Climate Change

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Climate Modeling Overview

Climate models (GCMs) reproduce the evolution of the Earth's climate by simulating exchanges of energy, mass and momentum among the atmosphere, oceans, cryosphere, biosphere and land.

They rely on numerical integration of physical laws under discretized spatial and temporal grids.

Core Physical Principles

- Mass conservation → continuity equations
- Momentum conservation → Navier–Stokes equations
- Energy conservation → first law of thermodynamics
- Radiative transfer → solar and infrared fluxes
- Boundary data: topography, composition, vegetation, albedo

Model Discretization

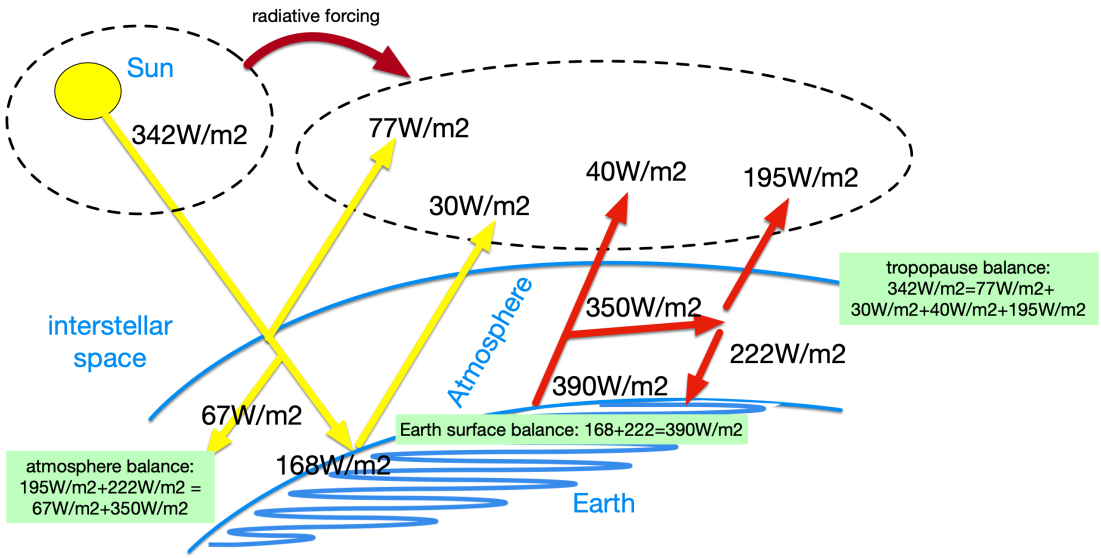
- 3D grid cells: horizontal (tens of km) × vertical (atmospheric layers)
- Each cell exchanges fluxes with neighbors
- Time step: few minutes → simulation of decades or centuries

Radiative Forcing

Change in Earth's energy balance (ΔF in W/m^2) caused by greenhouse gases, aerosols, or solar variations.

Main contributors:

- CO_2, CH_4, N_2O, halocarbons
- Aerosols (direct + indirect effects)
- Land-use and solar changes



Scenario Frameworks

Two main frameworks (they are used jointly, for instance: *SSP1-2.6*, *SSP5-8.5*):

- RCPs (Representative Concentration Pathways): radiative forcing targets (e.g. 2.6, 4.5, 8.5 W/m^2 in 2100)
- SSPs (Shared Socio-economic Pathways): narratives combining demographics, economy, and policies

Model Uncertainty Sources

- Internal variability (natural fluctuations)
- Model structure (parameterization, resolution)
- Scenario uncertainty (future emissions, behavior)

Applications

- Climate projections (temperature, precipitation, sea level)
- Regional impact studies (downscaling)
- Policy guidance and mitigation assessment

Key Takeaways

- GCMs combine physics and computation to reproduce the climate system.
- Radiative forcing links emissions to global temperature change.
- SSP/RCP frameworks describe plausible futures.
- Uncertainties remain but trends are robust: warming is unequivocal.

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1. Radiative forcing

1.1 Radiative forcing definition

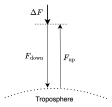
Radiative forcing is used to quantify the change in energy balance in Earth's atmosphere at the top of the troposphere (between 10 and 16 km above sea level).

- it is a consequence of a change in an external driver of climate change.

$$\Delta F = F_{\text{down}} - F_{\text{up}} [\,\mathrm{W/m^2}]$$

where F_{down} is the downward radiative flux and F_{up} is the upward radiative flux.

1.2 Characteristics of radiative forcing



The Intergovernmental Panel on Climate Change (**IPCC i.e. GIEC**) summarized the current scientific consensus about radiative forcing changes:

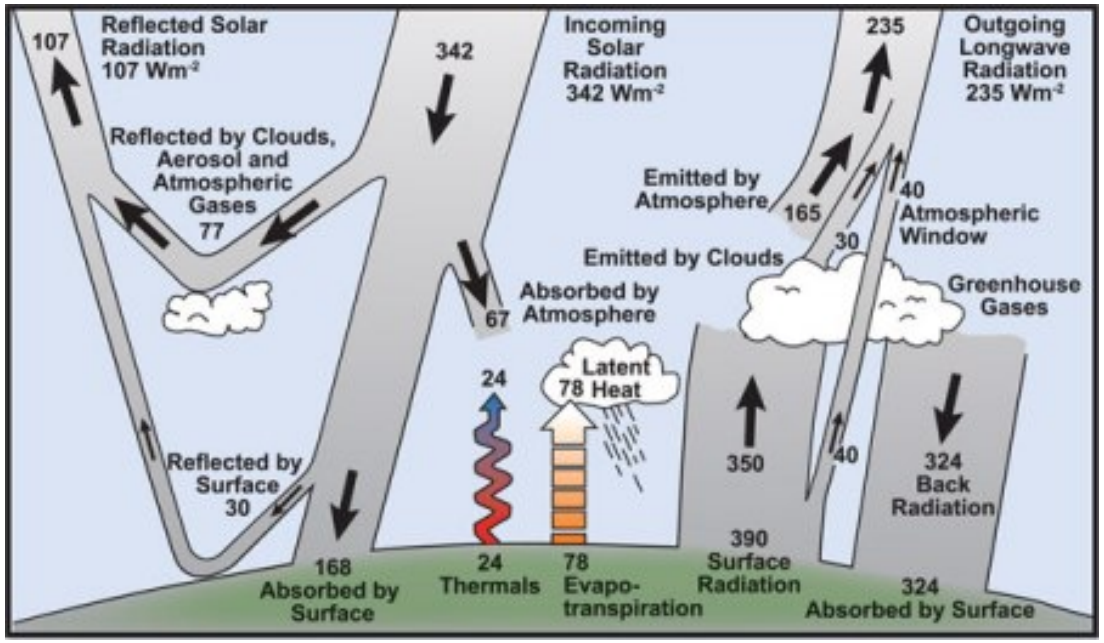
$$\Delta F = 2.98[\,\mathrm{W/m^2}]$$

Human caused part (from 1750 to 2019):

