-scale simulations from GCMs can be transferred to the output data of RCMs, a concept known as "garbage in-garbage out," indicating that inaccurate input data will lead to erroneous results. Additionally, RCMs (similar to GCMs) incorporate semi-empirical parameterization schemes, such as for convection, which assumes that these parameterization schemes will remain valid in a future climate. Another constraint is that the spatial resolution of most current-generation models is limited to approximately 1 km due to the substantial computational resources required for finer grids, as well as the lack of suitable numerical models for certain processes at such resolution values.

Regional Climate Models (RCMs) must undergo validation against observational datasets to assess the model's ability to replicate current climatic conditions. This validation process helps identify deficiencies in the model arising from various modeling assumptions and associated uncertainties. Two distinct types of data can be used as initial and boundary conditions for an RCM to evaluate its capability in simulating the current climate: (i) reanalysis data and (ii) GCMs trained with the currently observed radiative forcing of greenhouse gases. The most commonly used reanalyses for RCM simulations are the ERA-InterimHypL3, the latest atmospheric interim global reanalyses produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Reanalyses serve as our best estimates of the observed climate on a large scale at a particular time in recent years, as they are based on real observations of the climatic system. ERA-Interim data have been available since 1979 and are continuously updated in real-time.

Utilizing reanalysis data as initial and boundary conditions for RCMs allows for the evaluation of the model's ability to replicate the most crucial climatic features of a specific region. GCMs (with the current radiative forcing of greenhouse gases) are not constrained by atmospheric observations during their integration and thus may develop systematic errors (drift) that can contribute to errors in the RCMs they drive. Nonetheless, these experiments are valuable as they provide a basis for comparing RCM experiments driven by projections of climate change in GCMs (IPCC scenarios). In this manner, RCMs generate high-resolution estimates of climate change projections.

One significant source of uncertainty in Regional Climate Models (RCMs) stems from the multitude of parameterized physical processes in the climate model and the associated unrestricted model parameters. Several studies have highlighted the importance of this "parameter uncertainty" in simulating current and future climates by perturbing single and multiple model parameters within plausible ranges determined by experts (Giorgi & Mearns, 1991). Since uncertain parameters contribute significantly to modeling errors, parameter uncertainty is typically addressed through calibration or tuning methods aimed at enhancing the interface between the climate model and available observational data. This tuning process is one of the aspects that require highly specialized technical skills to ensure effective implementation and operation of the RCM.

III.3. Impact on the hydrological cycle

The hydrological cycle is influenced by changes in climate parameters and can have very significant local impacts.

III.3.1. Temperature changes

Since the beginning of the Industrial Revolution, humans have significantly altered the concentration of greenhouse gases (GES) in the atmosphere, primarily CO2, CH4, N2O.

The increase in Earth's heat flux by 2.3 W/m2 since 1750 has led to an estimated average surface temperature rise of 0.74°C over the past century. The rise in greenhouse gas concentrations results in increased infrared radiation, particularly towards the surface. This additional energy promotes evaporation and evapotranspiration, making the atmosphere more humid, thus favoring precipitation, explaining the impact of climate change on the hydrological cycle (Dayon, 2015). Climate feedbacks, especially those of water vapor, clouds, and surface albedo, are key components in amplifying the initial temperature variations resulting from doubling atmospheric CO2 concentration. According to the IPCC report in 2007, doubling atmospheric CO2 concentration could lead to a temperature increase ranging between 2 and 4.5°C, with an average of 3°C.

III.3.2. Changes in precipitation

Precipitation levels appear to have slightly increased over the past century, as illustrated by Solomon et al. (2007) and confirmed by the findings of Boe (2007), who noted that in recent decades, precipitation has increased at a rate close to 7% per 1°C of humidity and thus the Clausius-Clapeyron ratio. Opposing trends have been observed in many regions. Drying has been observed in the Mediterranean, southern Africa, southern Asia, and the Sahel, while a significant increase in precipitation has been noted in northern Europe, northern Asia, central Asia, South America, and North America.

Lespinas (2008) stated that precipitation tends to increase over continents located beyond 30° North, while it has decreased at tropical latitudes over the same period. Pall et al. (2006) confirmed that the most intense precipitation events globally occur primarily in the tropics. They investigated the link between extreme events and the Clausius-Clapeyron relationship and analyzed the distribution of extremes across latitudes (Figure. III.5). Between 60°N and 60°S, there is both a decrease in the intensity of low-intensity events and an increase in the intensity of rare events. Above 60°N and 60°S, precipitation increases for all quantiles. A compensation system is due to maintaining the constraint of the energy balance, where increased humidity enhances the development of the most intense convective precipitation systems, offset by a decrease in low-intensity events at middle and lower latitudes.

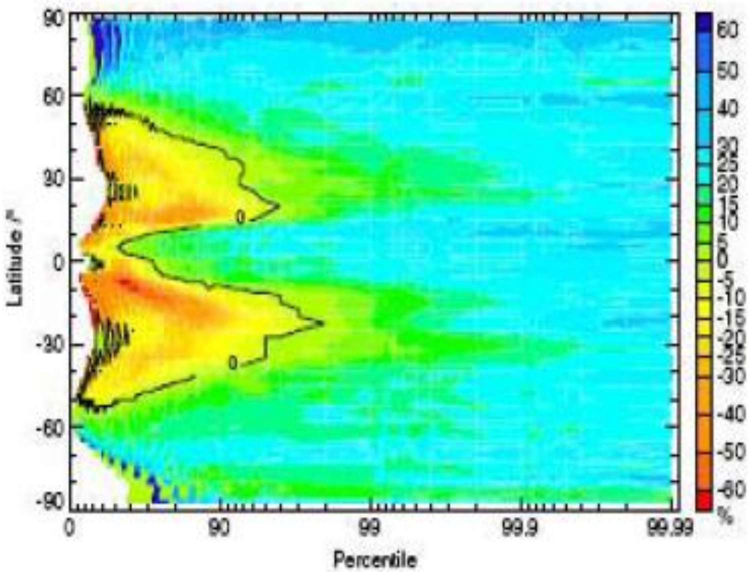


Figure III.5: Relative change in intensity of zonally aggregated precipitation percentiles.

Source: Pall et al., 2006.

The movement of precipitation follows a South-North direction. In July, heavy precipitation occurs in regions of West Africa, India, and Central America, while during the austral summer, it is concentrated in the Amazon and Indonesia.

The influence of orography on precipitation accumulation is significant. The Sahara, characterized by very low precipitation rates (subsidence region), contrasts with the Himalayas and the Andes, which contribute to significant precipitation in India and the Amazon (Figure III.6). These precipitation patterns result from the large-scale transport of humid air, evapotranspiration, condensation, and the distribution of solar energy on Earth (Dayon, 2015).

