Scientific guidelines to facilitate the use of climate projections

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Ouranos

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Context

Taking future climate into account is now a must, whether for the development of adaptation plans, or for risk or vulnerability analysis. However, the available and climate information can be difficult to interpret and use, as climate science is complex and rapidly evolving. To use the data properly, a good understanding of the climate modelling chain is therefore desirable.

Objectives and scope

This document provides recommendations on the information to be considered in climate change risk analysis. Based on current scientific knowledge, these recommendations aim to better understand certain concepts of climate modelling and are intended to inform the choice of:

- climate models
- emission scenarios (greenhouse gases, particulate aerosols, land use)
- time horizons and reference periods
- percentiles

The information contained in this document is based on the most up-to-date scientific knowledge. It will be updated, as necessary, to reflect new developments.

Climate Modelling and scenarios

A climate model simulation is a digital representation of the climate system. Different model configurations enable experiments to be carried out to understand how the climate reacts to different situations. Some experiments, for example, simulate volcanic eruptions, or changes in land use, to explore their effect on climatic conditions at different scales. The experiments most commonly used for climate change adaptation are those in which GHG and aerosol particle concentrations follow predefined scenarios.

The design of a climate experiment begins with GHG emission scenarios generated from integrated assessment models (Figure 1). The simplified Earth system model MAGICC7 converts these emissions into GHG concentrations in the atmosphere, which in turn serve as inputs to various global climate models. The results of the various climate models are then made available to researchers and the public to measure, among other things, the climatic consequences of policies aimed at reducing GHG emissions.

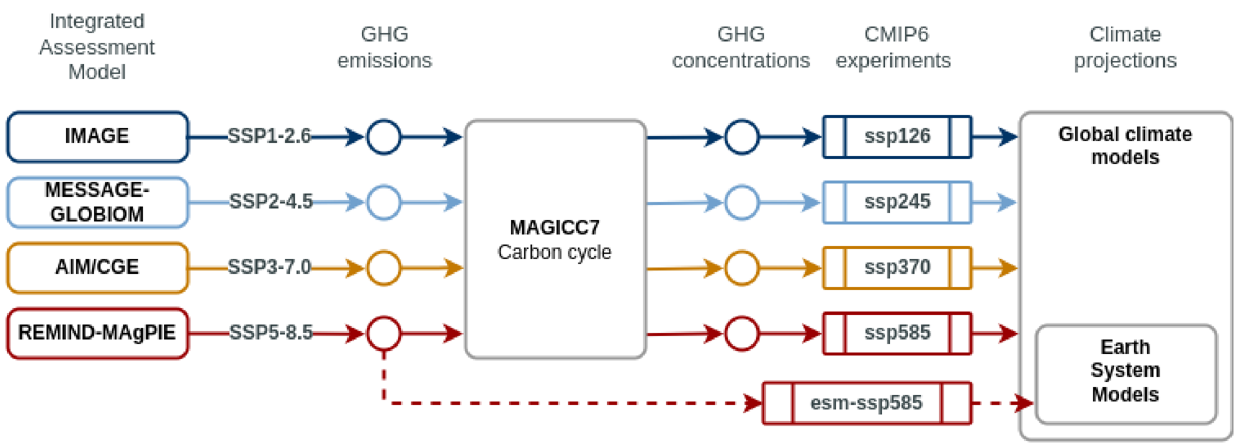

Figure 1. Stages in the generation of climate projections taking into account the future evolution of GHG emissions.

Updating the CMIP model set

Whereas:

- ➔ the results of the CMIP6 models are of comparable or slightly higher quality than those of CMIP5;
- ➔ it is rare for the new generation of models to call into question the major high-confidence conclusions of previous generations.

As part of a new study, it is recommended to:

- ➔ choose the latest models available, i.e. CMIP6.

In the context of an existing study, it is recommended to:

- ➔ update results with CMIP6 only:
  - when the original study is based on CMIP3;
  - when the original study is based on CMIP5 and the scientific literature suggests that phase 6 models perform significantly better for the variable and region of interest.
- ➔ Otherwise, keep CMIP5.

Coordinating climate modelling experiments

Nearly fifty organizations around the world are developing climate models and making the results of their simulations publicly available. These efforts are part of the Coupled Model Intercomparison Project (CMIP), a World Climate Research Program. In 2023, this project is in its sixth phase (CMIP6), offering an update on the results of the previous phase (CMIP5).

A CMIP experiment is an experimental protocol followed by the various climate modelling teams. By following this protocol, they ensure that the results of different simulations are comparable.

Every 6 or 7 years, the scientific community sets scientific objectives and designs experiments to meet them. Modelling groups then select the experiments in which they wish to participate, apply the experimental simulation protocols and then publish their results publicly.

Each phase of CMIP is an opportunity for modellers to evaluate the most up-to-date versions of their models, which correct the weaknesses of previous versions. Some experiments target an increase in the complexity of the simulated processes, aiming for a more realistic representation, while others aim to answer theoretical questions about how the climate system works.