$$\Delta F_{\mathrm{human}} = 2.72[\,\mathrm{W/m^2}]$$

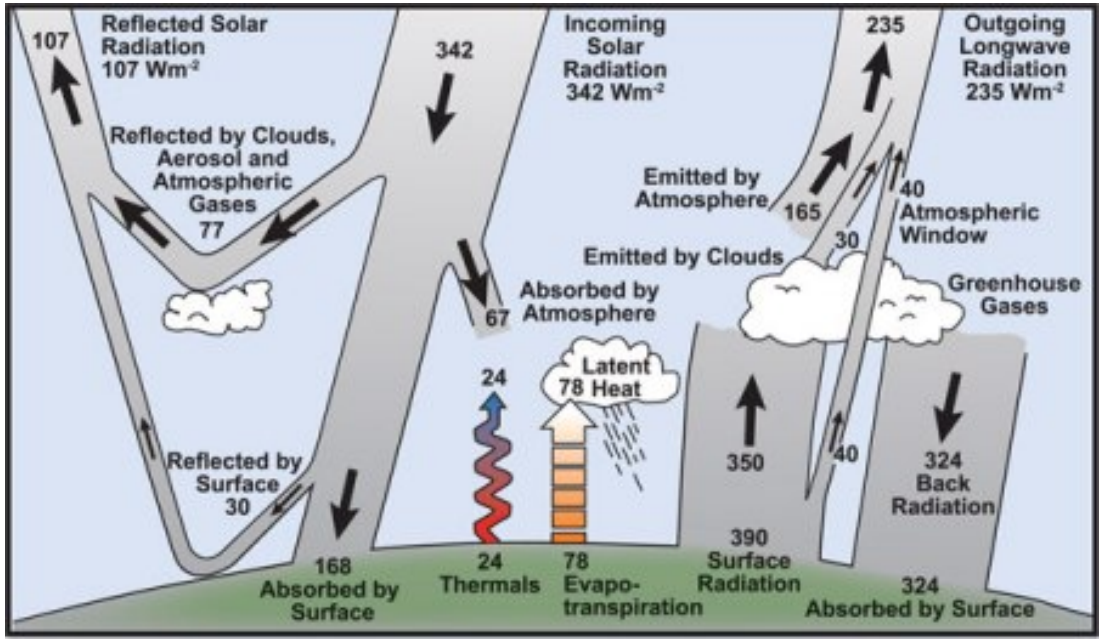
1.3 Positive radiative forcing (part 1)

- greenhouse gases (GHGs): The largest contributor to positive radiative forcing, with carbon dioxide (CO_2) alone accounting for about **2.17W/m²** of the total increase.
  - Assuming no change in the emissions growth path, a doubling of the CO_2 concentrations within the next several decades would correspond to a cumulative radiative forcing change of +3.71 W/m² whereas the balance from steady temperature is 0 W/m².
  - Water vapor is the most important GHG but it is not accounted because it has a short lifetime (days, weeks) and because it acts as a feed-back mechanism, it amplifies the radiative forcing caused by other GHG.



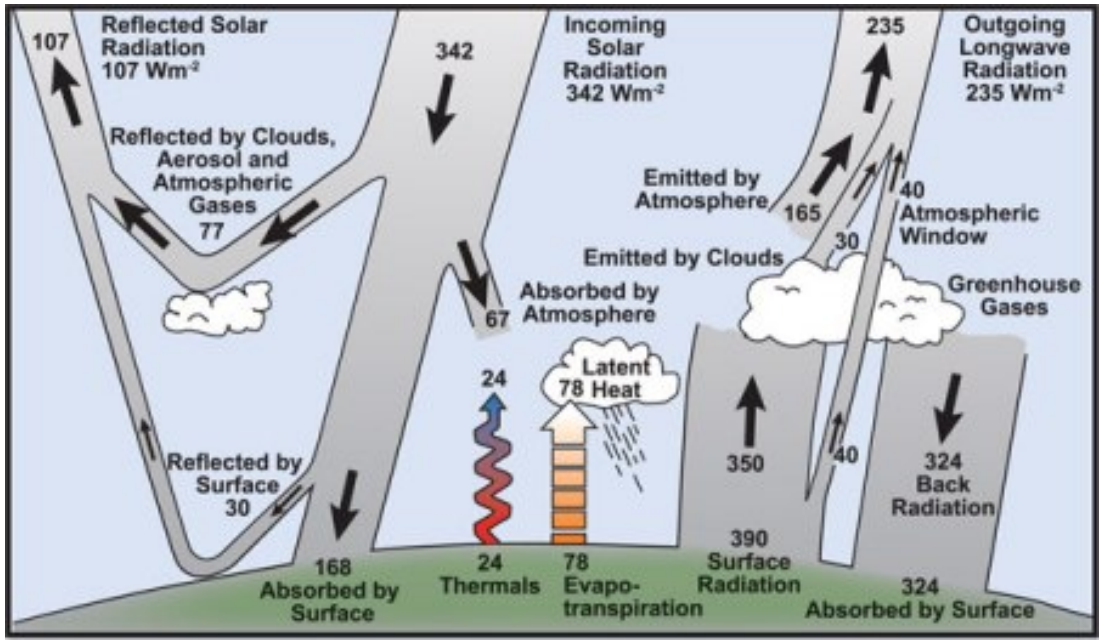
1.3 Positive radiative forcing (part 2)

- land use changes: These contribute to radiative forcing by altering surface albedo, though their overall effect is smaller compared to GHGs and aerosols.
- other minor factors that include black carbon on snow, which has a positive forcing effect
- changes in solar irradiance, which have a relatively small impact.

