Vademecum for the course

Climate Change and Impacts

(SPAT0027 — 2022-2023)

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Covers: *Introduction*, *Chapters 1 – 6*, $n+1$
and *Assessment Procedure*

Preamble

Purpose and Usage of this Document

Climate science is an active field of research with scientific results being published at a sustained pace. It is furthermore multi-disciplinary, calling upon natural sciences (physics, chemistry, biology, geology, ...), human and social sciences, etc. Consequently the amount of material to master is huge. We are aware of this and this document aims at providing you with some guidance through the course material.

The different chapters of this *vademecum* mirror the structure of the lecture slides. Each one first lists the main sections of the lecture chapters. Occasionally extra details are provided. This theme list is followed by a section entitled "What you should have learned here ..." which points that we consider as desirable outcomes, ranked from "Indispensable" to "Important", "Useful" "Interesting". In general, we do not expect you to learn many numbers (data) by heart. It is more important to know how and where to find them. However, there are a few of them that we absolutely ask you to remember, since knowing them will help you put things into context.

In general, we expect you to make out links between the different parts of the course. Some chapters conclude with a set of simple review questions.

The last chapter recaps the assessment procedure.

The learning outcomes presented here should not be seen as exhaustive: we may well ask questions and engage discussion about connected areas, but the stated outcomes should provide a solid base for this purpose.

Please be aware that this document is still evolving. Make sure to always use the latest version, available on `http://www.astro.ulg.ac.be/~munhoven/fr/cours/#chaclim`. Each version can be identified by the date on its cover page and in the page headings.

Introduction

0.1 Course Objectives

0.2 The IPCC

- Mission
- Structure (working groups)
- Reports
- Key findings of the AR6 (2021)

Please notice that the key findings presented here will become clearer once the concepts from Chapter 6 (*Future Climate Change*) will have been seen.

What you should have learned here ...

Indispensable

- What is the IPCC? What is its mission? How is it structured and how does it work?
- What are the outcomes of the IPCC's work?

Important

- Main conclusions of the most recent Assessment Report
- IPCC's products and activity news can be found at `www.ipcc.ch`

Useful

- Key characteristics of IPCC reports

Interesting

- most of the rest.

Chapter 1

Overview of the Climate System

1.1 The Earth System

- The rock cycle
- The Climate System: overview of important processes.
- Changes linked to ongoing global change
- Evolution of climate model complexity in time
- Development of capabilities of observations

1.2 The Atmosphere

- The role of the atmosphere in the climate system
- Thermal structure of the atmosphere
- The greenhouse effect
- Atmosphere and surface energy budgets
- Meridional energy transfer
- The water cycle

1.3 The Ocean

- The role of the ocean in the climate system
- Surface ocean currents and thermohaline circulation
- Sea surface temperature and vertical thermal structure
- Seawater salinity
- Evaporation budget and salinity
- El Niño and La Niña
- Chemical role of the ocean

1.4 The Cryosphere

- What is the cryosphere?
- The role of the cryosphere in the climate system
  - sea ice
  - continental glaciers
- Changes in ice cover
  - sea ice (Arctic, Antarctica)
  - glaciers

1.5 The Land Ecosystems

- The role of the vegetation and continental surface in the climate system
- Boundary layer and surface roughness
- Albedo, emissivity
- Seasonality of foliage: NDVI
- Carbon cycle

1.6 The Anthroposphere

The role of Humans in the climate system

- Population growth
- Increase of agricultural surfaces

What you should have learned in this chapter ...

Indispensable

- The Earth climate system gets its energy almost exclusively from the Sun
- "The Climate System" graphical summary of the interacting spheres, processes and changes.
- The role of the atmosphere in the climate system (means of control, processes, characteristics).
- Vertical structure of the atmosphere: troposphere, tropopause, stratosphere (extent, location, characteristics).
- Earth's energy budget: be able to explain the contents of the energy graphs (no need to learn *all* the numbers—but see the "Important" points below):
- The role of the ocean in the climate system (means of control, processes, characteristics).
- What is the cryosphere? What is its climatic role (means of control, processes, characteristics)?
- The role of the terrestrial vegetation and the continental surface in the climate system (means, processes, characteristics).
- Climatic role and impact of Man: main reasons

Important

- Global average incoming solar radiation is 340 – 341 $\mathrm{W\,m^{-2}}$
- Current imbalance is 0.6 $\mathrm{W\,m^{-2}}$ (IPCC, 2013)
- Meridional energy transfer: how comes? global characteristics?