A foundation for IPCC reports

CMIP results and analyses contribute to the assessments and reports produced by the Intergovernmental Panel on Climate Change (IPCC). For example, phase 5 of CMIP provided the information needed to present the conclusions of the IPCC's 5th report on climate science in 2014. Each new phase of CMIP is an opportunity for the experts invited by the IPCC to review the conclusions drawn from the previous phase.

The changes made to each new generation of models improve the models' performance in simulating observed climate and consolidate the scientific community's confidence in the models' ability to anticipate climate response to different GHG scenarios. It is rare, however, for the new generation of models to call into question the major conclusions of previous generations, particularly for high-confidence results. It is generally the less conclusive results at low or limited confidence levels that are most likely to change with the arrival of a new generation of climate models.

Choosing CMIP6 or CMIP5

The latest IPCC report incorporates the sixth phase of the project (CMIP6), where a new generation of Shared Socio-economic Pathways (SSPs) is used. These replace the Representative Concentration Pathways (RCPs) of the previous IPCC report. It is on the basis of these socio-economic evolution trajectories that GHG and particulate aerosol emissions are estimated, then translated into the concentrations used as inputs to climate models.

Overall, CMIP6 offers comparable, if not slightly superior results to CMIP5 in terms of reproducing the observed climate. However, a number of new questions, addressed in the following sections, arise concerning the choice of emissions scenarios and climate models to be used, depending on their climate sensitivity.

Given that the global model data from phase 6 are now available on the main climate data platforms, it is recommended that the results of phase 6 be used for further studies. However, it may be justified to use phase 5 results, for example if the study requires regional models, since regional multi-model ensembles driven by CMIP6 simulations will probably only be available from 2024 onwards.

In the case of an existing study based on CMIP5, a literature review is suggested to determine whether the content is likely to change significantly with CMIP6. An update is recommended only if this is the case. Note that impact and adaptation[1] studies are often based on climate data from the previous CMIP generation.

[1] 2014 IPCC Reports, Working groups II and III

How to tackle the problem of hot models with CMIP6?

Whereas:

- ➔ the so-called ‘hot” models are overrepresented in the CMIP6 ensemble, or more generally that the distribution of the effective climate sensitivity of the models in the CMIP6 ensemble is not representative of the state of knowledge based on historical and paleoclimatic observations

It is recommended that:

- ➔ statistics calculated on the CMIP6 ensemble consider the over-representation of so-called hot models. This can be done, for example, by selecting or weighting models according to their climate sensitivity.

Climate sensitivity of the CMIP6 ensemble

CMIP6 poses a problem of exacerbated global warming due to the over-representation of models whose future climate is particularly warm. These models are said to have high climate sensitivity. This sensitivity is defined as the global equilibrium temperature change for a CO_2 concentration twice the pre-industrial concentration. Each climate model therefore has its own climate sensitivity, which emerges from the different processes modelled. A "sensitive" model will show more intense warming for the same CO_2 concentration.

Climate sensitivity can be estimated on the basis of recent climate observations and paleoclimate reconstructions. Because of the uncertainties affecting observations and reconstructions, the estimate of climate sensitivity is not a single value, but a probability distribution, interpreted as a relative level of confidence. Figure 2 illustrates the difference between the climate sensitivity distribution of the models in the CMIP6 ensemble and that estimated from observations.

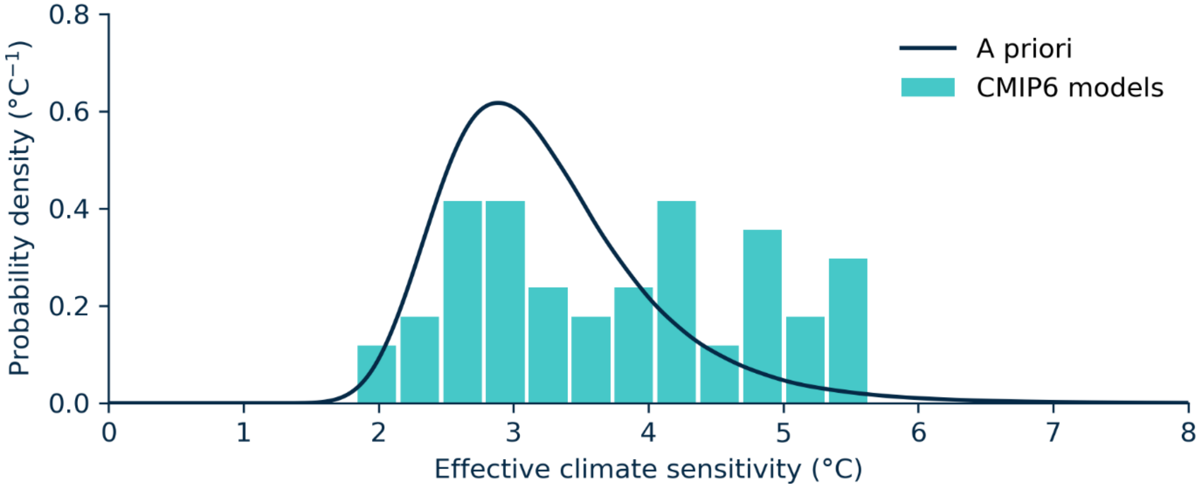

Figure 2 Histogram of the effective climate sensitivity of models in the CMIP6 ensemble (Zelinka et al. 2020), compared with the probability density of effective climate sensitivity estimated from historical climate, paleoclimate and the physics of climate change feedback (Sherwood et al. 2020).