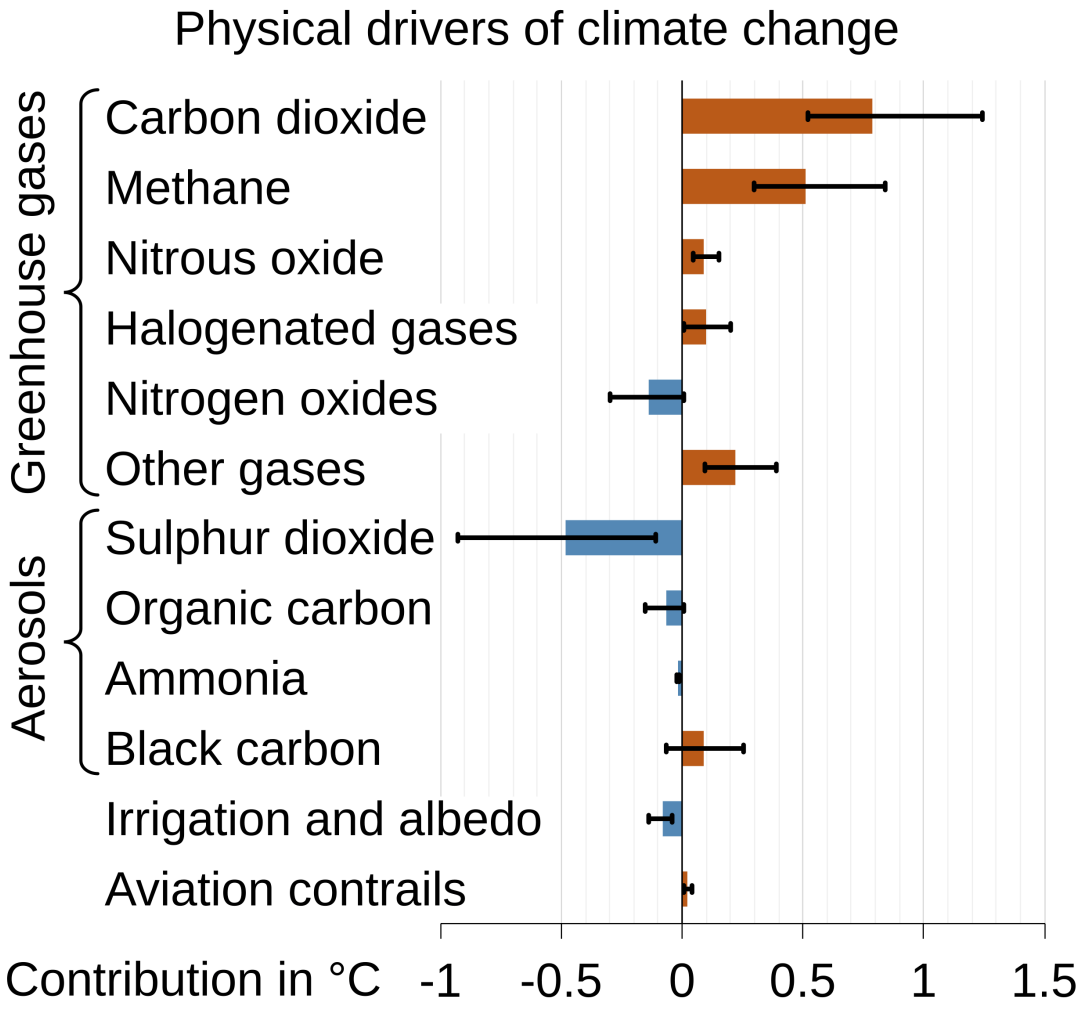


1.4 Negative radiative forcing

- aerosols and precursor gases: These have a net cooling effect, estimated to reduce radiative forcing by about -1.1 W/m² due to their reflective properties and interaction with clouds__



1.5 Physical drivers of radiative forcing



1.6 Radiative forcing impact on buildings and climate

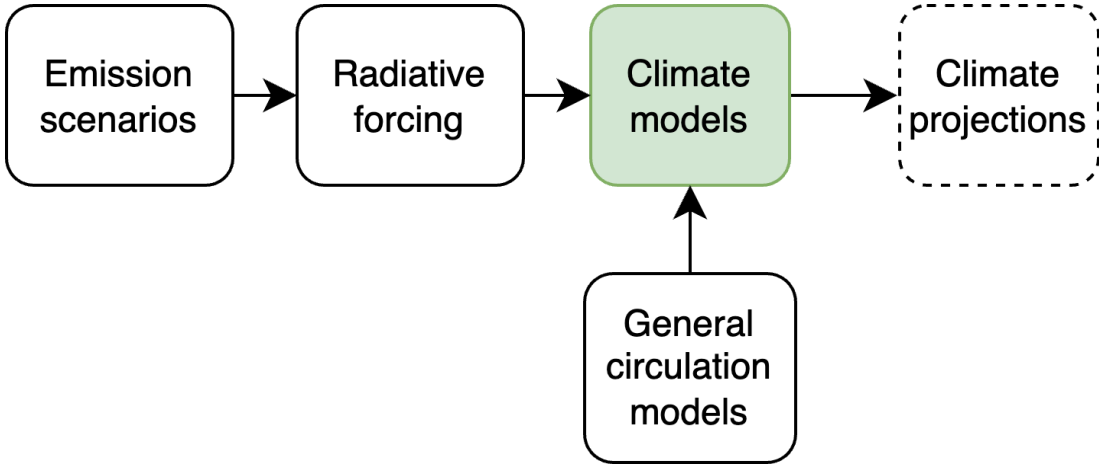
- A building designed today should be still performant in 2070 and probably still in 2100.
- We should be able to predict the ambient conditions in a mid/long-term taking into account climate change and its uncertainties particularly due to how people way of life will evolve.

2. Climate models

2.1 Basic concepts

Climate models simulate the Earth's response to radiative forcing.

- they take into account emission scenarios and the associated radiative forcing
- they consider the climate system response through general circulation models (GCMs)
- have many similarities with weather forecasting models.
    - however, they are not at all based on observations.

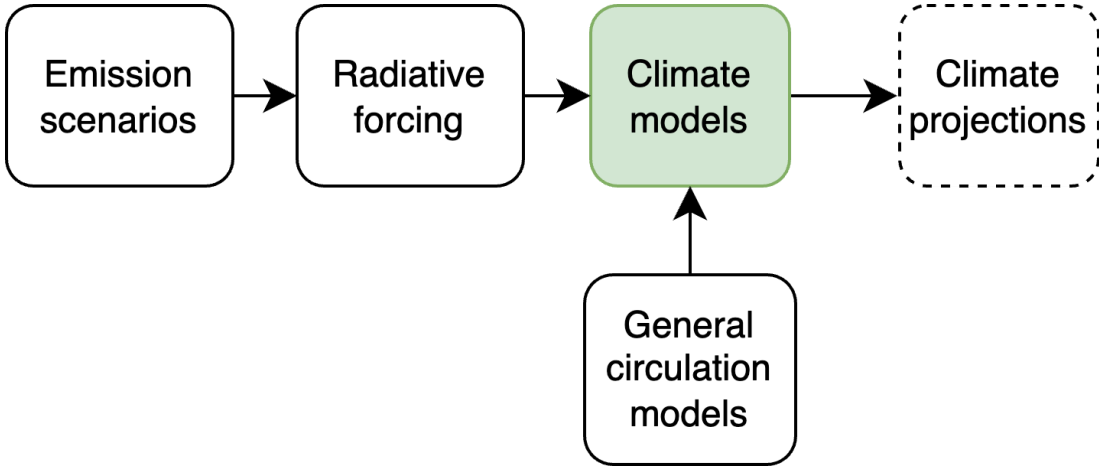


Note: In France, there is a web portal, named DRIAS les futurs du climate, which is publishing diverse simulation results about the possible climate evolution for the French territory.

2.2 General circulation

The climate system evolves completely freely.

- It receives energy in the form of solar radiation and losses it in the form of infrared radiation emitted into space.

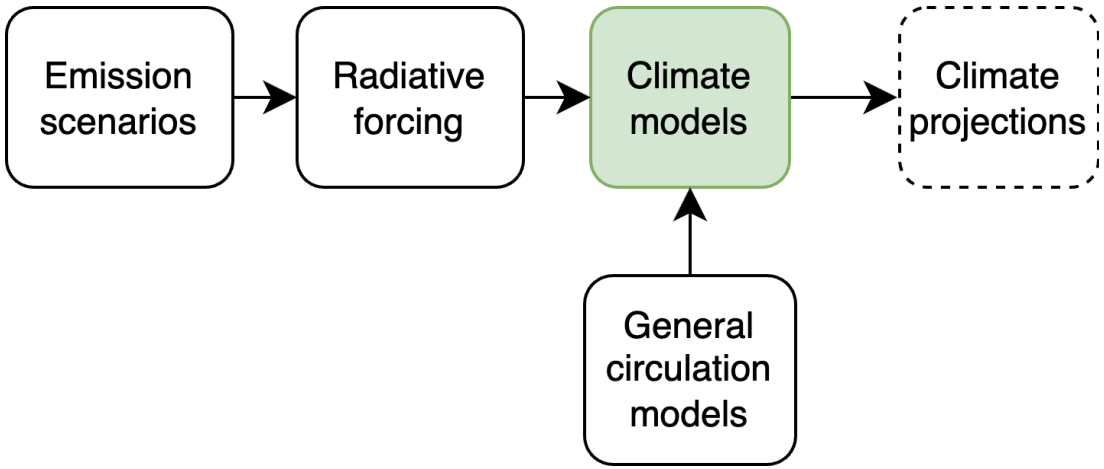


2.2 General circulation models

General Circulation Models (*GCM*, *Modèles Atmosphériques de Circulation Générale* in French) are the primary tools used in climate modelling.