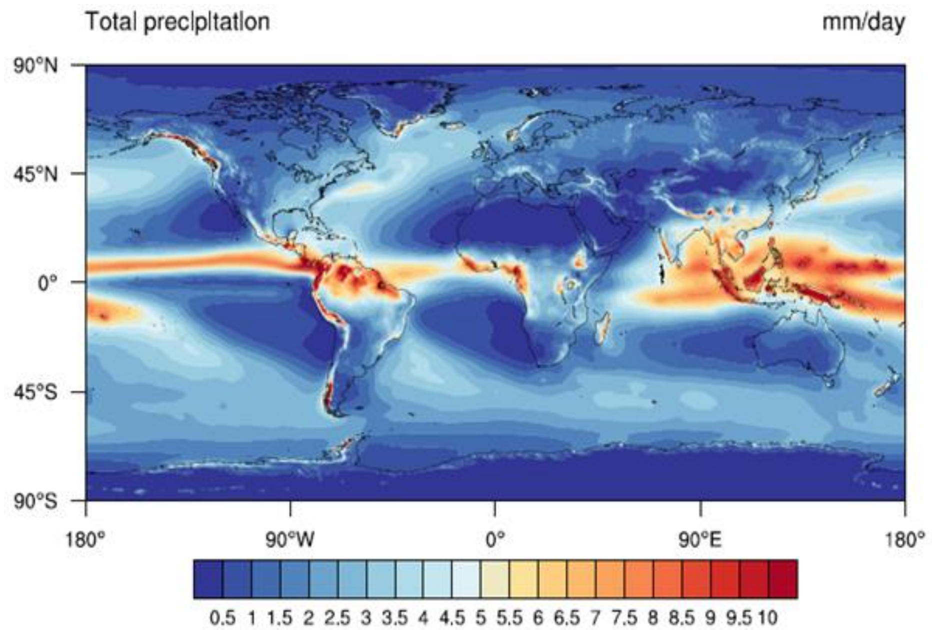


Figure III.6: Annual average precipitation (mm/day) during the period 1979-2014 estimated from the MERRA reanalysis.

III.3.3. Changes in Extreme Precipitation Values

Several authors have investigated changes in extreme precipitation values, focusing on limited parts of the globe. Alexander et al. (2006) examined these changes across most continental zones from 1951 to 2003, finding low spatial coherence in the observed changes and noting an increase in very rainy days in total annual observations over the past decades. Frich et al. (2002) confirmed the relatively low spatial coherence, particularly in the Northern Hemisphere, Australia, and South Africa. They reported significant trends, including an increase in the number of days with rainfall exceeding 10mm and in the annual maxima of five-day accumulations, as well as a decrease in the duration of longest dry periods. The frequency of extreme rainfall events has notably increased above the average in extratropical regions (Groisman et al., 2005).

Studies at the regional level have identified an increase in heavy rainfall events in specific areas: the United States (Karl and Knight, 1998; Trenberth, 1998), Russia (Gruza et al., 1999), Europe (Tank and Konnen, 2003; Moberg and Jones, 2005), Japan (Iwashima and Yamamoto, 1993), and Switzerland (Frei and Scha¨r, 2001).

In contrast, a decrease in heavy rainfall events has been observed in subtropical regions, such as Western Africa by Trenberth et al. (2007) and Panthou (2013), Southwest Australia by Hennessy et al. (1999), Niger by Shinoda et al., (1999), and the Sahel region of Sudan, including the Ethiopian Plateau, by Nicholson (1993); Tarhule and Woo (1998); and Easterling et al. (2000).

III.3.4. Changes in Evaporation

Held and Soden (2006) highlighted that the atmosphere can hold about 7% more water vapor before saturation with a 1°C increase in air temperature. This increase is a result of higher greenhouse gas concentrations. Boe (2013) suggested that human-emitted aerosols could significantly disrupt the hydrological cycle, leading to a reduction in available surface energy due to decreased solar radiation reaching the surface.

Romanou et al. (2007) concluded that aerosols can impact the hydrological cycle by reducing evaporation. They analyzed GISS model results over the 20th century and found that direct aerosol effects had the most significant modeled variation, followed by indirect aerosol effects, focusing primarily on changes in aerosols, water vapor, and clouds.

Ptashnik et al. (2011) emphasized the uncertainty in estimating the impact of water vapor changes on surface solar irradiance. They demonstrated that water vapor self-continuum models used in GCMs likely underestimate absorption in near-infrared transparent bands.

Haywood et al. (2011) concluded that historical changes in total surface solar irradiance are likely attributed to aerosols through direct and indirect effects. They also suggested that future changes in cloud-free surface solar irradiance will be mainly influenced by increased water vapor concentrations resulting from water vapor feedback.

Several authors have confirmed decreasing trends in evaporation over the past decades in various regions worldwide: the United States (Peterson et al., 1995; Golubev et al., 2001; Hobbins et al., 2004), India (Chattopadhyay and Hulme, 1997), Australia (Roderick and Farquhar, 2004), New Zealand (Roderick and Farquhar, 2005), China (Liu et al., 2004a), and Thailand (Tebakari et al., 2005).

This trend is more likely due to:

1. The decrease in surface solar radiation over the United States and certain parts of Europe and Russia (Abakumova et al., 1996; Liepert, 2002).
2. The reduction in sunshine duration in China (Kaiser and Qian, 2002), which may be linked to increased air pollution and atmospheric aerosols (Liepert et al., 2004).
3. The increase in cloud cover.

III.3.5. Changes in Evapotranspiration

Changes in evapotranspiration are often calculated using empirical models based on precipitation, wind, and net surface radiation (Milly and Dunne, 2001), or land surface models (e.g., Van Den Dool et al., 2003). Actual evapotranspiration increased during the latter half of the 20th century in most arid regions of the United States and Russia (Golubev et al., 2001). Qian et al. (2006a) found that global land evapotranspiration closely tracks land precipitation variability, especially in tropical areas. Changes in evapotranspiration depend not only on moisture availability but also on energy availability and surface wind (IPCC, 2007).

III.3.6. Soil Moisture Changes

Robock et al. (2000) focused on changes in soil moisture and found that only a few regions have archives of in situ measured soil moisture content. Robock et al. (2005) examined a 45-year history of soil moisture in agricultural areas of Ukraine, showing an upward trend in the series. During the 20th century, global soil moisture variations were estimated using Least-Squares Monte Carlo simulation models, which contradicted results based on forcings such as radiation (clouds), precipitation, winds, and other meteorological variables (IPCC, 2007).

Dai and Trenberth (2002) noted that available records of streamflow gauging cover only two-thirds of the actual drained areas globally, with gaps and variability in the recording period. Probst and Tardy (1987), (1989); and Labat et al. (2004) criticized estimates of global river flows (incomplete records) and confirmed significant decadal to multi-decadal variations in continental or global freshwater flows (excluding groundwater).

III.3.7. Runoff and River Flow Changes

Increased runoff has been observed in major global rivers during the latter half of the 20th century. Kundzewicz et al. (2004), (2005) demonstrated long-term changes in 137 out of 195 rivers worldwide, with two increases (in 27 cases), decreases (in 31 cases), and non-significant changes (10% of cases). Studies have shown that rapid warming since the 1970s has led to earlier snowmelt associated with peak flows: (Cayan et al., 2001) in the Western United States and New England, (Smith & Almaraz, 2004) early ice breakup in Arctic Russian rivers, and (Zhang et al., 2004) in Canada.

South America, authors such as Camilloni and Barros (2003), and Krepper et al. (2003) have confirmed that monthly and extreme river flows are linked to El Niño, La Niña, and ENSO phenomena. The Paraná, Paraguay, and Uruguay rivers have shown positive trends in annual mean flows since the 1970s, consistent with regional precipitation trends (García and Vargas, 1998; Liebmann et al., 2004) (Figure. III.7).