In summary, the CMIP6 ensemble does not form a representative sample of current knowledge of climate sensitivity, and consequently the ensemble mean and other statistics are biased. This implies that the mean temperature change of the CMIP6 ensemble is higher than expected based on the climate sensitivity estimate. This is the problem with the so-called hot models. By way of illustration, Figure 3 shows two histograms of temperature change, one calculated by weighting the models in the CMIP6 ensemble (SSP5-8.5) by their climate sensitivity, and the other without weighting. We can clearly see that an unweighted model ensemble overestimates global warming compared to the same weighted ensemble.

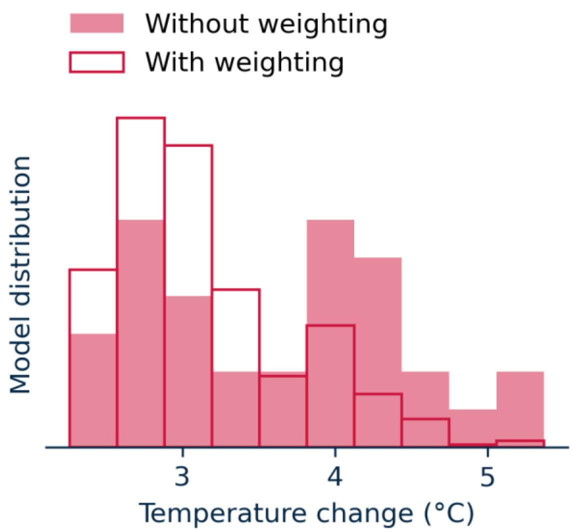

Figure 3 Histogram of global mean temperature change for the CMIP6 ensemble and SSP5-8.5 scenario models between 1990-2020 and 2070-2100, calculated with and without weighting by climate sensitivity estimated by Sherwood et al. (2020) and Zelinka et al. (2020).

Avoiding the hot models

In its latest report, the IPCC proposes the use of emulators (tools for selecting models according to different criteria) calibrated on the basis of multiple sources of information. These emulators can be used to produce projections in line with estimated climate sensitivity. However, this approach requires considerable expertise, and is difficult to apply to the myriad of climate adaptation studies.

Recent research (Hausfather et al. 2022) suggests cutting models whose transient climate response (another measure of climate sensitivity) is outside the plausible bounds (66%) defined by the IPCC (1.4-2.2°C). This selective approach may, however, prove inappropriate, if it is extended to the study of the risk of extreme events.

Greenhouse gas scenarios

Whereas:

- ➔ the new generation of concentration scenarios, called Shared Socioeconomic Pathways" (SSP), is now available and underpins the latest generation of climate simulations (CMIP6);
- ➔ in its latest report, IPCC Working Group III mentions that SSP5-8.5, based on the absence of climate policies, becomes more implausible with the implementation of emission reduction measures, and is only useful as a high-risk scenario;
- ➔ the CORDEX project has revised its scenario choices and now identifies SSP3-7.0 rather than SSP5-8.5 as the high-emissions scenario. SSP1-2.6 is considered a low-emissions scenario.

It is recommended to:

- ➔ adopt a sensitivity analysis perspective based on "median" (SSP2-4.5) and "high" (SSP3-7.0) concentration scenarios when planning adaptation.
- ➔ consider the "very high" concentration scenario SSP5-8.5 when dealing with highly unlikely hazards with catastrophic consequences, or as an analogue of a post-2100 climate.

The climate simulations available for analyzing the impacts of climate change are based on scenarios for atmospheric concentrations of GHGs and aerosol particles, and for changes in land use. For the latest generation of climate simulations, these scenarios describe both the history of 43 GHGs from 1860 to 2015, and their evolution from 2015 to 2500.

These concentration scenarios are based on GHG emission scenarios resulting from integrated assessment model (IAM) simulations. Based on demographic, economic, energy and emission reduction policy assumptions, these IAMs simulate anthropogenic GHG emission trajectories.

Of the thousands of emissions trajectories simulated by the IAM community, only a few are selected – the so-called "representative" scenarios – to design climate modelling experiments. In the sixth phase of CMIP, four key scenarios of GHG, aerosol and land use concentrations are proposed: SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. **These SSP scenarios are completely distinct from the RCP. Although the radiative forcing of RCP8.5 and SSP5-8.5 are, in theory, the same in 2100,**

the trajectories of GHG emissions and concentrations are different. Figure 5 illustrates the differences in emissions, CO2 concentrations and radiative forcings of RCP and SSP scenarios.