These models take into account:

- Energy cycles
- Water cycles
- Interactions between atmosphere, oceans, soils, vegetation, and ice
- Heat exchange, evaporation, precipitation, and other physical processes



Note: Today, models consider the atmosphere, oceans, soils and vegetation, sea ice, sulphate aerosols, and in some cases continental hydrology, the carbon cycle including the biosphere and marine ecosystems, and stratospheric ozone.

2.2 General circulation models

The main difference compared with a numerical weather forecasting model is the need to force the model towards monthly averages, allowing the annual seasonal cycle to be taken into account.

Atmospheric models are coupled with models representing other parts of the Earth system:

- the ocean,
- vegetation,
- rivers,
- marine biogeochemistry,
- atmospheric chemistry,
- polar ice caps
- the carbon cycle.

3. Emission scenarios

3.1 Context

- Socio economic changes (economy, technology, lifestyle, public policies) impact the climate change.
- The implications of climate change for the environment and society depend not only on the response of the Earth system to changes in radiative forcing, but also on how socio-economic changes (economy, technology, lifestyle, public policies) evolve.
- These scenarios take into account changes in population, economy, industrial and agricultural development and, in fairly simplified terms, atmospheric chemistry and climate change.
- IPCC has developed a set of scenarios to help understand the future climate and its impacts.

3.2 Types of emission scenarios

There are three main types of emission scenarios:

- SRES (Special Report on Emissions Scenarios) - simulations covering the period 1860-2000
- RCP (Representative Concentration Pathways) - simulations covering the period 2006-2300
- SSP (Shared Socioeconomic Pathways) - simulations covering the period 2006-2300, but with different socio-economic developments

3.3 The RCP scenarios

Since the 2000s, socio-economic determinants and knowledge of the climate system have evolved considerably.

- Examples:
  - demographic projections have been revised downwards,
  - development of emerging countries has been underestimated,
  - climate policies have been adopted on a global scale over the last fifteen years.

It was therefore necessary to update the tools used by the IPCC.

Thus, the *RCP* (Representative Concentration Pathways) scenarios were created by scientists, describing how greenhouse gas concentrations will evolve over the period 2006-2300.

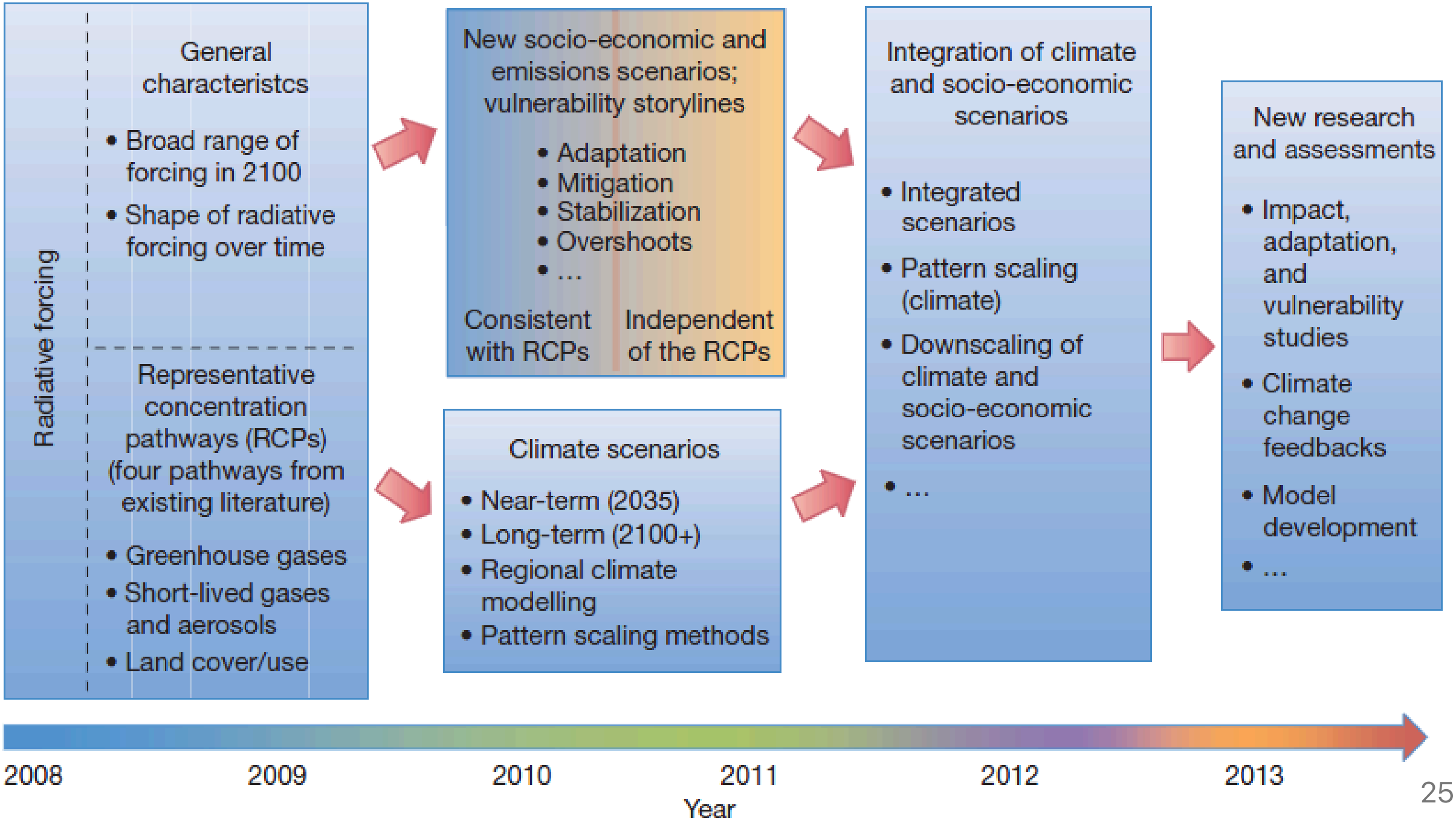
Note: In addition, unlike the SRES scenarios, the new scenarios will not be created by the IPCC itself, but will be provided by the scientific community for the IPCC's use.