In Asia, Yang et al. (2002) noted a decrease in ice thickness during the cold season, snowmelt in spring, and increased peak flows in June in the Lena River basin in Siberia due to rising temperatures and precipitation. In the Yellow River basin in China, there has been a negative trend in flow over the last fifty years of the 20th century).

In Africa, Jury (2003) observed a decrease in flow in the Senegal, Congo, Niger, and Egypt rivers. The five lowest flow years for these rivers have been observed after 1971.

In Europe, the Meuse River basin, originating in France, flowing through Belgium and the Netherlands, and ultimately reaching the Haringvliet estuary, has been studied by Bauwens et al. (2013). They concluded that low water levels and droughts, attributed to climate change, impact navigation, agriculture, and water availability during the summer season.

In Australia, the Murray-Darling Basin supports around 70% of irrigated land and 40% of the country's agricultural production. This basin has been severely affected by drought, with water levels in the river remaining very low (the river no longer reaches the sea 4 days out of 10), causing damage not only to agriculture but also to the ecological health of the river and ecosystems (Melanie, 2011).

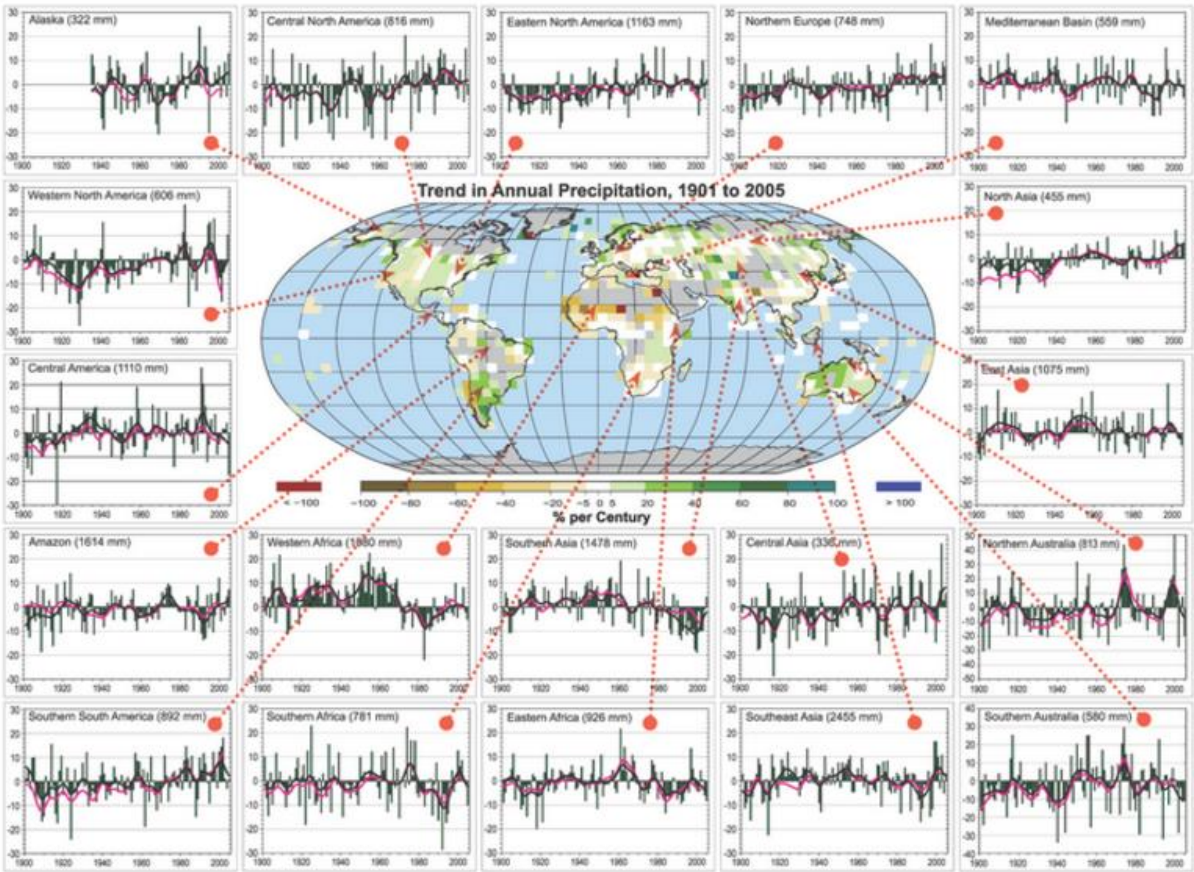


Figure III.7: displays precipitation from 1900 to 2005. The central map illustrates average annual trends (% per century), while the surrounding time series show annual precipitation (% of the average, with the mean provided at the top from 1961 to 1990) for regions indicated by the red arrows. Source: (IPCC, 2007).

Chapter IV:
Water management in a context of variability

IV.1. Managing risks and increasing resilience

Managing risks of natural disasters and enhancing resilience are essential components of the adaptation concept. Climate change leads to an increase in the frequency and intensity of extreme weather events. This trend is already noticeable and is expected to intensify in the coming years. The number of people affected and the economic costs of these disasters will also rise due to demographic and socioeconomic changes. While it is impossible to prevent a natural disaster, preparations and strategies can be implemented to mitigate and respond to them. In line with this goal, the United Nations adopted the Hyogo Framework for Action in January 2005. This framework is based on five pillars:

- Priority 1: Ensure that disaster risk reduction is a national and local priority with a strong institutional basis for implementation.
- Priority 2: Identify, assess, and monitor disaster risks and enhance early warning.
- Priority 3: Use knowledge, innovation, and education to build a culture of safety and resilience at all levels.
- Priority 4: Reduce the underlying risk factors.
- Priority 5: Strengthen disaster preparedness for an effective response at all levels.

By focusing on these pillars, countries can enhance their disaster risk management strategies and build resilience to cope with the increasing challenges posed by climate change and natural disasters.

To effectively manage risks and enhance resilience, there are key strategies outlined in the Hyogo Framework for Action:

1. **Establish disaster risk reduction as a priority:** Ensure that disaster risk reduction is a national and local priority with a strong institutional framework, incorporate hazard considerations into decision-making, and enact necessary legislative and organizational measures for disaster risk reduction integration.
2. **Identify risks and take action:** Highlight, evaluate, and monitor disaster risks, and strengthen early warning systems.
3. **Promote risk understanding and awareness:** Utilize knowledge, innovation, and education to foster a culture of safety and resilience at all levels.
4. **Reduce underlying risks:** Implement construction standards, limit development in vulnerable areas, and decrease vulnerability.
5. **Prepare and be ready to respond:** Enhance disaster preparedness to enable effective response at all levels, establish emergency plans and special funds, improve coordination and dialogue among various stakeholders.

By following these actions, countries can enhance their resilience to disasters and effectively manage risks associated with climate change and natural hazards.