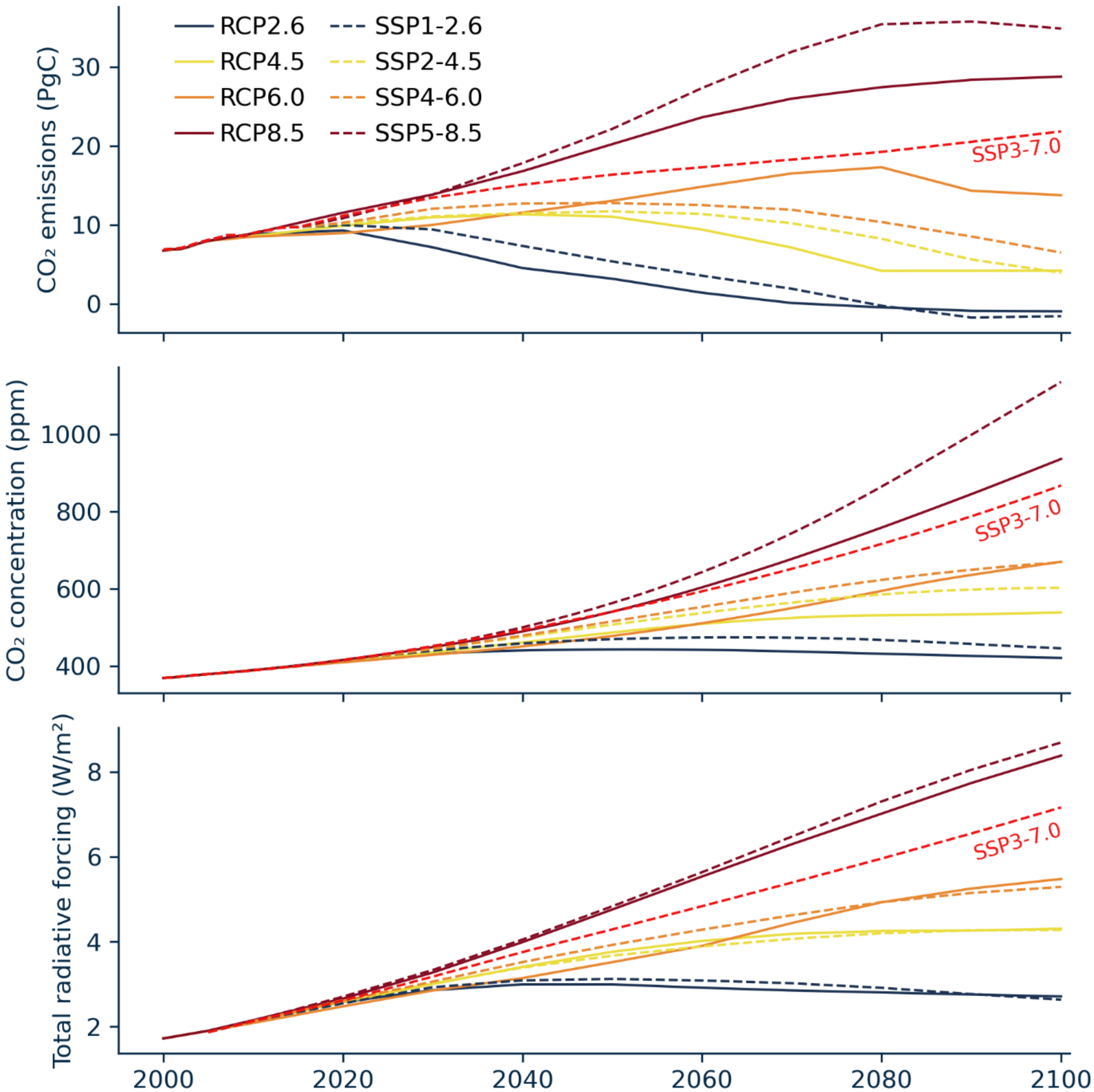

Figure 5 Time series of annual CO_2 emissions (top panel) and concentrations (middle panel) and total radiative forcing (bottom panel) of RCP and SSP scenarios. Significant differences are seen in emissions and concentrations, especially for the RCP8.5 and SSP5-8.5 scenarios.

In most climate change impact studies, results are presented conditional on the scenario. For example, sea-level rise will be presented as a function of different SSPs. This approach helps to illustrate the spectrum of possibilities, and to understand the sensitivity of a hazard to climate change.

Ideally, for risk-based decision-making, SSPs would be accompanied by probabilities. However, the scientific community is still reluctant to take a stand on the respective probability of different scenarios. At most, the latest IPCC report mentions that RCP8.5 and SSP5-8.5 do not represent a typical ("business-as-usual") scenario, and that they are only useful as high-risk scenarios, representative of the upper limit of different "no-climate-policy" scenarios (Riahi et al. 2022). Ouranos is working to develop approaches for assigning probabilities to concentration scenarios to enable climate risks to be quantified (Huard et al. 2022).