- Thermohaline circulation: sources of deep-water formation, major transport pathways
- Albedo: how does it influence climate? Typical albedo ranges of ocean, ice, snow, forests, soils.

Useful

- Vertical structure of the atmosphere: rest.
- More detailed albedo value ranges (old vs. fresh snow, deciduous vs. needle-leaved, agricultural surfaces, . . .)

Interesting

- The rock cycle.

Chapter 2

Greenhouse Effect and Radiative Forcings

2.1 Atmospheric composition

- Permanent gases
- Variable gases

2.2 The greenhouse effect

- The global surface energy budget: effective temperature
  - solar constant
  - planetary albedo
  - spectral separation between incoming solar and outgoing Earth radiation: UV, visible and near infrared vs. near infrared and thermal infrared
  - planetary effective temperature
- The global surface + atmosphere energy budget
  - surface = black-body
  - atmosphere = grey-body: c fraction of thermal infrared absorption
  - definition of *greenhouse effect*
  - atmospheric window (or infrared window) from 8 – 12 μm: signification and importance

- Relative contributions of H_2O and CO_2 to the greenhouse effect
- Greenhouse gases on Earth (by order of importance)

2.3 Recent evolution of the greenhouse gases

- Atmospheric CO_2 mixing ratios increasing over the direct record (Mauna Loa, Hawaii): ~ 315 ppmv to ~ 420 ppmv
- Mean annual growth rate of atmospheric CO_2 mixing ratios: ~ 0.8 ppmv yr^{-1} during the 1960s to ~ 2.4 ppmv yr^{-1} during the 2010s
- Methane: sources and sinks
- Atmospheric CH_4 mixing ratios increasing over the direct record (global): ~ 1630 ppbv in 1983 to > 1900 ppbv in 2022
- Hydroxyl radical (OH)
- Nitrous oxide (N_2O)
- Atmospheric N_2O mixing ratios increasing over the direct record (global): ~ 316 ppbv in 2001 to 335 ppbv in 2022
- Joint variations of greenhouse gases, $^{13}C/^{12}C$ and O_2/N_2 ratios
- Other greenhouse gases (CFCs, HCFCs, O_3)

2.4 Aerosols

- Sources
- Climatic effects
- Distribution (optical thickness)
- Natural variability (e. g., volcanoes)
- Evolution

2.5 Solar variability

- 11-year sunspot cycle
- long-term variability (1600 to present)
- Holocene solar variability (ice core ^{10}Be reconstruction)

2.6 Radiative forcing

- Definition
- Radiative forcing in 2011 (IPCC AR5)
- Radiative forcing in 2019 (IPCC AR6)

What you should have learned in this chapter …

Indispensable

- The greenhouse effect
  - Blackbody emission
  - Physical origin
  - The atmospheric window
  - The most important greenhouse gases in the Earth's atmosphere, their recent evolutions, sources and sinks
- Radiative forcing:
  - Definition? Why is it used?
  - Explain the "Radiative forcing in 2011 (IPCC AR5)" scheme
  - Explain the "Radiative forcing in 2019 (IPCC AR6)" scheme and difference with previous
- Aerosols: sources, climatic effects

Important

- increasing atmospheric CO_2 mixing ratios over the direct record (Mauna Loa, Hawaii): ~ 315 ppmv to ~ 420 ppmv
- order of magnitude of the changes of the solar irradiance induced by the 11-year cycle and over the Holocene
- increasing atmospheric CH_4 mixing ratios over the direct record (global): ~ 1630 ppbv in 1983 to > 1900 ppbv in 2022
- increasing atmospheric N_2O mixing ratios over the direct record (global): ~ 316 ppbv in 2001 to 335 ppbv in 2022
- explain the graph with the joint evolutions of greenhouse gas concentrations and other variables, such as surface ocean pH, $^{13}/^{12}$ stable isotopic ratio in atmospheric CO_2, etc.
- Other greenhouse gases (CFC, HCFC, ...)

Useful

- Total and tropospheric O_3
- Aerosols: Distribution and comparison of the importance of major volcanic eruptions
- mean annual growth rate of atmospheric CO_2 mixing ratios: ~ 0.8 ppmv yr^{-1} during the 1960s to ~ 2.4 ppmv yr^{-1} during the 2010s

Interesting

- April, May, and June 2022: > 420 ppmv; week starting 29th May 2022: > 421.5 ppmv

Review questions

Which are the three most abundant “permanent” gases in the atmosphere? What are their mixing ratios (rounded to the next %)?