The Hyogo Framework for Action, although not directly linked to international climate change negotiations, is inherently connected to adaptation. The Conference of the Parties to the UNFCCC in 2010 urges countries to apply the Hyogo Framework for Action. This framework is currently under review in the post-2015 context. The new framework is expected to focus on implementation mechanisms. Consultations have highlighted the need to strengthen pillar 4 of Hyogo on underlying factors, involve all stakeholders and relevant actors, including civil society, the private sector, and the scientific community. It should also enhance monitoring using impact indicators rather than means.

IV.2. Adaptation and development

While mitigation is a global issue, adaptation is specific to each context based on geographical, socioeconomic data, and expected climate changes. Adaptation will not be the same in Asian regions subject to the monsoon system as in arid and semi-arid regions in Africa. The adaptation challenges differ between urban and rural environments. One of the primary conditions necessary for adaptation is the improvement of information and knowledge related to climate changes. Indeed, while global climate changes are relatively well modeled, the modeling of changes at smaller scales and understanding their impacts vary significantly among regions. However, this information is essential for implementing effective adaptation strategies.

Adaptation challenges span across various sectors, emphasizing the importance of fostering synergies between adaptation, development, and disaster risk management actions. Institutional strengthening, capacity building, and governance improvement in all sectors help enhance overall resilience capacity and should be key components of all adaptation strategies.

Enhancing adaptation and increasing resilience of populations and societies also require investments, particularly in infrastructure. These infrastructures may include climate monitoring systems, early warning systems, and essential service access infrastructure, especially in least developed and developing countries where poverty is a significant vulnerability factor to climate change. Given the uncertainty regarding the specific impacts of climate change, the concept of "no-regrets investments" has emerged, which are investments with positive returns regardless of the climate scenario.

According to Hallegatte et al (2008), an adaptation measure is considered "no-regrets" if the decision is not regretted even if the anticipated risk does not materialize. This means that the measure has reasons beyond adaptation for its implementation. For instance, strengthening rainwater drainage systems is a no-regrets measure as it helps mitigate flood risks and remains beneficial even if the flood does not occur. Systematically integrating the risk concept into investment decision-making processes is also a factor in resilience and adaptation.

IV.3. Limits of Adaptation

The main challenge of adaptation is to prepare societies for ongoing and future changes, but it has its limitations. Considerations must be given to maladaptation issues, where adaptation policies may inadvertently increase vulnerability instead of reducing it. This can occur when present adaptation measures compromise future adaptive capacity. Misuse of resources or calibration errors can lead to maladaptation due to uncertainty. Opting for no-regrets solutions, which are beneficial regardless of climate scenarios, can mitigate the risk of maladaptation. Additionally, adaptation has tangible limits, as beyond a certain threshold of climate change, societies or biological systems may no longer be able to adapt. In response to this, developing countries advocate for a separate mechanism for loss and damage distinct from adaptation in climate negotiations, to address situations where adaptation is no longer feasible. However, developed countries are cautious about emphasizing this mechanism to avoid potential financial compensation demands, preferring to connect it with the adaptation pillar.

IV.4. The Strategic Role of Water in Adaptation

Water is at the core of adaptation strategies because it is central to climate change. It will be the primary conduit for the disruptions experienced and lived by populations. Moreover, due to its transversal nature, water impacts all aspects of human development.

IV.4.1. Drinking Water

Adaptation measures related to drinking water primarily focus on improving water and sanitation services management. The widespread adoption of Integrated Water Resources Management (IWRM) is key to climate change adaptation. Water management has always involved considering the natural variability of water supply. Climate change exacerbates this variability. Therefore, water resources need to be sustainably managed, considering this new uncertainty in developing management strategies and decision-making. Managing or reducing this uncertainty involves better information and knowledge management, assessing expected climate-related changes along with other socioeconomic factors, and developing suitable monitoring systems. It is also crucial to plan for new investments, focus on system maintenance and rehabilitation to ensure universal access to safe drinking water and secure water supply. Access to essential services is fundamental for adaptation and enhancing the resilience capacity of populations.

IV.4.2. Agricultural Water

Managing agricultural water is a crucial aspect of adaptation in the water sector. Agriculture accounts for 70% of freshwater resource use. It is essential to enhance or implement new practices that enable optimal water resource utilization (Bates et al., 2008). Adopting drought and heat-resistant crop varieties or species, changing irrigation techniques, implementing practices for soil moisture conservation (e.g., crop residue retention), reducing waterlogging and soil leaching, establishing seasonal climate forecasts, and potentially changing land use are pathways for adapting the agricultural sector in water management. Scientific projections indicate that while irrigation water helps mitigate climate impacts in a context of mild to moderate warming, it also imposes additional constraints on water resources and ecosystems as warming increases. In this context, family farming systems are particularly vulnerable to climate change, especially in the Global South. While climate variability has always been part of traditional agricultural management practices, increased variability coupled with growing challenges in accessing water resources due to heightened sectoral competition pose a significant threat to small-scale farmers in the Global South. Developing water-efficient agricultural techniques is only part of the solution. Progress in water governance and management approaches is also essential to ensure water access for small-scale farmers, who are key to food security.

IV.4.3. Ecosystem Preservation

The preservation of ecosystems primarily depends on the rate at which climate change occurs: the slower the changes, the more species will have the capacity to adapt to these changes (IPCC, 2014), for example, by developing migratory strategies. Therefore, if climate changes are too rapid, numerous species extinctions can be expected. In the realm of water, conserving wetlands, which are true biodiversity hotspots, is essential. Once again, the development of integrated water management systems should enable better consideration of the impacts of human activities on ecosystems.

IV.4.4. Sanitation

According to the IPCC (Bates et al., 2008), the most significant impacts of climate change on human health will involve malnutrition and water scarcity (for drinking and production). Poor health significantly increases population vulnerability and has significant socio-economic consequences. Inadequate sanitation also has serious health implications through diseases associated with consuming contaminated water. Enhancing access to safe water and efficient sanitation systems is the primary adaptation response to climate change concerning health, along with improving access to basic healthcare services.

This brief overview of the connections between "water and adaptation" and "water and mitigation" highlights the interrelations between water and various sectors: energy, global warming, agriculture. A strong integration of these policies is essential to create synergies, as evidenced by current research on the "water, global warming, agriculture, and energy" nexus.

IV.5. Legal and Institutional Frameworks

Legal and institutional frameworks are crucial for climate change adaptation as they encompass essential minimum provisions for water governance, such as water quality standards, water management objectives, dispute resolution mechanisms, negotiation of compromises, and means to prioritize water allocation. Legislative frameworks also establish institutions and designate specific bodies to regulate water use and management. Legislation can identify actors participating in decision-making at the basin level. This section examines specific provisions of legal frameworks, which are fundamental for building adaptive capacity in transboundary basins, and general factors enabling the implementation of these provisions. Legal frameworks must ensure stability and security in relationships through clear rules, standards, and strict enforcement, while allowing for some flexibility through amendments, revisions, or monitoring. Legal frameworks should be adaptable and flexible to address uncertainties, complexities, power shifts, and climate change impacts in a transboundary context. Legal frameworks play a significant role in creating favorable conditions to enable (or restrict) decision-making and the implementation of effective transboundary adaptation measures. Four key favorable factors enhancing the resilience of legal frameworks are outlined below.