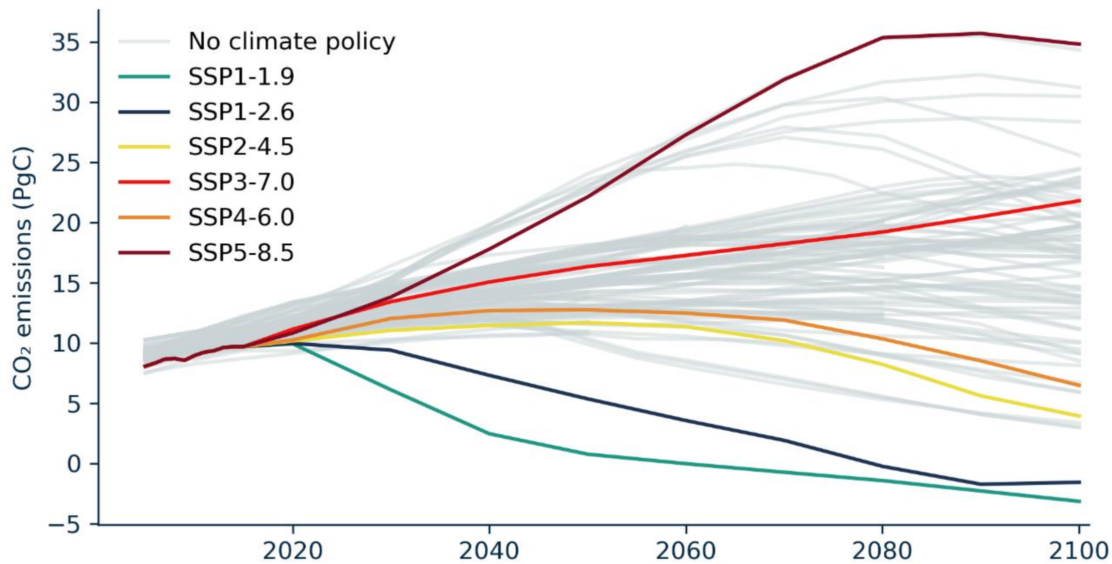

Figure 6 Comparison of the CO_2 emission trajectories of the SSPs (colored lines) with those of the integrated assessment models validated by IPCC Working Group III, and assuming that no emission reduction policy is implemented (gray).

Until the scientific community agrees on clear guidelines for the choice of concentration scenario, Ouranos suggests adopting a sensitivity analysis perspective, and interpreting SSP2-4.5 as the median scenario and SSP3-7.0 as the upper scenario. For exemple:

- a climate hazard with serious consequences, whose severity or frequency is amplified by climate change, should be analyzed with the SSP3-7.0 scenario.

- a hazard with **no major consequences** can be analyzed with scenario SSP2-4.5.

The use of the SSP5-8.5 scenario may be relevant in a context of unlikely hazards, but with catastrophic consequences, or as an analogue of a post-2100 climate relevant to land-use planning.

In practice, other pragmatic considerations may come into play in the choice of scenario. For example, the number of simulations available varies according to the scenario. A scenario may be discarded if it has too few models for a given variable.

The influence of the scenario is also closely linked to the time horizon. In this sense, the different scenarios may follow the same trajectories for the first few decades, and start to diverge from 2040 onwards. The choice of scenario is therefore of no consequence in an analysis up to 2040, whereas it can be decisive in 2100.

Time horizons and reference periods

Whereas:

➔ climate change scenarios compare the climatology of a past period, called the reference period, with that of a future period, called the time horizon,

It is recommended to:

➔ use a reference period and time horizons that are long enough to estimate changes in climate normals and thus moderate the influence of natural climate fluctuations. Averages over a 30-year period are recommended.

- Reference period: The climate normal covering the present/recent past climate recommended by the WMO is 1991-2020.
- Time horizons: 30-year periods are recommended, e.g. 2021-2050, 2041-2070, 2071-2100 to represent short-, medium- and long-term horizons.

A reference period based on standards

The WMO recommends 30-year periods for calculating climate normals. This period is long enough to take proper account of inter-annual variability, while at the same time preventing abnormal years - caused, for example, by intense El-Niño episodes - from distorting climate statistics. Traditionally, it was reasonable to assume that the climate was stationary over this 30-year period, which greatly simplified statistical processing. However, the intensification of warming temperatures is increasingly undermining the assumption of stationarity. We can therefore turn to so-called non-stationary statistics, or, following the example of the IPCC, shorten the time window to 20 years. For several years now, the IPCC has been multiplying comparisons between 20-year horizons, particularly for variables likely to undergo the most marked changes.

While periods of 30 or 20 years reasonably take into account interannual variability, they are too short to adequately include decadal variability. The contribution of this component of variability can be significant for certain variables or indicators, and can differ from one location to another. Under the effect of decadal variability, it is common to see a trend change sign depending on the time window considered. For these reasons, trends calculated over periods shorter than 50 years should be viewed with great caution, and the temptation to extrapolate a trend over a longer period than that used for its calculation should be resisted. It should also be kept in mind that, as temperatures rise, it will become increasingly difficult to represent the evolution of certain variables and indicators using a linear trend.

Time horizons adapted to the challenges

In a climate change impact study, it is important to specify which emission scenarios and which years are under consideration. This period, often referred to as the "time horizon" (see Figure 4), must be determined according to the questions the analyst is trying to answer (nature of the measures to be put in place, lifespan of the systems, ease of adjusting the systems in place, etc.).