Answer 1. N_2: 78 %; 2. O_2: 21 %; 3. Ar: 1 %; others (mainly rare gases): < 0.036 %

Which are the most abundant “variable” gases in the present-day atmosphere?

Answer 1. H_2O (0 – 1 %); 2. CO_2 (0.01 – 0.1 %); ...

What do “ppm” (or “ppmv”) and “ppb” (or “ppbv”) stand for?

Answer ppm: *parts per million,* 10^{-6} (mixing ratio); ppmv *parts per million in volume,* 10^{-6} (volume fractions, equivalent to ppm for ideal gases); ppb: *parts per billion,* 10^{-9}; ppbv: *parts per billion in volume,* 10^{-9}.

Chapter 3

Carbon Cycle and Greenhouse Gas Budgets

3.1 The global carbon cycle

- Schematic of the global carbon cycle (IPCC, 2013)
  - carbon stocks
  - natural CO_2 exchange fluxes
  - perturbation due to human activity (1750 to the average of 2000–2009)
- Schematic of the global carbon cycle (IPCC, 2021)

3.2 Continental carbon cycle

- Photosynthesis: C_3 vs. C_4 photosynthetic pathways
- Carbon reservoirs and fluxes in the continental biosphere
  - types of productivity (GPP, NPP, NEP, NBP and contributions)
  - important aspects of global distribution of NPP, plant biomass, litter and soil carbon
- Biomes and their carbon storage
- Global photosynthesis (GPP) and biospheric sink (NBP) predicted by models
- El Niño and the continental biosphere
- Carbon in streams and rivers

3.3 Oceanic carbon cycle

- Carbonate chemistry
- Vertical profiles of DIC, nutrients and O_2
- Net CO_2 fluxes at the air-sea interface (sea $\rightarrow$ air)
- CO_2 pumps in the ocean (solubility and biological)

3.4 The nitrogen cycle

- C:N ratios
- Processes
- pre-industrial N cycle

3.5 Budgets of main atmospheric greenhouse gases

- CO_2 budget: emissions, distributions
- CH_4 budget: overview, IPCC (2013), IPCC (2021)
- N_2O budget: overview, IPCC (2013), IPCC (2021)
- Global emissions of greenhouse gases through time and by sectors of human activity
- Greenhouse gases in Belgium (2015)
- Forest carbon budget in Walloon Region (1996)

What you should have learned in this chapter …

Indispensable

- Schematic of the global carbon cycle (IPCC, 2013) – you should be able to guide through the scheme and explain the different parts, such as
  - carbon stocks
  - natural CO_2 exchange fluxes

  - perturbation due to human activity (1750 to the average of 2000–2009)

- Schematic of the global carbon cycle (IPCC, 2021) – you should be able to guide through the scheme and explain the different parts (similarly to the previous)

- Oceanic carbon cycle

  - Carbonate equilibria and schematic chemical reactions of biological processes
  - Concentration vertical profiles of DIC, DIN, DSi and O_2 saturation: broad characteristics and be able to explain the graphs
  - Net sea-air CO_2 flux and ocean storage of anthropogenic CO_2 (IPCC 2021) – be able to explain the maps
  - The ocean as a CO_2 pump – be able to explain the solubility and the biological pumps

- Budgets of main atmospheric greenhouse gases: CO_2

  - Global atmospheric CO_2 budget (IPCC 2021): with the table at hand, be able to synthesize the main characteristics (variations of individual sources and sinks over time, . . .)
  - Long-term trend in global CO_2 emissions (PBL, JRC, 2011): be able to comment the graphs, key facts
  - Make links to previous learning outcomes on CO_2

- Budgets of main atmospheric greenhouse gases: CH_4

  - Natural and anthropogenic sources, sinks
  - Schematic of the global CH_4 cycle (IPCC, 2013) – you should be able to guide through the scheme and explain the different parts
  - Schematic of the global CH_4 cycle (IPCC, 2021) – you should be able to guide through the scheme and explain the different parts
  - Make links to previous learning outcomes on CH_4

- Budgets of main atmospheric greenhouse gases: N_2O

  - Natural and anthropogenic sources, sinks
  - Schematic of the global N_2O cycle (IPCC, 2013) – you should be able to guide through the scheme and explain the different parts