- **Legal and institutional "flexibility":** What is the degree of flexibility in the relationships between water management entities? Can they be easily adjusted or renegotiated when climate change alters relevant parameters of freshwater resources, regimes, and precipitation variability? How are crisis periods managed? However, flexibility mechanisms can reduce the certainty and stability envisioned by the law; thus, flexibility must be reconciled with legal rigidity.
- **Multi-level governance:** How are water management issues consistently addressed across governance levels? How are new problems identified?
- **Engagement of actors and public participation:** Can new institutions be integrated into governance relationships? How are compromises evaluated? Who is identified as an actor, and how are these voices articulated? What happens when the needs or priorities of institutions change over time?
- **Environmental allocations (environmental flows or e-flows):** How are environmental allocations identified, monitored, assessed, and compensated? Are

ecological and biophysical processes related to water clearly defined? Who "owns" the water, and what is the long-term sustainability vision of eco-hydrology used to guide values and decisions on the environment?

These favorable factors are interdependent and mutually reinforcing, and their operation influences the successful implementation of best practices. As climate change poses a significant challenge to water governance, legal and institutional frameworks can either enhance or impede adaptive capacity and the integrity of eco-hydrology and institutions. Multi-level governance can also enhance the development of legal or regulatory strategies at a specific scale and other adaptation measures to manage water-related climate change impacts.

IV.6. Adaptable Legal Frameworks

Legal frameworks delineate formal cooperation processes, such as communication methods, water allocation strategies, and ways to prevent and assist each other during extreme weather events. They may include provisions on prevention, emergency measures, and response to flow variability (such as floods), information exchange, adaptive capacity, and natural resource monitoring. Numerous aspects of international water law can also facilitate adaptation to climate change, including principles of equitable and reasonable use, the "no significant harm" principle, and the precautionary principle. For instance, as per the United Nations Convention on watercourses, climatic conditions are pivotal factors in equitable and reasonable utilization. Moreover, international law encompasses procedural regulations, such as those related to notification and consultation, dispute resolution, and data sharing, which are crucial and beneficial for climate change adaptation.

IV.7. Agricultural Adaptation Strategies in the Face of Climate Change: Innovative Techniques and Regional Approaches

Contemporary agriculture faces unprecedented challenges related to climate change, requiring the adoption of robust and innovative adaptation strategies. This in-depth research explores advanced irrigation techniques, soil conservation methods, the integration of wastewater reuse, and presents concrete regional examples. Recent data indicates that agriculture, heavily dependent on climatic conditions, is undergoing major upheavals that demand a transformation of traditional agricultural practices[1.] High-resolution spatial agro-climatic projections developed in 2023 now make it possible to anticipate these changes and develop precise adaptive responses for different agricultural regions, thus offering operators operational tools to guide their agronomic decisions in a changing climate.

IV.7.1. Smart Agriculture and Irrigation Automation

Smart agriculture represents a significant evolution in how agricultural operators manage their water resources in the face of climate challenges. This approach offers numerous opportunities to optimize agricultural practices, particularly regarding crop irrigation, a crucial element for plant productivity and health. Farmers frequently face problems such as water wastage, over-irrigation, or under-irrigation, which can compromise yields and increase operating costs.

The automation of irrigation systems constitutes a technological response adapted to these challenges. Thanks to the use of IoT (Internet of Things) solutions and advanced technologies, operators can now precisely control the water supply to their crops. A particularly relevant use case concerns the automation of the opening and closing of gate valves. This system enables remote and programmed management of water flows, optimizing the distribution of this precious resource according to the actual needs of the crops and the weather conditions.

This automation presents multiple advantages for agricultural operators. First, it allows them to simplify and accelerate irrigation actions, freeing up valuable time that can be devoted to other aspects of the operation[2] Instead of manually performing these repetitive and time-consuming tasks, farmers can entrust these operations to automated systems that guarantee precise and efficient execution of irrigation protocols. This optimization also contributes to a more rational use of water resources, a particularly crucial aspect in a context of water scarcity and intensification of drought periods linked to climate change (Figure IV.1).

[1] https://hydroclimat.com/fr/etude-de-cas/projections-agro-climatiques-a-haute-resolution-spatiale/
[2] https://www.synox.io/cat-smart-agriculture/agriculture-intelligente-automatisation-irrigation/

Figure IV.1: IOT application in China farming (www.fao.org › files › FAO-ITU_China__Wu_Yin__Final_Revision)

IV.7.2. Adapting Irrigation Schedules to New Climatic Conditions

Adapting irrigation schedules represents an essential component of agricultural adaptation strategies. Faced with changes in rainfall patterns and rising temperatures, farmers must revise their traditional irrigation plans[3]. Future weather projections at different time horizons make it possible to anticipate these changes and adapt practices accordingly, taking into account variations in the frequency and intensity of heat waves that directly affect the water needs of crops[4].

These adaptations require a scientific approach based on precise historical weather data and reliable climate projections. The creation of high-resolution spatial historical weather databases, integrating key variables such as temperatures, precipitation, humidity, and wind, provides an essential reference for evaluating future climate variations and identifying trends likely to influence agricultural activities. The use of this data allows farmers to develop proactive rather than reactive irrigation strategies, optimizing water use while maintaining or improving agricultural yields.

IV.7.3. Soil Conservation and Sustainable Agricultural Practices

Soil conservation agriculture (SCA) represents an innovative systemic approach that places soil and organic matter at the center of agricultural concerns. Faced with the global depletion of arable land, this method is emerging as a sustainable alternative to conventional practices that have contributed to soil degradation. According to the Food and Agriculture Organization of the United Nations (FAO), SCA is based on three fundamental interdependent pillars that form a coherent land management system.

[3] https://www.synox.io/cat-smart-agriculture/agriculture-intelligente-automatisation-irrigation/
[4] https://hydroclimat.com/fr/etude-de-cas/projections-agro-climatiques-a-haute-resolution-spatiale/

The first pillar concerns the limitation of mechanical disturbances to the soil. Unlike traditional plowing, a symbol of agriculture for millennia, which turns and mixes the earth in depth, SCA favors minimal intervention on the soil[3]. This approach preserves the natural structure of the soil, thus promoting the development of a rich and diverse microbial life, essential to the fertility of the land. Farmers practicing SCA can opt for direct seeding, a technique that consists of sowing directly into the residues of the previous crop or into a living plant cover already in place, also called no-till under cover[3]. Intermediate solutions also exist, such as Simplified Cultivation Techniques (SCT), which involve superficial soil work without completely turning it over.

The second pillar of SCA is the permanent covering of the soil, which plays a fundamental role in protection against erosion, regulation of soil temperature, and conservation of humidity[3]. This covering can be ensured by the residues of previous crops left on the surface or by the planting of intermediate crops specifically intended to protect the soil during periods when it would otherwise be left bare. This practice also contributes to enriching the soil with organic matter, thus improving its structure and its water retention capacity, a major asset in the face of more frequent drought episodes.

The third pillar is based on the lengthening of rotations and the diversification of cultivated species[5]. This diversification makes it possible to break the cycles of parasites and diseases, thus reducing dependence on plant protection products. It also promotes a more balanced use of soil nutrients and contributes to the improvement of its structure thanks to the variety of root systems of the different crops. A well-designed rotation can thus contribute significantly to the resilience of the farm in the face of climatic and sanitary hazards.