3.3.1 The RCP scenarios and radiative forcing

For the 5th IPCC report, 4 RCP scenarios of greenhouse gases (GHG), ozone and aerosol precursors for the 21st century and correspond to greater or lesser efforts to reduce GHG emissions at global level.

Four *a priori* greenhouse gas emission scenarios have been established:

1. RCP8.5: high emissions scenario (radiative forcing 8.5 W/m2 in 2100)
2. RCP6.0: medium-high emissions scenario (radiative forcing 6 W/m2 in 2100)
3. RCP4.5: medium emissions scenario (radiative forcing 4.5 W/m2 in 2100)
4. RCP2.6: low emissions scenario (radiative forcing 2.6 W/m2 in 2100)


Radiative forcing
General characteristcs
• Broad range of forcing in 2100
• Shape of radiative forcing over time
Representative concentration pathways (RCPs) (four pathways from existing literature)
• Greenhouse gases
• Short-lived gases and aerosols
• Land cover/use
New socio-economic and emissions scenarios; vulnerability storylines
• Adaptation
• Mitigation
• Stabilization
• Overshoots
• …
Consistent with RCPs
Independent of the RCPs
Climate scenarios
• Near-term (2035)
• Long-term (2100+)
• Regional climate modelling
• Pattern scaling methods
Integration of climate and socio-economic scenarios
• Integrated scenarios
• Pattern scaling (climate)
• Downscaling of climate and socio-economic scenarios
• …
New research and assessments
• Impact, adaptation, and vulnerability studies
• Climate change feedbacks
• Model development
• …
2008
2009
2010
2011
2012
2013
Year

3.6 Socio-economic scenarios

Compared with the RCPs, the new Shared Socioeconomic Pathway (SSP) scenarios provide economic and social reasons for socio-economic developments in relation to the different trajectories of greenhouse gas concentrations.

Five families of SSP scenarios have been defined: it enables climatologists and economists to work in parallel.

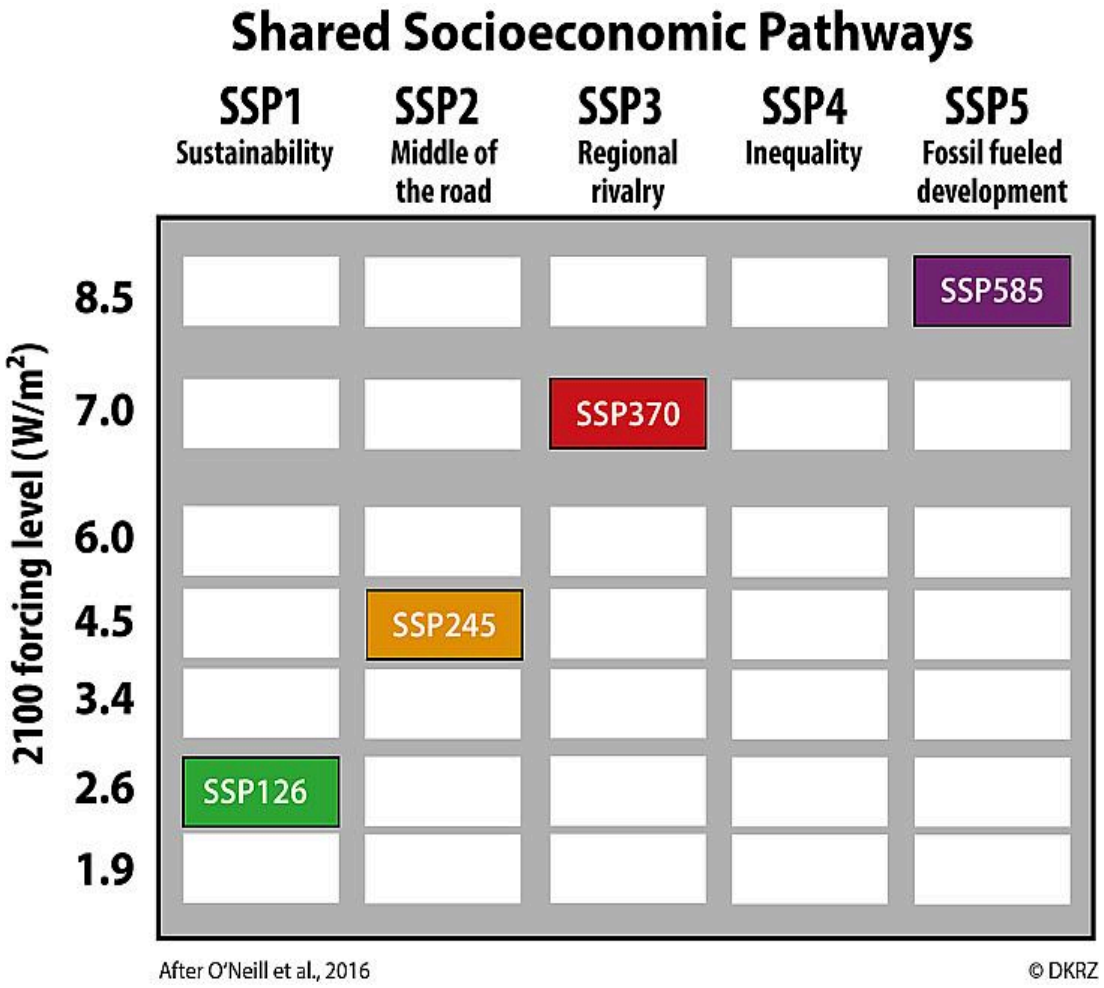
- SSP1: radiative forcing 2.6W/m2 associated with sustainability
- SSP2: radiative forcing 4.5W/m2 associated with middle of the road
- SSP3: radiative forcing 7W/m2 associated with regional rivalry
- SSP4: radiative forcing ?W/m2 associated with inequality
- SSP5: radiative forcing 8.5W/m2 associated with fossil fuel development