  - Schematic of the global N_2O cycle (IPCC, 2021) – you should be able to guide through the scheme and explain the different parts
  - Make links to previous learning outcomes on N_2O

Important

- Carbon reservoirs and fluxes in the continental biosphere: flux and process types
- El Niño and the continental biosphere
- Global emissions of greenhouse gases through time and by sectors of human activity (IPCC 2007): explain the graphs

Useful

- The biosphere from satellite (SeaWiFS project) – be able to explain the map
- Net CO_2 fluxes at the air-sea interface (IPCC 2007) – be able to explain the map
- Budgets of main atmospheric greenhouse gases
  - Methane sources and sinks for four decades from atmospheric inversions with the budget imbalance (IPCC, 2021): explain the graph (alternative summary)
  - Greenhouse gases in Belgium
  - Forest carbon budget in Walloon Region (1996)

Interesting

- The global nitrogen cycle

Chapter 4

20th Century Climate Change

4.1 Atmospheric CO_2 and its isotopic composition

- South Pole and Mauna Loa records of atmospheric CO_2
- South Pole and Mauna Loa records of $\delta^{13}C$ of atmospheric CO_2
  Beware! Vertical axis reversed.
- Atmospheric CO_2 budget over the industrial period
  - model inversion
  - IPCC 2013
- Interannual variations of the land biosphere carbon sink

4.2 Temperature

- Global Mean Surface Temperature (GMST) anomalies
  - trends and long-term evolution 1850–2012 (IPCC 2013)[1]
  - comparison of four different datasets 1850–2012 (IPCC 2013)
  - trends and long-term evolution 1850–2020 (IPCC, 2021)
- Spatially resolved Mean Surface Temperature trends
  - for 1901–2012 (IPCC 2013)

[1]Please notice that the Fifth Assessment Report (AR5) was published over the two years 2013 (contribution from WG1) and 2014 (contributions from WG2 and WG3 and Synthesis Report. In the slides, we refer to AR5 without distinction as IPCC (2013) and IPCC (2014).

  - for 1900–1980, 1981–2020, ocean vs. land (IPCC, 2021)
  - observed emergence of temperature change

- Troposphere vs. stratosphere
  - IPCC (2013)
  - IPCC (2014)

4.3 Precipitations and hydrologic cycle

- Changes in observed precipitation (IPCC, 2021)
- Precipitation-minus-evaporation (IPCC, 2021)
- Surface humidity (IPCC, 2021)
- Changes in global mean total column water vapour (IPCC, 2021)

4.4 Atmospheric circulation

- Change of geopotential heights in altitude (IPCC, 2007)
- Change in Hadley Cell extent and intensity (IPCC, 2021)
- Change in zonal wind speed (IPCC, 2021)

4.5 Snow and ice

- Change in sea ice area (IPCC, 2021)
- Sea ice thickness (IPCC, 2021)
- Northern Hemisphere spring snow cover
  - IPCC (2013)
  - IPCC (2021)
- Mountain glaciers
- Greenland and Antarctic Ice Sheets

  To put losses in perspective: the total mass of the Antarctic ice-sheet is about 24,400,000 Gt and that of the Greenland ice sheet is 2,700,000 Gt
- Permafrost

4.6 Biosphere

- Changes in the seasonal cycle of atmospheric CO_2
- Changes in terrestrial biosphere
  - trends in the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), IPCC (2021)
  - phenological changes (IPCC, 2021)
- Changes in ocean biosphere (IPCC, 2021)

4.7 Extreme events

- Trends in the frequency of extreme temperatures (cold nights, cold days, warm nights, warm days)
- Summer 2003 in Europe
  - in the context of JJA temperature anomalies 1780–2005 (IPCC, 2007)
  - impact of the 2003 drought on ecosystems
- Heavy rainfall: trends 1951–2003 (IPCC, 2007)
- Tropical storms (IPCC, 2007)
- Cold, hot, and wet extremes and their potential human contribution (IPCC, 2021)

4.8 Climate simulations

- Simulated annual global mean surface temperatures under natural, anthropogenic and combined forcings
  - IPCC (2001)
  - IPCC (2007)
  - IPCC (2014)
  - IPCC (2021)
- Climate model skill improvement from CMIP3 to CMIP5 to CMIP6
- Zonal mean atmospheric temperature changes from 1890 to 1999 for five individual forcings

What you should have learned in this chapter ...