For example, a study of shipping in the Arctic will be interested in sea ice concentrations between now and 2035, and will opt for an analysis running from 2021 to 2050, focusing on the decade of interest. The design of a building's air-conditioning system could consider the maximum summer air temperature up to 2060, given the time horizon for major refurbishments of this type of system. Another example would be the safety assessment of a dam, which will require estimating the risk of overflow up to 2100 or even beyond.

The confidence attributed to model projections depends intimately on the time horizon considered. Indeed, there is little uncertainty about the trajectory of GHG concentrations and other forcings between now and 2030, whereas these uncertainties are considerable by 2100. What's more, since models differ in the way they simulate climate response to GHGs, discrepancies between models tend to increase as concentrations rise. Unsurprisingly, confidence in the projections decreases as the timeframe lengthens.

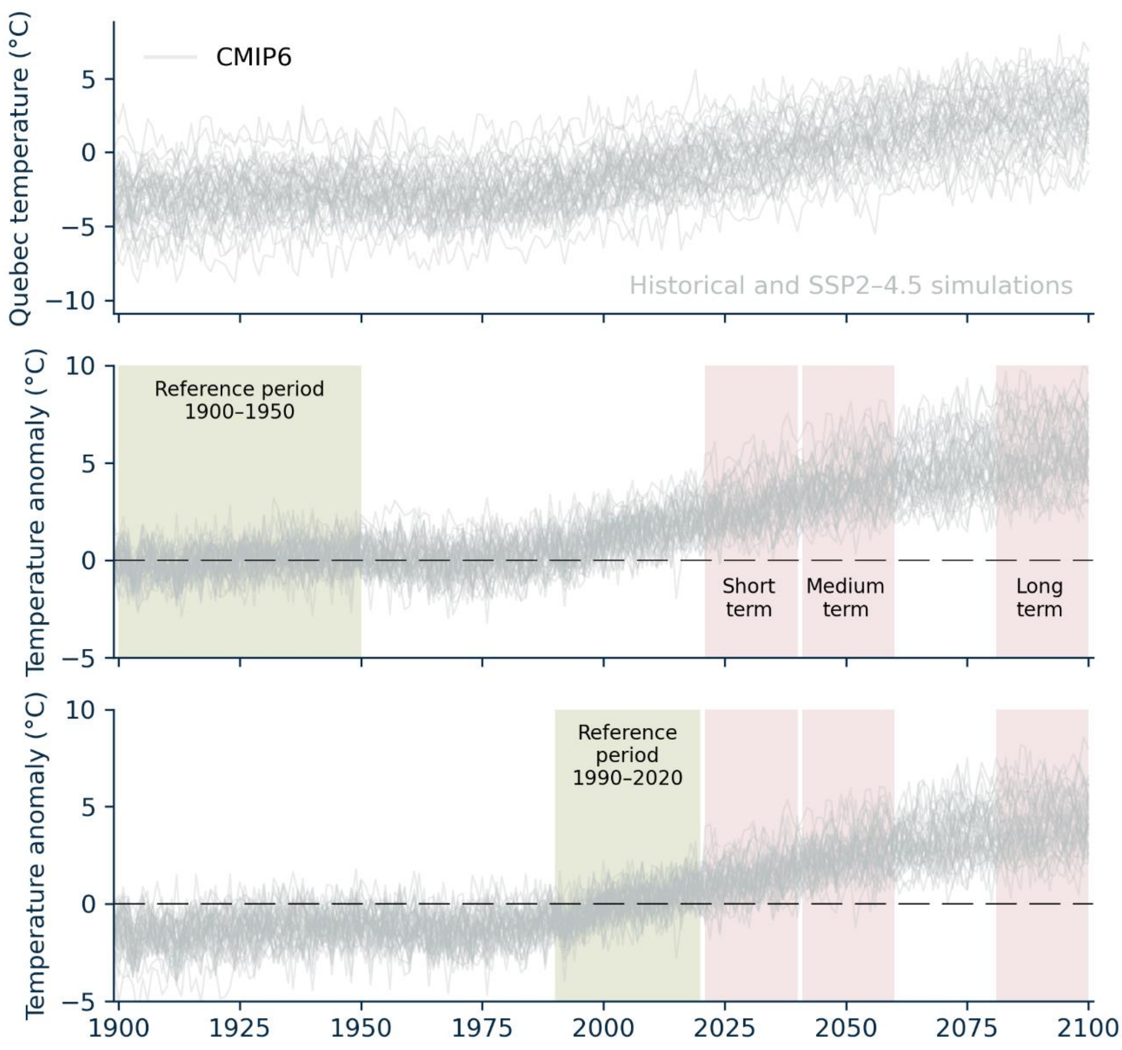

Figure 4 The top panel shows the mean temperature for Quebec simulated by 46 climate models in the CMIP6 ensemble, according to the SSP2-4.5 scenario. The middle panel shows the temperature anomaly, calculated using the period 1900-1950 as reference, while the bottom panel uses the period 1990-2020. The figure illustrates the influence of the choice of reference period on the mean and dispersion of anomalies.