IV.7.4. Flexibility and Contextual Adaptation of Conservation Practices

One of the major assets of conservation agriculture lies in its flexibility of application. French farmers can adapt their practices to the particular context of their farm, which generates a great diversity of systems in the field[5]. This adaptability makes it possible to take into account local specificities, whether pedological, climatic, or socio-economic, while respecting the fundamental principles of SCA. Nevertheless, it is important to emphasize that the combination of the three pillars is necessary to optimize the success of the system and obtain the expected environmental and agronomic benefits.

In some situations, occasional plowing may be necessary, especially when the risks of diseases, pests, or weeds become too important, or before the planting of particularly demanding crops[5].

[5] https://agricultureduvivant.org/les-types-dagriculture/lagriculture-de-conservation/

This pragmatic flexibility, far from calling into question the principles of SCA, testifies to its adaptive character and its capacity to integrate into varied agricultural contexts.

IV.7.5. Wastewater Reuse: A Circular Approach to Water Resource Management

Wastewater reuse represents an innovative and promising strategy for facing the growing water deficits in the context of climate change. The main objective of this approach is not only to provide additional quantities of good quality water by accelerating the natural purification cycle, but also to ensure the balance of this cycle and the protection of the environment[6]. This approach is part of a logic of circular economy of water resources, particularly relevant in regions facing recurrent water stress.

By definition, wastewater reuse constitutes a voluntary and planned action that aims at the production of complementary quantities of water for different uses, in order to fill water deficits[6]. This approach makes it possible to valorize a resource generally considered as waste, transforming it into a precious asset for various economic sectors, including agriculture. Depending on the quality requirements of consumers, two major classes of reuse can be defined: potable uses, which can be direct after advanced treatment or indirect after passage in the natural environment, and non-potable uses in the agricultural (irrigation), industrial, and urban sectors[7].

IV.7.6. Global Distribution and Sectoral Applications

On a global scale, the use of this technique covers respectively 70% of the water needs of agriculture, 20% of those of industry, and 10% of domestic uses[7]. This distribution demonstrates the particular importance of this approach for the agricultural sector, the main consumer of fresh water on a planetary scale. Reuse for irrigation is particularly developed in countries with an agricultural vocation where water resources are limited, such as the countries of the Mediterranean basin or the South of the United States[7].

The most ambitious projects in terms of wastewater reuse have been developed in regions facing major water challenges: the West and East of the United States, the Mediterranean area, Australia, South Africa, as well as the semi-arid zones of South America and South Asia[7]. These initiatives testify to the relevance of this approach in contexts of water scarcity, a situation that climate change tends to accentuate in many regions of the world.

The integration of wastewater reuse into agricultural irrigation systems represents a major opportunity to improve the resilience of farms in the face of droughts. This approach not only secures the water supply but also provides nutrients to crops, as treated wastewater often contains fertilizing elements beneficial for plant growth. However, this practice requires

[6] https://www.u-picardie.fr/beauchamp/duee/ecosse/ecosse.htm
[7] https://www.u-picardie.fr/beauchamp/duee/ecosse/ecosse.htm

rigorous management to avoid any health or environmental risk, involving treatments adapted to the types of crops and local conditions(Figure IV.2)..

Figure IV.2 : Using treated wastewater in forestry and agroforestry in drylands (https://www.fao.org/sustainable-forest-management/toolbox/modules-alternative/)

IV.7.7. Climate Projections and Scientific Data Serving Agriculture

The integration of climate projections into agricultural planning constitutes a major axis of innovation for the adaptation of the sector. In 2023, high-resolution spatial agro-climatic projections were carried out on French territory, providing valuable tools to guide agronomic decisions in a changing climate context[8]. These works respond to a growing need to anticipate the impacts of climate change on agriculture, a sector particularly vulnerable to variations in weather conditions.

The development of these projections is based on a rigorous methodology that combines the analysis of historical meteorological data, future projections, and the generation of specific indicators adapted to the needs of the agricultural sector[9]. This scientific approach aims to provide the actors in the sector with reliable and precise information to guide their adaptation strategies and ensure the resilience of their activities in the face of climate upheavals.

The first phase of this approach consists of the elaboration of a high-resolution spatial historical meteorological database for the territory concerned. This database integrates key variables such as temperatures, precipitation, humidity, and wind, thus drawing a precise portrait of past climatic conditions[9]. This data serves as a reference for evaluating future climate variations and identifying trends likely to influence agricultural activities at different temporal and spatial scales.

[8] https://hydroclimat.com/fr/etude-de-cas/projections-agro-climatiques-a-haute-resolution-spatiale/
[9] https://hydroclimat.com/fr/etude-de-cas/projections-agro-climatiques-a-haute-resolution-spatiale/

The second phase focuses on the production of a set of meteorological variables projected onto a "typical year" at three future time horizons. These projections, located in the short, medium, and long term, make it possible to anticipate the impacts of the different RCP (Representative Concentration Pathways) climate scenarios on the various agricultural regions[9]. The data generated includes crucial information such as the frequency and intensity of heat waves, determining elements for the planning of adapted agricultural practices (Figure IV.3).

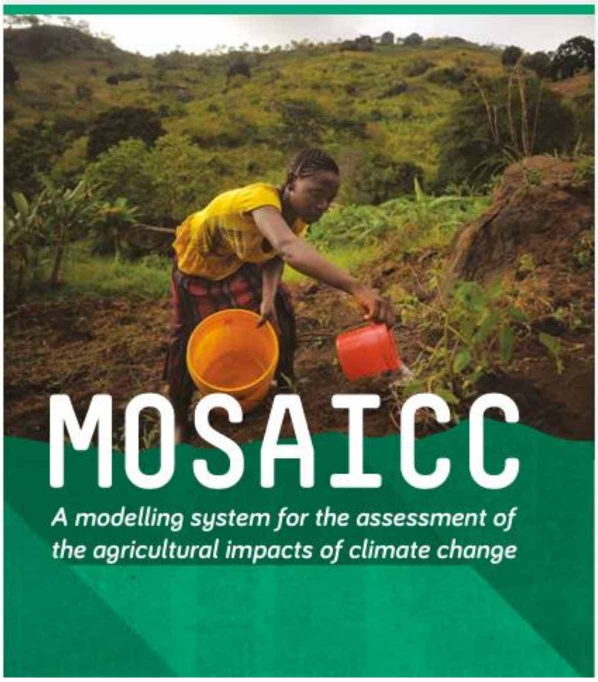


Figure IV.3: MOSAICC model to carry out inter-disciplinary climate change impact assessment on agriculture, water resources, forestry, economy through simulations at national level (www. https://www.fao.org/cliamtechange/ MOSAICC)

IV.7.8. Practical Applications of Climate Data in Agricultural Management

The use of these agro-climatic projections finds numerous concrete applications in the daily management of agricultural holdings. They make it possible, in particular, to adapt cropping calendars, to select the varieties most appropriate to future conditions, and to optimize irrigation systems according to the predictable evolution of precipitation and temperatures [9,10] . This anticipation helps to reduce the vulnerability of agricultural systems in the face of climatic hazards and to maximize the efficiency of the resources used.