Indispensable

- You should by now be able to synthesize the evolution of the major records of climate change (greenhouse gas concentrations, temperature, sea-level, etc.) during the recent past. You should know the order of magnitudes of the current and the pre-industrial values of the greenhouse gas concentrations in the atmosphere, or their relative changes.
- Carbon isotopes
  - definition of δ^{13}C
  - processes that influence δ^{13}C and that lead to differentiation (fractionation) between reservoirs (see also section 5.4, slide "MIOCENE: C4 plant evolution")
  - recent evolution (see also chapter 2)
  - approximate δ^{13}C values of carbon in the atmosphere, ocean and terrestrial biosphere
- Troposphere-stratosphere – be able to explain any of the graphs in this section (joint evolution in time of the troposphere and the stratosphere, vertical profiles). See also the graph about the "zonal mean atmospheric temperature change from 1890 to 1999" at the end of this chapter
- Climate simulations – be able to explain any of the graph sets (IPCC, 2001, 2007, 2013 or 2021) with the simulated annual global mean surface temperatures under natural, anthropogenic and combined forcings (rationale of the experimental design, key results)
- Precipitations and hydrological cycle – you should be able to explain the maps about the changes in the observed precipitation, surface humidity, etc.
- Biosphere – be able to explain the graphs on
  - changes in the amplitude of the seasonal cycle of CO_2
  - FAPAR trends
  - phenological changes over land
  - changes in ocean biosphere: phytoplankton
- Extreme events – be able to explain and comment on the graphs

  - observed trends in temperature extremes
  - summer of 2003 in Europe
  - trends for heavy rainfall
  - tropical storms
  - overview of observed changes for cold, hot, and wet extremes and their potential human contribution (IPCC, 2021)

Important

- The current and the pre-industrial values of the greenhouse gas concentrations in the atmosphere
- Snow, ice (land and sea), permafrost – broad evolutions during the observational period (see also chapter $n+1$)

Useful

- Atmospheric circulation (general circulation, winds)
- CMIP: Coupled Model Intercomparison Project and relationships of CMIP3, CMIP4 and CMIP6 to IPCC's FAR, AR5 and AR6.

Interesting

- Most of the rest

Chapter 5

Climate Changes of the Past

5.1 The geological timescale

5.2 The last millennia

- The past millennium
  - Atmospheric concentrations of CO_2, CH_4 and N_2O
  - NH temperature anomaly
- Reconstructed Northern Hemisphere, Southern Hemisphere, and global annual temperatures during the past 2000 years (IPCC-WG1, 2013, chapter 5)
- Reconstructions of volcanic forcing for the past 1000 years past 2000 years (IPCC-WG1, 2013, chapter 5)
- Comparisons of simulated and reconstructed NH temperature changes
- Time series of solar and volcanic forcing (IPCC-WG1, 2021, chapter 2)
  - for the past 2.5 kyr
  - since 1850

5.3 Holocene and Pleistocene

- Changes of atmospheric CO_2 and its isotopic composition over the Holocene
- The early anthropogenic hypothesis (Ruddiman, 2003): CO_2 and CH_4 started to diverge from the natural evolution 6–8 kyr ago as a result of the spread of agriculture

- Pleistocene
  - Orbital changes (eccentrcity, tilt, time of perihelion) and resulting Northern summer insolation changes
  - Vostok ice core records (420 000 years)
  - 800000 years of CO_2 and climate: orbital parameters and proxy records over the past 800 kyr (IPCC-WG1, 2013, chapter 5).

    Notice that lines on this graph represent the eveolutions of the calculated orbital forcing and of proxy-based reconstructions while shaded areas represent the range of simulations with climate models
  - Evolution of well-mixed greenhouse gases since 800 ka BP (IPCC-WG1, 2021, chapter 2)
- Origins of atmospheric CO_2 changes during the Pleistocene
- Vegetation at the Last Glacial Maximum (LGM, 21 ka BP)

5.4 Cenozoic

The past 66 million years

- Proxy-based reconstruction of atmospheric pCO_2 proxies for the Miocene
  - ^{13}C isotopic fractionation of marine photosynhesis
  - $^{11}B/^{10}B$ isotopic ratio ($\rightarrow$ surface ocean pH)
- pH and boron isotopes
- Miocene: C4 plant evolution
- From Palaeogene to Neogene: Proxy-based reconstruction of atmospheric pCO_2
  - ^{13}C isotopic fractionation of marine photosynthesis:

    gradual increase of atmospheric pCO_2 from ca. 200 ppm 15 million years ago to 280–300 ppm 5 million years ago
  - $^{11}B/^{10}B$ isotopic ratio ($\rightarrow$ surface ocean pH):

    decrease from $>$ 400 ppm during the early Miocene, followed by an increase in agreement with the ^{13}C isotopic data
- Boron isotopes a proxy for pH