Percentiles

Whereas:

- ➔ percentiles are values corresponding to a rank in a sample or statistical distribution;
- ➔ The distribution of climate simulation results, for a given emissions scenario, illustrates both the dispersion due to differences between models and the effects of natural variability.
- ➔ the 10th, 20th, 50th, 75th and 90th percentiles of a set of simulations are the values represented in climate projections;
- ➔ percentiles allow us to consider rare and sometimes high-impact events (10th and 90th percentiles);
- ➔ assuming that the distribution of the models represents the uncertainties well, the 50th percentile has a 50% chance of being exceeded for a given GHG scenario.

It is recommended to:

- ➔ consider the range or the totality of the projections, especially if high-impact events are important in the decision-making context;
- ➔ choose the percentile according to the decision-maker's risk tolerance and the sensitivity of measures and actions to the scale of change.

Climate model ensembles can include several dozen different models, each producing one or more simulations. It is possible to visualize the temporal evolution of such an ensemble by illustrating each simulation with a line. However, this type of "spaghetti" graph can become very busy, and the level of detail can make it difficult to understand. It is customary to simplify it by plotting the ensemble mean, accompanied by percentiles illustrating its dispersion. The choice of percentiles is not standardized and depends on the application. For example, Ouranos uses the 10th, 25th, 50th, 75th and 90th percentiles on its "Climate Portraits" platform, but another application might choose the 5th and 95th percentiles. In the former case, the percentile envelope describes the behaviour of 80% of the models, while 50% of the models are represented between the 25th and the 75th percentiles.

While choosing a wider range of percentiles allows us to represent a greater fraction of models, percentile values near 0 or 1 are noisier than percentiles near the median. It should also be remembered that percentile time series do not correspond to the results of a particular model, but are rather statistics of the whole. The 90th percentile values for 2050 and 2051 may therefore come from different models.

Since the ensemble of models does not form a representative sample of reality, it is not possible to interpret a 90% percentile strictly as a value with a one-in-10 chance of being exceeded in the real world (see Figure 7). The percentiles of a climate ensemble are only an approximation of the probability of occurrence. Nevertheless, the presentation of percentiles enables us to appreciate the modelling uncertainty affecting the results.

If a percentile is to be chosen for the implementation of a climate change adaptation solution, the decision context must be taken into account. How sensitive are measures to the extent of climate change? What is the risk tolerance? What are the associated costs and benefits? How will the adaptation measure be accepted by the community?

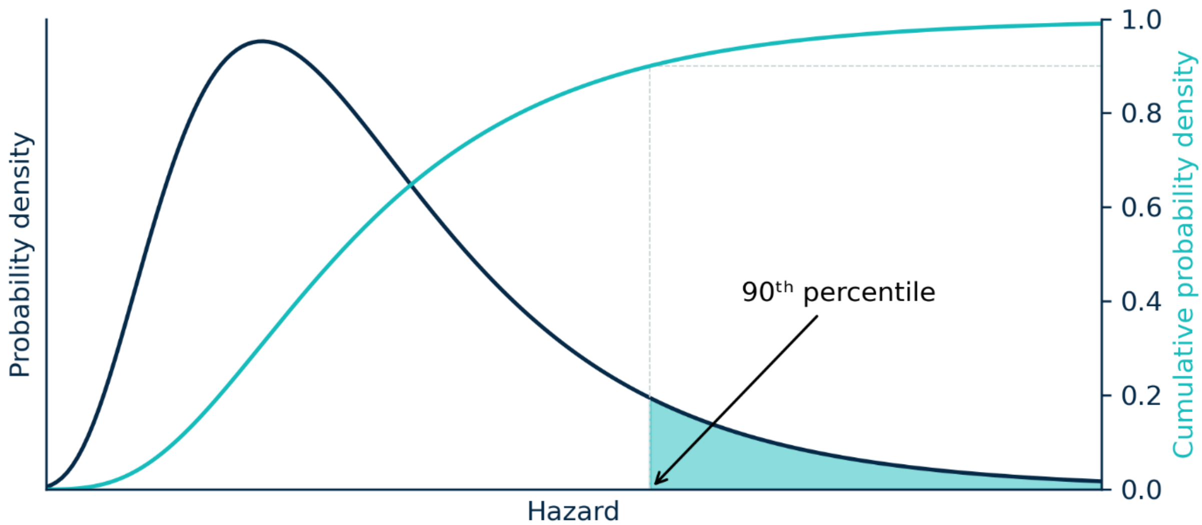

Figure 7 Conceptual illustration of the distribution of a hazard via its probability density and cumulative probability density. In theory, the 90th percentile corresponds to the hazard value with a 1-in-10 chance of being exceeded. In practice, however, there is no guarantee that the sample of models is an accurate representation of reality.

Percentiles of change are often found in the presentation of climate projections. For example, for a given GHG scenario, it is possible to see the 10th, 50th and 90th percentiles of change in precipitation. These percentiles correspond to the rank of the different models that make up the ensemble. In other words, the precipitation change is first calculated for each climate model, then the values are ordered in ascending order, and finally the value closest to the desired percentile is extracted.