3.6.1 The SSP scenarios - RCPs vs SSPs

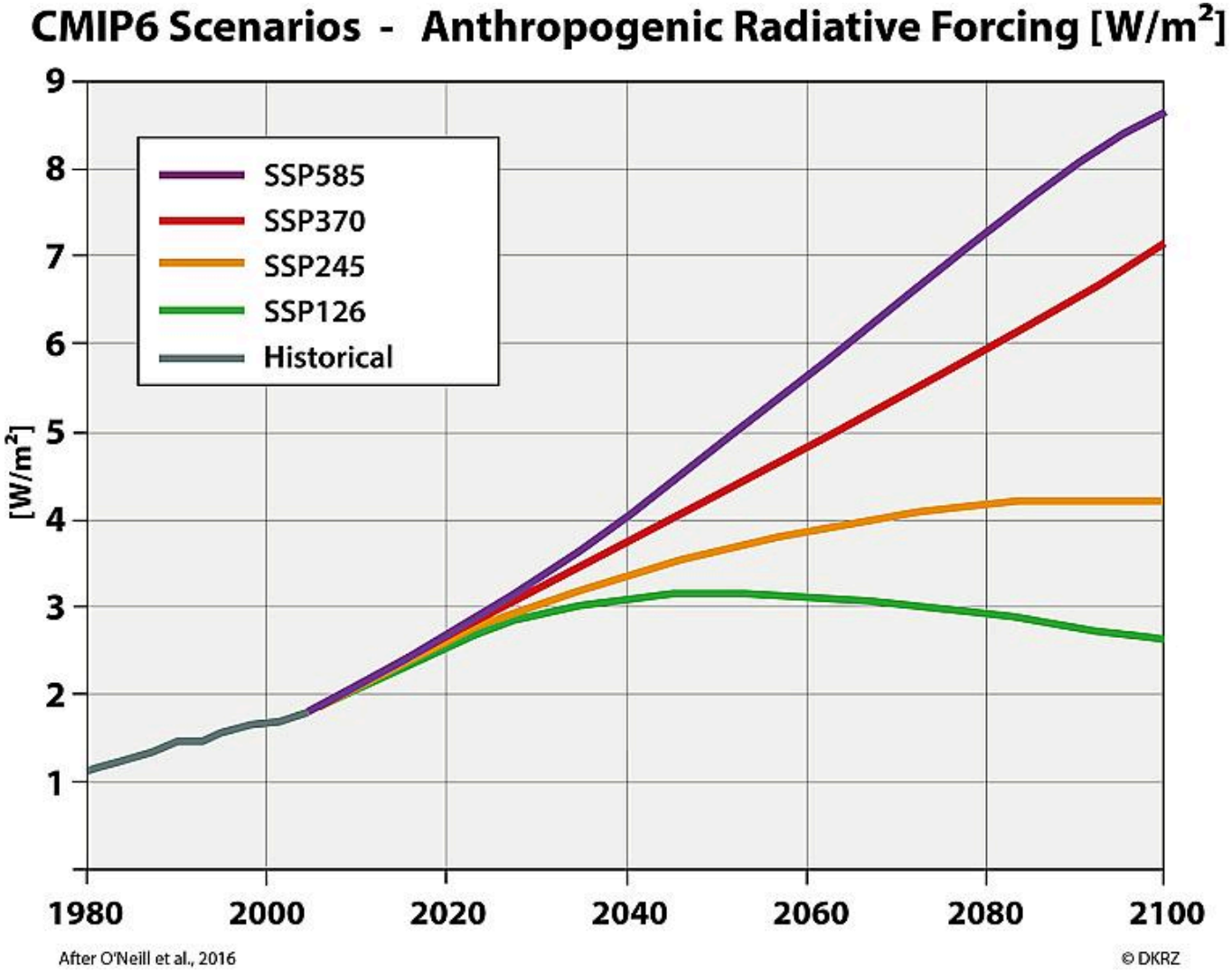
- RCPs focus primarily on the radiative forcing, while SSPs focus on the socio-economic developments up to 2100.
- Compared with the RCPs, the new SSP scenarios illustrate different socio-economic developments in relation to the different trajectories of greenhouse gas concentrations in the atmosphere.

3.6.1 The SSP scenarios - RCPs vs SSPs

Unlike the RCP scenarios, the new SSP-based scenarios provide economic and social reasons for the assumed emissions trajectories.



3.6.2 The SSP scenarios - radiative forcing



4. Global warming level approach

4.1 Core Concept

Aside from climate models, another approach consists considering a global warming level with respect to 1850-1900.

When analysing climate change with global warming, we look directly at the global warming level: +1.5°C, +2°C and +3°C relative to 1850-1900.

The aim of this approach is not to identify when these levels are reached, but to describe the climate in a world at a given level of warming.

4.2 Method

Using global climate projections, based on global circulation models (GCMs), the correspondence between the level of global warming and the associated impacts is immediate:

- individually for each global simulation, we determine the 20-year period during which the level of global warming relative to the pre-industrial period is reached.
- The final results are usually presented in probabilistic form (multi-model medians, distribution products).

Applying the global warming level approach to regional climate projection involves establishing a correspondence between the regional projections and the global mean temperature.

4.3 IPCC Framework

- The latest IPCC report (AR6; IPCC 2021) puts forward an approach aiming at documenting the global climate for different levels of warming.
    - The aim is to describe the climate in a world at a given level of warming, rather than at a given timeframe and for a given emissions scenario.
- For the first time, in AR6, the IPCC decided to base its estimates on statistical combinations of models and observations (a method known as "observational constraints").
- The results obtained on mean global warming indicate a significant reduction in uncertainty.

4.4 Warming Levels and Timelines

In the light of the information provided by the IPCC, 3 levels of global warming have been selected:

- Global warming limited to +1.5°C: reached by the early 2030s, unless global emissions are drastically reduced immediately;
- Global warming of up to +2°C: if very large reductions in GHG emissions are made after 2030 and if global carbon neutrality is achieved in the second half of the 21st century;
- Global warming of up to +3°C: This level lies between the warming that would result from the commitments announced by governments (+2.8°C in 2100) and the warming that would result from the global policies in place at the end of 2020 (+3.2°C in 2100).

4.5 Regional Variations

Global warming doesn't affect all places in the same way.

For example, when the Earth warms by +1.5°C globally:

- France might warm by +2°C
- Some other regions might warm more or less

4.6 Regionalization

Regionalization increases model resolution to 10-100 km scales for impact studies. It establishes correspondence between regional and global mean temperature projections.

Downscaling refines model resolution for local studies through dynamic (physics-based) or statistical approaches. Bias correction methods adjust model outputs to match observations.

5. Narrative approach

5.1 Basic concepts

A narrative is defined as a physically coherent sequence of past or future events.

- This approach seeks to develop descriptive 'narratives' of possible future climates.
- Several narratives need to be considered in order to explore several possible futures.
- In addition, it is important to describe how they have been selected and how they fit within the distribution of the set of models.
- The Explore2-Climate game is based on 17 EURO-CORDEX projections at 12 km resolution, which have been corrected for their biases using the ADAMONT and CDF-t methods.
- From these projections, four narratives were selected in co-construction with hydrologists, to illustrate possible climate futures in mainland France.

Note: Daily simulations of climate change from 2006 to 2100 are available on the DRIAS website: https://www.drias-climat.fr

5.2 Narative approach example: Explore2-Climate

Four narratives illustrate contrasting climate futures based on 17 EURO-CORDEX projections:

- Orange: strong warming and drying
- Yellow: moderate changes
- Purple: strong warming with seasonal precipitation contrasts
- Green: marked warming with increased precipitation