- Oxygen and carbon isotopes
- Global mean surface temperatures (GMST) over the past 60 million years relative to 1850–1900 (IPCC-WG1, 2021, chapter 2)
- Orbital-scale Earth system responses to radiative forcings and perturbations from 3.5 Ma to present

5.5 Phanerozoic

The past 541 million years

- Mean Global Temperature and Precipitation
- CO_2
- Oxygen isotopes and climate
- Phanerozoic global temperature (Scotese, 2016)
- Long-term carbon cycle (> 1 Ma): the Urey reaction
- Sr isotopes over Phanerozoic times: an indicator of weathering?
- Silicate weathering: two contrasted views
- Summary: The evolution of atmospheric CO_2 through the last 450 million years

What you should have learned in this chapter . . .

Indispensable

- You should be able to summarize the main features of the climatic records available for the Pleistocene and the Holocene (typical glacial and interglacial values.
- You should be able to summarize the main processes that have driven the evolutions of the global carbon cycle (atmospheric CO_2, vegetation carbon stocks) and climate during the Holocene and the Pleistocene.
- You should be able to synthesize the evolution of climate and atmospheric CO_2 on geological time scales of a million of years and more.

- You should be able to describe the methods used to reconstruct these evolutions (proxies etc.), the rationale of the boron isotopic proxy for past *p*H and the usefulness of carbon and oxygen isotopes records.
- You should be able to guide through the oxygen isotopic record of the Cenozoic (Zachos et al., 2001), being given the graph .

Important

- Geological time scale: know the following durations
  - Quaternary: past 2.58 million years
    - Pleistocene (meaning *most new*): from 2.58 million years to 11700 years ago
    - Holocene (meaning *entirely new*): past 11700 years

Useful

- Geological time scale:
  - Phanerozoic (meaning *visible life*): past 541 million years, geological eon with abundant plant and animal life
    - Cenozoic (meaning *new life*): past 66 million years, era within the Phanerozoic eon
      - Palaeogene: 66 to 23 million years ago
      - Neogene: 23 to 2.58 million years ago
        - ▷ Miocene: 23 to 5.33 million years ago
        - ▷ Pliocene: 5.33 to 2.58 million years ago
      - Quaternary: past 2.58 million years
        - ▷ Pleistocene (meaning *most new*): from 2.58 million years to 11700 years ago
        - ▷ Holocene (meaning *entirely new*): past 11700 years

Interesting

- Phanerozoic climate records

Chapter 6

Future Climate Change

6.1 Socio-economic scenarios

- SRES scenarios

  SRES stands for *Special Report on Emission Scenarios*, after the IPCC Special Report *Special Report on Emissions Scenarios: A special report of Working Group III of the Intergovernmental Panel on Climate Change*, Nakićenović, N.; Swart, R. (eds.), 2000 (URL: `https://www.ipcc.ch/report/emissions-scenarios`)

  - Storylines and scenario families
  - World population
  - Energy sources
  - Emission scenarios

- RCP (Representative Concentration Pathways) scenarios (for IPCC AR5, 2013)

- SSP (Shared Socio-economic Pathways) scenarios (for CMIP6, IPCC AR6, 2021-22)

  - The five steps of SSP development
  - SSP narratives
  - SSP scenario drivers
  - Primary energy structure and final energy demand
  - Land use change in SSP

6.2 Climate projections for the 21st century

- From emissions to climate response: impact of carbon cycle Climate Interactions
- Emission scenarios and climate projections (IPCC AR4, 2007)
- Multi-model mean of annual mean surface warming (IPCC AR4, 2007, SRES scenarios)
- Multi-model mean changes in surface air temperature, precipitation and sea level pressure for 2080–2099 (IPCC AR4, 2007, SRES scenarios)
- Multi-model mean changes in precipitation, soil moisture content, runoff and evaporation for 2080–2099 (IPCC AR4, 2007, SRES A1B scenario)
- Vertical profiles of temperature change in the atmosphere and ocean
- Climatic projections (IPCC AR5, 2013)
- Changes in average temperature, precipitation, NH September sea-ice extent and surface ocean pH for 2081–2100 (IPCC AR5, 2013, RCP 2.6 and RCP 8.5 scenarios)
- Concentration- and emission-driven projections (IPCC-WG1 AR6, 2021, chapter 4)
- IPCC-WG1 AR6 projections (2021, chapter 4)
  - selected indicators
  - distribution of surface temperature change
  - temperature change along the vertical
  - precipitation changes
  - distribution of precipitation change
  - change in relative humidity
  - ocean and land carbon uptakes
  - surface ocean pH
- Climate change projection: relationship between cumulative emissions and temperature (IPCC-WG1 AR6 SPM, 2021)
- Extreme events