Interpreting a quantile map is tricky, as the percentile calculated for each grid point is usually illustrated independently of the others. The value for one point may therefore come from a different model than that of the neighbouring point. As the values represented are not spatially consistent, the percentile values should not be spatially averaged. The correct approach is to calculate the spatial average for each model, then estimate the percentile based on these averages.

Global warming levels

The IPCC's special report "1.5C Global Warming" describes the climate impacts associated with global warming of 1.5°C and 2°C, as well as emission reduction strategies compatible with these levels of warming. This description of impacts by warming level enables us to contrast the effects of climate change. For example, in a 2°C world, the Arctic Ocean would be ice-free one year in 10, and one year in 100 in a 1.5°C world (Hoegh-Guldberg et al. 2018). This approach has been taken up in the latest IPCC Working Group II report, which breaks down climate impacts according to the occurrence of 1.5, 2, 3, and 4°C warming (see example in Figure 8).

Such an approach has the advantage of being, at first glance, independent of time. That is, it describes the impacts of a 2°C warmer world without knowing when this will happen. In practice, this makes it possible to combine all the simulations produced, regardless of the emission scenario, the years and the climate sensitivity of the models. In fact, warming levels make it possible to bypass the methodological issues associated with scenario choice and model weighting discussed above. (How to tackle the problem of hot models with CMIP6?).

In terms of communications, it allows us to discuss the impacts of climate change without describing the different emissions scenarios, which are sometimes a point of contention in a decision-making context. Moreover, as it is widely used by the IPCC, we can expect the public to be familiar with this way of presenting impacts.

One drawback, however, is the absence of continuous time series between today and a future horizon, a typical requirement of economic analyses. Also, in an adaptation context, the choice of the degree of warming is likely to depend on the time horizon, and therefore implicitly on the emission scenario. In practice, therefore, the approach is not entirely independent of time and scenarios. Finally, as the degree-of-warming approach is relatively recent, there is less experience in the field of its use in support of adaptation decisions.

That said, the warming level approach is of great interest for certain applications, such as communicating with the general public, or guiding design standards for issues that are well represented by them (heating and cooling, permafrost, snow cover). Conversely, it is not recommended for risk related to sea-level rise, or for analyses requiring continuous time series.

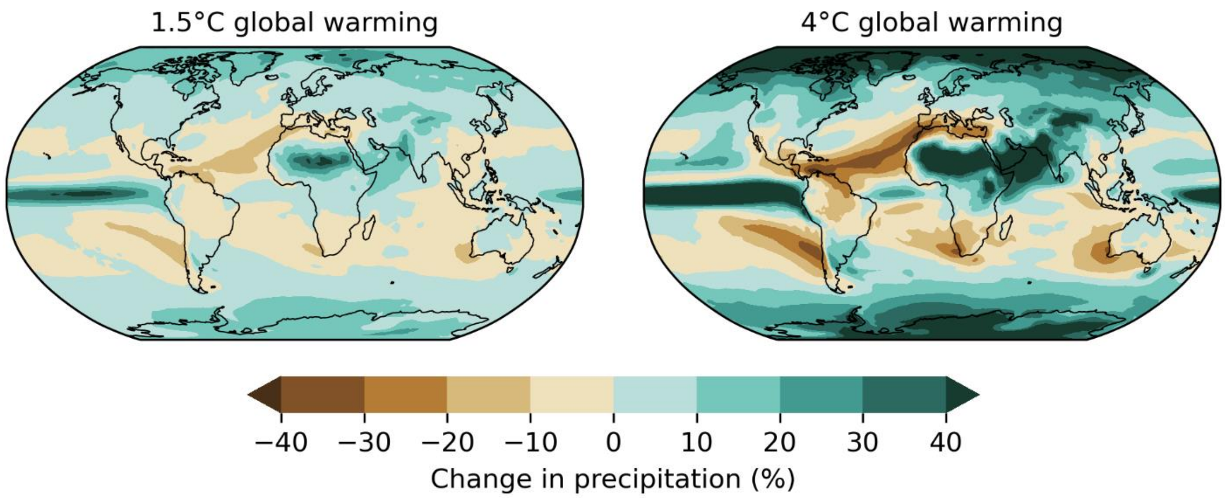

Figure 8 Simulated change in mean annual precipitation (%) relative to 1950-1900 for global warming of 1.5°C and 4°C. Inspired by figure 5 of the Summary for Policymakers (IPCC 2021). Data from Fischer and Hauser. (2021).

To estimate impacts in the form of warming levels, all simulations of all scenarios and all models are first pooled. For each simulation, the global mean temperature over a centered 20-year moving window is calculated, and then, for each warming level, the year in which that level is reached is identified. For each level, the 20-year simulations of all the models that reach it are combined, forming an ensemble that has reached the same level of warming. The years used vary according to the GHG scenario used and the climate sensitivity of the models. This approach is known as "transient", referring to the fact that the climate has not stabilized at this level of warming. The approximate dates at which these warming levels are reached can be linked to the different GHG emission scenarios (Tableau Cross-Chapter Box CLIMATE.1 , Rawshan Ara Begum et al. 2022). Another approach, known as "equilibrium", selects a period when the climate has stabilized at a given level of warming.

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