6. Model selection

6.1 Context

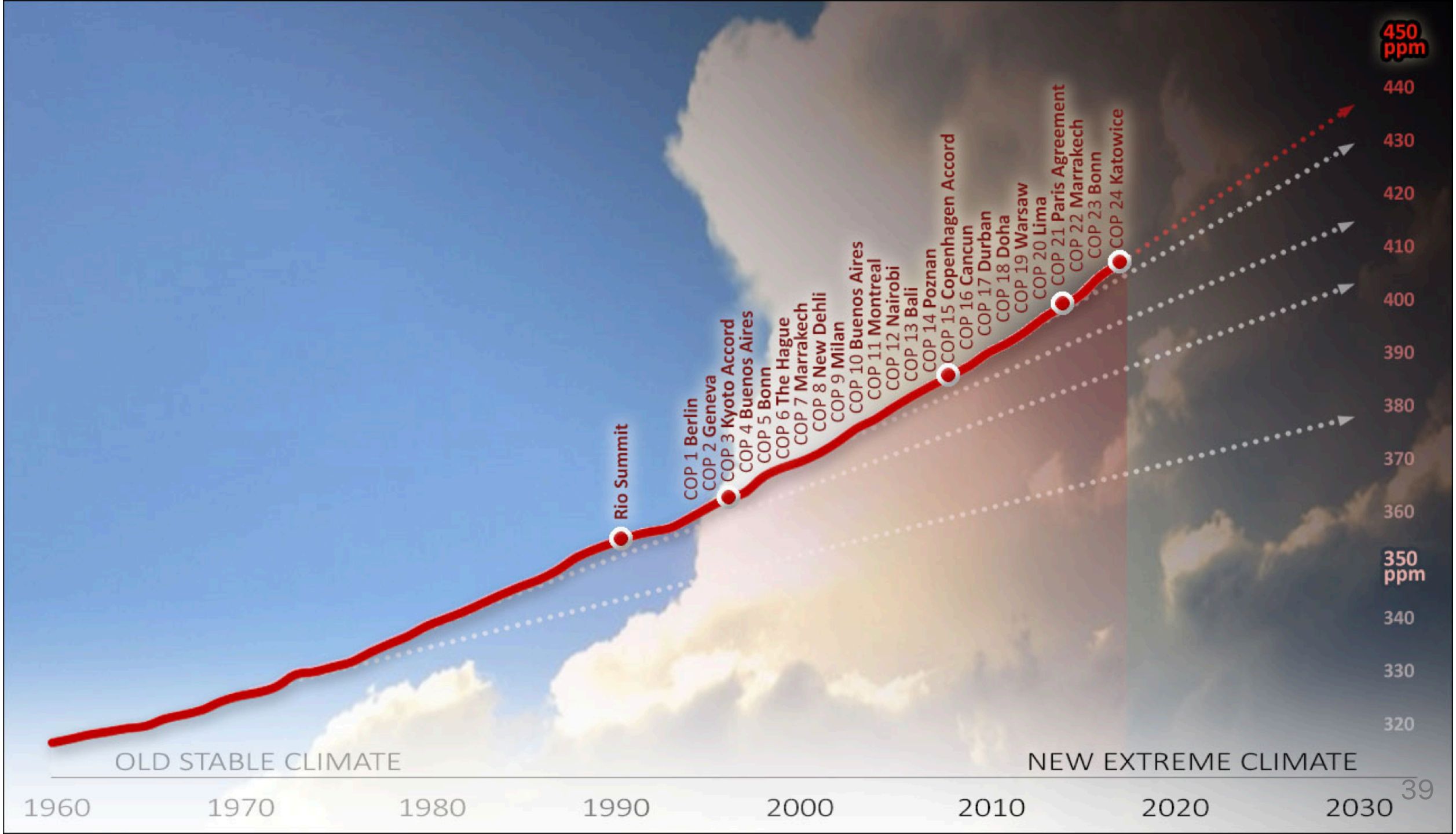
- One of the major difficulties in carrying out an impact assessment is selecting the climate projections that will be used to determine the adaptation measures.
- These climate projections correspond to different emission scenarios and different models (GCM/RCM pairs), which need to be chosen according to the objectives of the impact study.

6.2 Choice of individual simulations for France

- The DRIAS portal offers a selection of climate simulations, chosen to optimize the dispersion of the climate signal, as well as a wide range of climate indices.
- For the DRIAS-2020 ensemble, no fewer than 30 simulations are available, including 8 models for RCP2.6, 10 models for RCP4.5 and 12 models for RCP8.5.

6.3 Model selection approaches

Multi-model ensembles represent uncertainty through probabilistic distributions (median, 5th and 95th percentiles). Models are selected based on temperature and precipitation indicators, balancing computational constraints with uncertainty coverage.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350 ppm
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Rio Summit
COP 1 Berlin
COP 2 Geneva
COP 3 Kyoto Accord
COP 4 Buenos Aires
COP 5 Bonn
COP 6 The Hague
COP 7 Marrakech
COP 8 New Dehli
COP 9 Milan
COP 10 Buenos Aires
COP 11 Montreal
COP 12 Nairobi
COP 13 Bali
COP 14 Poznan
COP 15 Copenhagen Accord
COP 16 Cancun
COP 17 Durban
COP 18 Doha
COP 19 Warsaw
COP 20 Lima
COP 21 Paris Agreement
COP 22 Marrakech
COP 23 Bonn
COP 24 Katowice
OLD STABLE CLIMATE
NEW EXTREME CLIMATE
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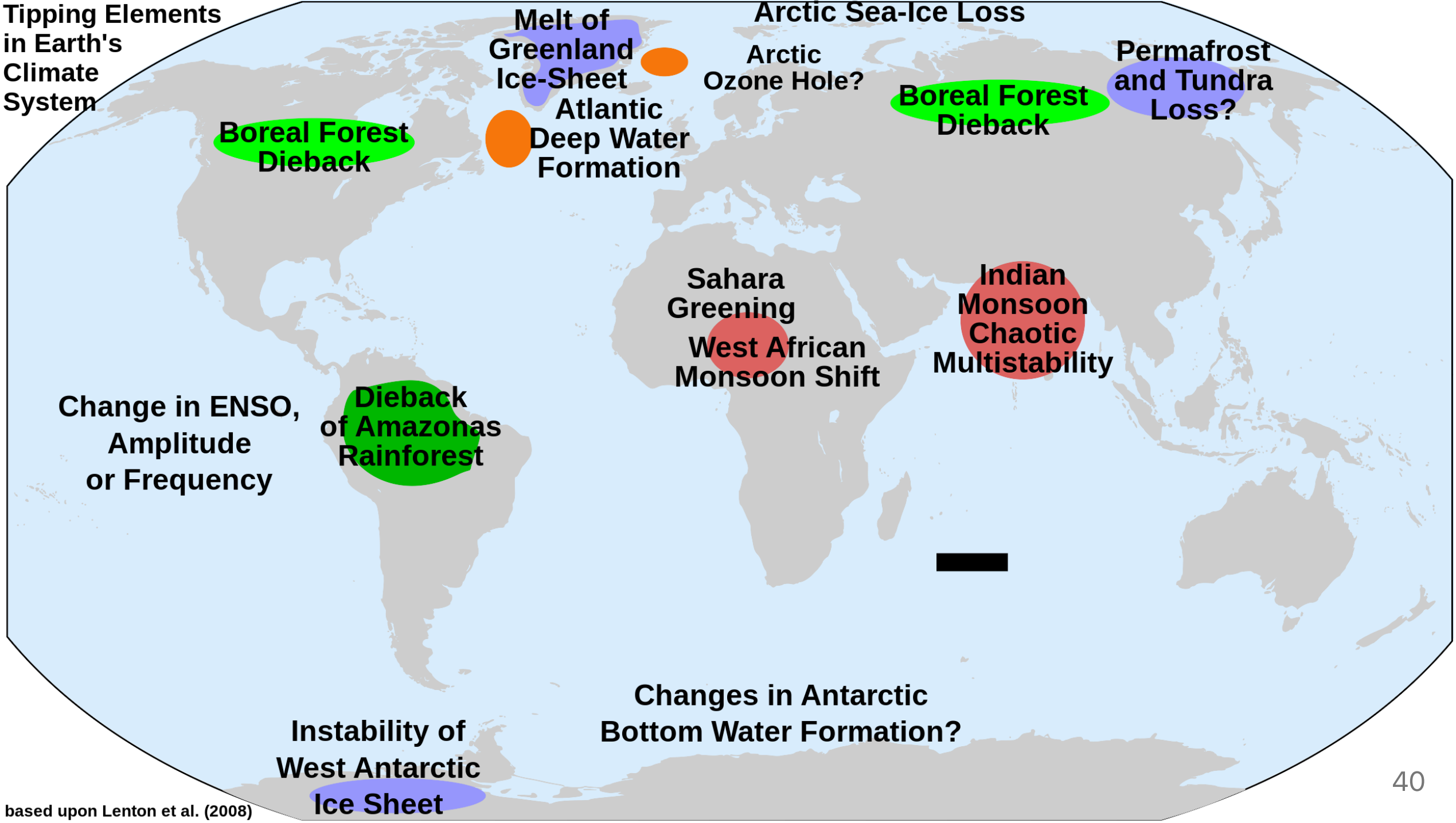