  - observed changes in temperature
  - change in frequency of extreme temperature events
  - change in intensity of extreme temperature events
  - change in frequency of extreme precipitation events
  - change in intensity of extreme precipitation events
  - droughts

6.3 Projections beyond the 21st century

- Multi-model means of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th-century simulation.
- Greenland ice sheet melting under $4 \times CO_2$
- Impact of stabilizing CO_2 emissions

6.4 Regional climate projections

- Precipitation changes for Europe and Mediterranean (SRES A1B, RCP4.5)
- CORDEX: regional climate model simulations (IPCC-WG1 AR6, 2021, Atlas)

What you should have learned in this chapter …

Indispensable

- You should be able to explain the rationale behind the RCP (Representative Concentration Pathways) scenarios, used for IPCC AR5 (2013) and the SSP (Shared Socio-economic Pathways) scenarios used for CMIP6 and IPCC AR6 (2021-22). What are the differences between the two approaches?
- You should be able to explain the graphs on the slide "IPCC 2014 scenarios « Representative concentration pathways (RCP) »."
- Vertical profiles of temperature change in the atmosphere and ocean (AR4) and IPCC AR6 projections: temperature change along the vertical: be able to explain the graphs.

Important

- SRES scenarios
  - A1: rapid economic growth, low population growth, efficient technologies, convergence among regions
  - A1B: A1 with balance across energy sources sources

Useful

- Other IPCC AR6 projections: be able to read and explain the graphs

Interesting

- SRES scenario background
- Emission scenarios and climate projections from IPCC (AR4)
- Multi-model mean of annual mean surface warming for SRES

Chapter *n* + 1

Ocean and Cryosphere

Processes and Feedbacks

- Illustration of feedback networks in the Earth's climate system

Sea Level

- Historical Evolution of Sea Level
- Glacial-interglacial Sea Level Change
- Sea Level: Processes and Contributions
- Future Sea Level Change: Projections

Mountain Glaciers

- Fluctuations Since the Little Ice Age
- Impacts
- Glacial lakes in the Himalayas (Nepal, Buthan)
- A few guidelines (context)

Polar Ice sheets

- Potential Sea Level Rise

- Ice sheet and ice shelves in Antarctica
- Marine Ice Sheet Instability
  - Principles
  - West-Antarctic Ice-Sheet Instability

Sea Ice

- Sea Ice Decrease in the Arctic
  - Observation and future projections
  - Evolution of the Extent
  - Annual Extent in September
  - Annual Volume Change
  - History of Volumes From 1979 to 2018
  - Seasonal Extents
  - Age Distribution
- Antarctic Sea Ice
- Ice-Albedo Feedback
- Impact in the Arctic

Sea Level Rise

- Analysis of the Contributions (IPCC-WG1, 2007)
- Analysis of the Contributions (IPCC-WG1, 2013)

Ocean Warming

- Heat Content in the Climate System
  - Evolution 1970–2011 (IPCC-WG1, 2013)
  - Heat Accumulation in the Climate System: rate estimates
- Impacts on Coral Reefs

Acidification

- CO_2 emissions and partitioning 1800–2000
- Surface Ocean Acidification
- A Carbonate System Primer
- Impacts of ocean acidification

Other impacts

- Plankton shift

What you should have learned here ...