High-resolution spatial climate data also offers the possibility of developing differentiated strategies according to the territories, taking into account local specificities and microclimatic variations[9]. This territorialized approach, in line with the orientations of the Regional Climate

[10] https://www.synox.io/cat-smart-agriculture/agriculture-intelligente-automatisation-irrigation/

Air Energy Schemes (SRCAE) and the Regional Agriculture Plans, makes it possible to optimize adaptation to the particular conditions of each agricultural region, thus reinforcing the effectiveness of the measures implemented[11].

IV.8. Climate Projections and Regional Case Studies for Agricultural Adaptation

Climate change presents unprecedented challenges to global agricultural systems, requiring evidence-based adaptation strategies that combine scientific projections with localized implementation. This comprehensive research examines cutting-edge climate modeling approaches and their applications to agricultural adaptation across diverse regions. Recent climate projections indicate substantial variation in agricultural impacts, with projected yield losses exceeding 10% for key crops in southern Europe under a 2°C warming scenario, while some northern regions may experience modest gains[12] . These regional disparities highlight the necessity for territorially-adapted approaches that integrate scientific data with local knowledge.The case studies presented from Europe, Africa, and Asia demonstrate how successful adaptation strategies often emerge from this integration, combining technical innovation with contextual relevance and farmer participation.

IV.8.1. Scientific Foundations of Climate Projections in Agriculture

Agricultural systems are uniquely vulnerable to climate variations, necessitating precise projection tools to facilitate effective adaptation planning. Modern climate models have evolved substantially to provide increasingly relevant data at territorial scales, essential for guiding agronomic decisions in a changing climate.

General Circulation Models (GCMs) form the foundation of global climate projections, utilizing mathematical descriptions of the physical processes within the climate system. These sophisticated models integrate principles of momentum, mass, and energy conservation to simulate potential climate evolution. For analyzing past climate patterns, they employ measuredvalues of atmospheric composition and land use, while future projections rely on various socioeconomic scenarios represented through Representative Concentration Pathways (RCPs). However, their horizontal grid resolution, currently ranging from 50 to 150 km, represents a significant limitation for agricultural applications that require more localized data[12] .This resolution constraint is particularly problematic in regions with complex topography. In global models, mountain ranges like the Pyrenees rarely exceed 1000 meters in elevation in numerical representations, while the Massif Central and Alps may be rendered as a single geographic block. This simplification obscures

[11] https://reseauactionclimat.org/wp-content/uploads/2017/06/Adaptation-de-l'agriculture-aux-changements-climatiques-–-Recueil-d'expériences-territoriales.pdf
[12] https://joint-research-centre.ec.europa.eu/system/files/2020-09/02_pesetaiv_agriculture_sc_august202 0_en.pdf

important local meteorological phenomena such as regional wind patterns that significantly influence agricultural conditions. These approximations make direct application of these models difficult for agricultural decisions thatdepend on specific microclimatic conditions that operate at much finer scales than the models can represent.

IV.8.2. Regionalization of Climate Projections

To address the specific needs of the agricultural sector, a crucial methodological step involves regionalizing global climate projections. This process, also termed "downscaling" or "disaggregation," allows for spatial refinement of climate data by integrating local spatial heterogeneities poorly represented by global models, such as relief features, coastlines, or landuse patterns. This regionalization process is essential given the diversity of pedoclimatic conditions and agroecosystems present across territories.

The regionalization process aims to precisely represent potential modifications in temperature and precipitation regimes in response to climate change signals. Depending on the precision ofhistorical records, chosen emission scenarios, and models used, this approach enables understanding of potential impacts on cultivated systems and livestock in a given territory.

These regionalized projections constitute a valuable decision-making tool for farmers who must adapt their practices to new climate conditions[13].

In Europe, specialized climate data portals play a central role in disseminating these regionalized climate data. These platforms make projections from different models and scenarios available to users, facilitating their appropriation by territorial actors, particularly in the agricultural sector.

The resulting applications provide farmers and agricultural advisors with actionable climate information specifically tailored to agricultural decision-making contexts.

IV.8.3. High-Resolution Agro-climate Projections and Their Applications

Agro-climate projections represent a significant advancement in agricultural adaptation to climate change. These specialized analyses involve modeling meteorological and climate data to produce indicators specifically adapted to agricultural sector needs, translating general climate variables into metrics with direct relevance to farming operations and plant physiology.

Recent projects have focused on developing high-resolution spatial agro-climate indicators for agricultural territories. These initiatives typically follow a structured methodological approach beginning with the development of comprehensive historical meteorological databases at high spatial resolution. These databases integrate essential variables such as temperatures, precipitation,

[13] https://joint-research-centre.ec.europa.eu/system/files/2020-09/02_pesetaiv_agriculture_sc_august202 0_en.pdf

humidity, and wind patterns, providing a detailed portrait of past climate conditions. These data serve as a reference for evaluating future climate variations and identifying trends likely to influence agricultural activities at different temporal and spatial scales[13].

The subsequent analytical phase focuses on producing sets of meteorological variables projected onto "typical years" at multiple future time horizons—typically short, medium, and long term. These projections help anticipate the impacts of different RCP climate scenarios on various agricultural regions. The generated data include crucial information such as the frequency and intensity of heat waves, determining factors for planning adapted agricultural practices. The PESETA IV project, for instance, indicates that under a 2°C warming scenario, grain maize yields could decline significantly across southern Europe, while wheat yields may increase by approximately 5% in northern Europe due to changing precipitation patterns and elevated CO2 levels.

The practical applications of these projections are diverse and directly relevant to farm management. They enable farmers to adapt their crop calendars, select varieties most appropriate for future conditions, and optimize irrigation systems based on foreseeable changesin precipitation and temperature patterns. This scientific approach thus contributes to strengthening agricultural sector resilience in the face of ongoing and future climate disruptions.

IV.8.4. Projected Climate Impacts on European Agriculture

Climate model projections reveal significant geographic disparities in how climate change will affect European agriculture. The data indicate that southern European regions will likely experience substantial negative impacts, while northern areas may see modest benefits from warming temperatures and extended growing seasons.

For grain maize, a crucial European crop, model simulations suggest yield reductions exceeding 10% across southern regions under a 2°C warming scenario. These losses are slightly less severe under a 1.5°C warming scenario, highlighting the importance of ambitious climate mitigation efforts. Water availability emerges as a critical factor, with irrigation capacity significantly influencing projection outcomes. Under the extreme assumption of no irrigation in the future, severe declines in grain maize yield are projected across Europe, with yield decreases exceeding 20% for all EU countries and reaching up to 80% in some southern European nations including Portugal, Bulgaria, Greece, and Spain. These projections suggest that without significant adaptations, grain maize production may no longer be viable in areas facing water scarcity and precipitation decreases[14].

[14] https://joint-research-centre.ec.europa.eu/system/files/2020-09/02_pesetaiv_agriculture_sc_august202 0_en.pdf

Wheat projections present a more varied geographic pattern. Northern Europe may experience yield increases of approximately 5% on average, benefiting from changing precipitation patternsand enhanced growth stimulated by rising atmospheric CO2 concentrations. Conversely, southern European regions face projected yield reductions averaging around 12%, reflecting empirical evidence suggesting limited CO2 fertilization benefits under water-restricted conditions. Limiting global warming to 1.5°C could potentially reduce these losses by approximately 5% [14].