based upon Lenton et al. (2008)

Self-check questionnaire

12 questions — climate change and projections

Choose the best answer each time.

(In class: discuss in pairs; answers on the following slides.)

Q1 — Radiative forcing (definition)

On the slides, radiative forcing ΔF quantifies a change in the Earth's energy balance at the top of the troposphere as:

- A. $\Delta F = F_{\text{down}} - F_{\text{up}}$ in W/m²
- B. $\Delta F = T_{\text{surface}} - T_{\text{space}}$ in kelvin only
- C. The annual-mean precipitation rate in mm/day
- D. GDP growth rate minus inflation

Q2 — Human-caused forcing (order of magnitude)

For the period 1750–2019, the slides cite a human-caused radiative forcing of about:

- A. $\Delta F_{\text{human}} \approx 0.27\ \mathrm{W/m^2}$
- B. $\Delta F_{\text{human}} \approx 2.72\ \mathrm{W/m^2}$
- C. $\Delta F_{\text{human}} \approx 27\ \mathrm{W/m^2}$
- D. $\Delta F_{\text{human}} \approx 0\ \mathrm{W/m^2}$ by definition

Q3 — Positive forcing (GHGs)

According to the lecture, the largest contributor to positive radiative forcing since pre-industrial times is:

- A. Changes in greenhouse gases (with CO_2 alone cited at about 2.17 W/m^2)
- B. Stratospheric ozone depletion only
- C. Increased surface albedo from afforestation everywhere
- D. A sustained increase in total solar irradiance dominating all other terms

Q4 — Negative forcing

Aerosols and precursor gases are presented on the slides as contributing roughly:

- A. +1.1 W/m² warming
- B. –1.1 W/m² (net cooling through reflection and cloud interactions)
- C. No effect on radiative balance
- D. Exactly –2.72 W/m², cancelling all human GHG forcing

Q5 — Water vapour

Why is water vapour usually not listed like CO_2 as a primary external radiative forcing in IPCC-style summaries?

- A. It has a short atmospheric lifetime and mainly acts as a feedback amplifying forcing from other GHGs
- B. It does not absorb infrared radiation
- C. Its concentration is fixed and never changes
- D. It is absent in the real atmosphere

Q6 — RCP scenarios

An RCP2.6 pathway is named for its target of about 2.6 W/m² of radiative forcing in 2100. This framework primarily describes:

- A. Representative Concentration Pathways — trajectories of greenhouse-gas concentrations and associated forcing
- B. Regional Construction Permits for buildings only
- C. A single fixed global temperature with no emissions link
- D. Historical simulations for 1860–2000 only (SRES period)

Q7 — SSP vs RCP

Which pairing best matches the slides?

- A. RCPs emphasize radiative forcing / concentration pathways; SSPs add socio-economic narratives (demographics, economy, policies) often combined with forcing levels (e.g. SSP1-2.6, SSP5-8.5)
- B. SSPs are only weather forecasts for one week; RCPs are only ocean tides
- C. RCP and SSP are identical acronyms for the same thing
- D. SSPs replace all physics in climate models

Q8 — Climate models (GCMs)

General circulation models (GCMs) in this lecture are used to:

- A. Simulate exchanges among atmosphere, oceans, cryosphere, biosphere, and land under physical laws on a discretized grid
- B. Replace radiative transfer with a single albedo constant for all cells
- C. Predict stock markets from CO_2 concentrations
- D. Ignore emission scenarios entirely

Q9 — Global warming level approach

The global warming level approach (e.g. +1.5°C, +2°C, +3°C vs 1850–1900) mainly aims to:

- A. Describe the climate in a world at a given warming level, rather than fix a single calendar year and scenario as the only framing
- B. Prove that regional warming is always exactly equal to global warming everywhere
- C. Eliminate all model uncertainty
- D. Replace downscaling with global means only

Q10 — Regional vs global warming

When global mean warming is about +1.5°C, the slides note that France might warm by about:

- A. +2°C (regional warming can differ from the global mean)
- B. 0°C always
- C. −1.5°C
- D. Exactly +1.5°C in every grid cell by definition

Q11 — Model uncertainty

The introduction lists three main sources of uncertainty in climate projections. Which set appears on the slides?

- A. Internal variability, model structure (resolution, parameterizations), and scenario uncertainty (emissions, behaviour)
- B. Only measurement error in thermometers from 1850
- C. Only building U-values
- D. Only lunar phases

Q12 — Impact studies (France)

For climate projections over France, the slides point to the DRIAS portal and stress that choosing simulations requires balancing:

- A. Different emission scenarios and GCM/RCM pairs according to the impact study objectives, often using multi-model ensembles (e.g. medians, percentiles)
- B. A single model and single scenario always sufficient for all decisions
- C. Ignoring aerosols and using only RCP8.5
- D. Replacing physical models with one narrative colour (Orange/Green) only, with no ensemble

Answer key (1/2)

Q	Answer	Short rationale
1	A	$\Delta F = F_{\text{down}} - F_{\text{up}}$ at tropopause; W/m².
2	B	$\Delta F_{\text{human}} \approx 2.72\ \text{W/m}^2$ (1750–2019).
3	A	GHGs dominate positive forcing; $CO_2 \approx 2.17\ \text{W/m}^2$.
4	B	Aerosols $\approx -1.1\ \text{W/m}^2$ net cooling.
5	A	Short lifetime; feedback, not primary external forcing like CO_2.
6	A	RCP = concentration/forcing pathways (2.6, 4.5, 8.5 W/m²…).

Answer key (2/2)

Q	Answer	Short rationale
7	A	RCP forcing paths; SSP socio-economics; combined labels (SSP×RCP).
8	A	GCMs: full Earth-system physics on a grid.
9	A	Warming-level framing: climate at +1.5°C, +2°C, +3°C worlds.
10	A	Example: France ~+2°C when global ~+1.5°C.
11	A	Internal variability + model structure + scenarios.
12	A	DRIAS; scenario/model choice; ensembles for uncertainty.

Open and solve the questions of the workshop02_climate.ipynb