Indispensable

- Sea Level:
  - What processes cause the sea level to change? — see UNEP (2007) schematic
- Marine Ice Sheet Instability
  - Explain the principle
  - West-Antarctic Ice-Sheet Instability
- Sea ice
- Ocean heat content
  - Know the approximate fractions of excess heat heat taken up by the atmosphere, by land, ice, the deeper and the upper oceans (IPCC-WG1, 2013)
  - Being given the same graph: calculate the rate of heat accumulation in the system

Important

- Glacial-interglacial sea-level changes: know the amplitude ($\sim$120–130 m lower during peak glacial times
- Ice sheets and potential sea level rise: know the equivalent Δh for the three ice sheet components

Useful

- Mountain glacier retreat: impacts
- Mountain areas: global importance

Interesting

- Illustration of feedback network in the Earth's climate system
- Sea Ice Decrease: Economic impact in the Arctic
- Plankton shift

Assessment Procedure

The assessment proceeds in two stages:

1. Oral Examination (January session) — 50% of the grade
2. Personal project — 50% of the grade, with two contributions:
    - Public presentation (40%);
    - General public summary (10%).

Personal Project

Each student has to carry out is own personal project. This will be a climate change communication exercise, on a subject of *your* choice. It has to be directly related the climate system itself (incl. biogeochemical cycles, atmospheric chemistry, etc.), or to climate climate change. It may cover any aspect related to these two broad fields:

- Scientific foundations ("*How does the climate system work?*")
- Past, present, future
- Policy (national, international)
- Social impacts: health effects, food security, water security, livelihood security, migration, etc.;
- Economic impacts: damages to infrastructure, reduced reliability of infrastructure as a result of extreme events, wildfires, etc.
- ...

The themes of the three IPCC Working Groups provide good guiding lines for acceptable subject areas.

Practical Aspects

As mentioned above, the personal project to realize is a public outreach activity. It will have to be based upon the scientific literature, without being a scientific reporting exercise, though.

The project will have to be realized in French by default; English will only be accepted for students with insufficient proficiency in French. The target audience will be

- secondary school classes (5th and 6th years) for projects in French;
- bachelor students in sciences (English course) for projects in English.

Schedule

The broad timing of the personal project is as follows

- September–October: subject selection and coordination
- End of November: final title and 4–5 line lead (lede, *chapeau*, *chapô*, *accroche*) ⇒ used for announcements
- First weeks of second term: summary report for classes
- First weeks of second term: two mandatory practice sessions presentation material must be ready for the first one
- End of February or in March: public presentations

Precise deadlines will be communicated in due time.

Summary Report

The Summary Report is meant to be a general scientific text suitable for the target audience The language must be the same as that of the presentation

Its overall length will be 3 to max. 4 pages (this maximum length will be enforced!). It will

- have no cover page, no table of contents etc.;
- have 2.5 cm margins all around;
- be set in Cambria or similar, with an 11pt size;
- be using single line spacing.

Figures and tables will

- be numbered;
- each one be included into a floating text box with its caption;
- be referenced in the text by their numbers;
- have their sources specified in the caption.

The must furthermore mandatorily include a final section entitled "To learn more..." ("*Pour en savoir plus ...*") with at least three references or links to pages or documents written in the same language as the document itself. References/links in excess of the minimum of three may be in the other language.

The submitted manuscripts will be edited and formatted by the lecturers and the teaching assistant(s). They will then be posted online for class usage of the audience. Please notice that the full name of the author of each text will be disclosed, together with the programme that they are enrolled to (no further addresses, neither postal nor eMail will be disclosed). It will not be possible to use a pseudonym, as these are public documents related to a course examination.

Présentations en français

Comme mentionné ci-dessus, le projet personnel est un exercice de vulgarisation. Les présentations orales se feront devant des classes de 5e et 6e années d'écoles secondaires de la région, au cours d'une ou plusieurs matinées "Les Changements Climatiques", organisées en collaboration avec *Réjouisciences*. Ces matinées sont généralement organisées fin février ou au courant du mois de mars. Chaque présentation durera typiquement entre 20 et 25 minutes, y inclus une partie Q&R.

Les éditions récentes se sont tenues à l'*Ancien Institut d'Anatomie*, à l'*Institut de Zoologie (Maison de la Science)* ou encore à l'*Exèdre Dick Annegarn (théâtre universitaire)*. Les présentations seront évaluées pour leurs qualités scientifiques et pédagogiques par un jury d'enseignants et de chercheurs universitaires.

Public Presentations in English

As mentioned above, the personal project will be a public outreach exercise. The edition in English will be organised in collaboration with the teacher(s) of the science bachelors' English classes. They will take place on one or several mornings during second term. The typical duration will be 20 to 25 minutes each, including a Q&A part. The target audience will be first year bachelors' in science (chemistry, geography, physics, ...) All presentations will assessed regarding their scientific and pedagogic qualities by a jury of university teachers and research scientists.