IV.8.5. Adaptation Case Studies Across Regions

Agricultural adaptation strategies vary considerably across regions, reflecting differences in climate impacts, farming systems, and socioeconomic contexts. Examining specific case studies provides valuable insights into effective adaptation approaches and their implementation challenges.

The Save and Grow project in Sri Lanka offers an instructive example of integrated adaptation strategies addressing multiple climate-related challenges. This initiative supports resource-poor smallholder farmers whose agricultural operations often struggle with profitability and environmental sustainability challenges. The project focuses on transitioning to more productive and resilient farm systems while simultaneously reducing greenhouse gas emissions in rice production. This is achieved through the adoption of climate-smart crop production practices, integrated landscape planning and management, and improved access to inputs, technical advice, and financial services[15].

The project has delivered measurable results through its climate-smart approach. Farmers reduced irrigation water requirements by 10-20% through improved water management practices, enabling water storage for subsequent cropping seasons. This water efficiency improvement allowed a 15% expansion of irrigated land during the dry season. Additionally, precise nutrient management using soil testing kits and leaf color charts resulted in a 27% reduction in fertilizer use, delivering both economic and environmental benefits. The initiative demonstrates how integrating multiple adaptation technologies and approaches can address several climate vulnerabilities simultaneously[15].

IV.8.6. Farmer-Led Adaptation in Africa

African agricultural systems face particularly severe climate challenges, yet the continent alsohosts numerous innovative adaptation initiatives led by farmers themselves. These bottom-up approaches leverage farmers' intimate knowledge of local ecosystems and agricultural conditions to develop

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[15] https://openknowledge.fao.org/3/cb5359en/cb5359en.pdf

context-appropriate solutions.

Recent initiatives have focused on documenting and promoting good adaptation practices led by farmers to manage climate change impacts on agriculture. These cases span various geographical regions of Africa and vary according to their scale, objective, and ambition level. A key characteristic of these initiatives is their collaborative selection process, involving regional farmer organizations, local communities, NGOs, and other relevant stakeholders. This participatory approach ensures the documented solutions remain relevant and territorially anchored[15].

Climate change adaptation led at the local level in African agriculture encompasses strategies and actions designed and implemented locally by farmers and their communities. These initiatives address climate-induced challenges including droughts, unpredictable weather patterns, declining soil productivity, and increased crop and livestock disease incidence. Their endogenous character and fine adaptation to local contexts distinguish these approaches fromtop-down interventions. Farmers leverage their in-depth ecosystem knowledge to develop solutions integrating traditional wisdom with technical innovations appropriate to their specificresource constraints [16] [17].

IV.8.7. Linking Climate Change to Agricultural Production Loss

Understanding the specific relationship between climate change and agricultural yield losses represents a crucial research frontier. Recent methodological advances in attribution science have enabled more precise analysis of how climate change affects crop yields across differentregions and production systems.

A recent study applied attribution science to estimate crop loss and damage in four countries, focusing on their most economically and nutritionally important crops: soy in Argentina, wheat in Kazakhstan and Morocco, and maize in South Africa. The analysis attributed the influence of climate change—integrating both slow-onset changes and extreme weather events—on yield anomalies over the period 2000-2019[17].

The results revealed divergent climate change impacts across regions and crops. For Argentina's soybean production, the model indicated that climate change has been statistically significantly beneficial, increasing average yields by approximately 3% during the study period.This case demonstrates that climate change impacts can sometimes be positive for specific crops in certain regions, though such benefits are typically unevenly distributed and often temporary as warming continues[17].

[16] https://openknowledge.fao.org/3/cb5359en/cb5359en.pdf

[17] https://www.fao.org/3/cc7900en/online/impact-of-disasters-on-agriculture-and-food-2023/climate-ch ange-and-agricultural-production-loss.html

In contrast, the model showed that climate change has been statistically significantly detrimentalto wheat yields in Morocco, decreasing average yields by approximately 2% during the same period. The analysis indicated that variations in temperature variability, high temperatures, drought, and high precipitation explained a large share of the recorded wheat yield variability in Morocco's highest-producing regions. These findings highlight the vulnerability of wheat production in North African regions to climate change impacts[17].

IV.8.8. Integrating Scientific Data with Local Knowledge

The most effective agricultural adaptation strategies integrate rigorous scientific projections with local knowledge and farmer-led innovation. This integration ensures that adaptation measures remain both scientifically sound and contextually appropriate, addressing the specific challenges faced by agricultural communities.

Climate-smart agriculture (CSA) exemplifies this integrated approach, simultaneously addressing food security, climate adaptation, and climate mitigation. The CSA approach recognizes that rather than implementing one-size-fits-all solutions, a range of proven agronomic practices can be adapted to address farmers' specific needs and resource endowments. This approach enables farmers to cope with climate change while maintaining or improving agricultural productivity[18].

The experience in Sri Lanka's Save and Grow project demonstrates how scientific assessment of climate change impacts on crops provides a foundation for developing evidence-based adaptation policies. The project assessed future climate impacts on six economically and nutritionally important crops: rice, maize, green gram, onion, chilli, and potato. This scientific foundation was then combined with practical training for farmers on optimizing water, labor, and machinery use to improve efficiency and reduce resource inputs[19] (Figure IV.4).

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[18] https://openknowledge.fao.org/3/cb5359en/cb5359en.pdf

[19] https://openknowledge.fao.org/3/cb5359en/cb5359en.pdf

Figure IV.4: Greenhouse farming as a climate-smart technology (FAO, 2018)

Similarly, climate projection studies like PESETA IV provide valuable data on potential yield changes, but acknowledge that adaptation strategies must be tailored to specific contexts. For example, while changing sowing dates and crop varieties would likely be insufficient to offset projected reductions in grain maize yields, these same strategies could substantially benefit rain-fed wheat production. The development of "faster" wheat varieties that reach flowering stage earlier could potentially transform projected yield reductions into yield gains in some regions[20].

The case studies examined across Europe, Africa, and Asia demonstrate that effective adaptation strategies often emerge from the integration of multiple approaches and knowledgesystems. In Sri Lanka, the combination of water management techniques, nutrient management,and mechanization delivered measurable improvements in resource efficiency and productivity. In Africa, farmer-led initiatives leveraging traditional knowledge provide valuable examples of contextually appropriate adaptation.

The scientific evidence is clear regarding the uneven distribution of climate change impacts on agriculture. Southern European regions face substantial yield decreases for key crops, while northern areas may experience modest gains. Some crops like wheat may benefit from warmingin certain regions if water remains available, while others like maize face severe challenges across larger geographic areas. These divergent outcomes highlight the need for regionally differentiated adaptation strategies.

As climate change progresses, the agricultural sector must continue developing more resilient

[20] https://openknowledge.fao.org/3/cb5359en/cb5359en.pdf

farming systems through ongoing integration of scientific projections with local innovation.

Adaptation will require not only technological solutions but also institutional support, knowledge transfer, and policy frameworks that enable farmers to implement appropriate measures. The diversity of successful adaptation examples provides hope that, with proper support and knowledge sharing, agricultural systems can evolve to meet the challenges of a changing climate.

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