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The Scenario Model Intercomparison Project for CMIP7 (ScenarioMIP-CMIP7)

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Abstract

Scenarios represent a critical tool in climate change analysis, enabling the exploration of future evolution of the climate system, climate impacts, and the human system (including mitigation and adaptation actions). This paper describes the scenario framework for ScenarioMIP as part of CMIP7. The design process, initiated in June 2023, has involved various rounds of interaction with the research community and user groups at large. The proposal covers a set of scenarios exploring high levels of climate change (to explore high-end climate risks), medium levels of climate change (anchored to current policy action), and low levels of climate change (aligned with current international agreements). These scenarios follow very different trajectories in terms of emissions, with some likely to experience peaks and subsequent declines in greenhouse gas concentrations. An important innovation is that most scenarios are intended to be run, if possible, in emission-driven mode, providing a better representation of the earth system uncertainty space. The proposal also includes plans for long-term extensions (up to 2500 AD) to study slow climate change-related processes, and (ir)reversibility. This proposal forms the basis for further implementation of the framework in terms of the derivation of climate forcing pathways for use by earth system models and additional variants for adaptation and mitigation studies.

1 Introduction

Scenarios represent a critical tool in climate change analysis. Defined as plausible alternative descriptions of how the future may develop based on a coherent set of assumptions, they are used by different research communities to explore potential future avenues in socio-economic conditions, assess the effects of different drivers of climate change, characterize future climatic conditions, and assess impacts of climate change as well as adaptation and mitigation responses. In this sense, scenarios are also useful to bridge across different research communities. The World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project (CMIP) has been organizing the development and use of such scenarios already in several rounds. The CMIP scenarios play not only a pivotal role in climate research but also act as integrating tools for scientific assessment processes and policy analysis. In the most recent phase 6 (CMIP6), CMIP delegated the organization of experiments targeting specific research areas and questions to the scientific community, and CMIP6-Endorsed Model Intercomparison Projects were established (Eyring et al., 2016). The Scenario Model Intercomparison Project (ScenarioMIP) formed a primary activity within CMIP6 that facilitated multi-model climate projections based on alternative plausible forcing scenarios that are directly relevant to societal concerns regarding climate change mitigation, adaptation, and future climate impacts and risks[1] (O'neill et al., 2016; Tebaldi et al., 2021).

In this continuing role, ScenarioMIP's goal for CMIP7 is the design of a limited set of scenario-based experiments to be run by climate models, that serve 1) direct science question, 2) functions as input to other (science) communities and 3) supports policy. With regard to the direct science contribution, the scenario information is used to study and understand climate processes and how their response to anthropogenic forcings emerges from internal variability and model structural uncertainties. To accomplish this aim, it is important that the set of forcing variables considered is internally consistent and varies over a plausible range of forcing levels, and that the set explores futures that may result in very different climate process dynamics (such as increasing and declining concentrations). With regard to the contribution to other (science) communities, ScenarioMIP ensures that data becomes available about future changes in climate variables (such as temperature, precipitation, humidity, etc.) together with information on human forcings/drivers (such as population, economic activity, land use, etc.) to a diverse set of user communities beyond the physical climate sciences. This aim is in service of further understanding of climate change, its impacts, risks and response options, including adaptation and mitigation choices. Targeted communities include, for instance, researchers on impacts and mitigation, but also practitioners, who might use this information for national or sub-national or local risk assessment, climate finance, mitigation policy or adaptation planning. Finally, with regard to policy, ScenarioMIP aims to provide relevant outputs to support climate policy development. This is done, among others, via the use in IPCC assessments. Despite these important roles, ScenarioMIP can only

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[1] In this paper, we are specifically concerned with those scenarios that are used as external forcings to climate models, including Earth System Models (ESMs), General Circulation Models (GCMs), Climate Models of Intermediate or Reduced Complexity (CMICs) and Simple Climate Models (SCMs). These external forcings encompass elements such as emissions and atmospheric concentrations of greenhouse gases, chemically reactive gases, aerosols, and land use.

run a limited set of scenarios. Computational expenses associated with setting up, running and archiving output from climate model experiments pose strict constraints on the number of scenarios that ScenarioMIP's protocol can include. Therefore, the small set of scenarios needs to be selected as a compromise that satisfies the three critical goals.

In preparation of the ScenarioMIP experimental design, the first meeting of the ScenarioMIP project under CMIP7 was held on June 20-22, 2023, in Reading, UK. Based on the meeting report, the Scientific Steering Committee (SSC) of ScenarioMIP formed several task groups, including external experts, and continued to work on an experimental design for the next round of ScenarioMIP. The results are captured in this document. The meeting also led to the expansion of the SSC for ScenarioMIP as well as the creation of a large advisory group (see https://wcrp-cmip.org/model-intercomparison-projects-mips/scenariomip/). Both these changes responded to the desire to make ScenarioMIP more inclusive and broaden awareness of diverse viewpoints and concerns. Since then, the ScenarioMIP proposal was elaborated in conjunction with various rounds of review and participation. September 2023, the first ideas were shared with the research community in two webinars, asking for direct feedback. Subsequently, draft versions of the proposal were sent out for review end 2023 (to a group of around 80 people worldwide that expressed interest to be involved the advisory group) and May 2024 (open review process to scientists and other user groups). Both rounds resulted in a large set of review comments (with traceable responses). It is intended that the IAM scenarios based on this proposal are developed in the period September 2024 until summer 2025, so that the climate model simulations can start after summer 2025. The process will include a period in which the emission/land use scenarios can be tested in ESMs for quality control.

2 Overall experimental design

2.1 Role of ScenarioMIP in CMIP6

Before discussing the design of the current scenario round, it is useful to briefly evaluate the role of ScenarioMIP in CMIP6 (Tebaldi et al., 2021; O'neill et al., 2016). In CMIP6, ScenarioMIP specified four Tier 1 and four Tier 2 scenarios to be run by ESMs/GCMs, coordinating the production of these scenarios by the IAM community and the process to deliver them in the form that ESMs/GCMs need to make use of them as external forcings. These experiments (especially those in Tier 1) were run by most modeling teams participating in CMIP6 and are by far the most used scenario-based simulations of CMIP6. The results of the ScenarioMIP experiments led to many physical science papers describing changes in climate characteristics, but also to a very large number of papers characterizing the impacts of those changes. Further, ScenarioMIP results contributed to the assessment reports of all Working Groups of IPCC, supplying a dimension of integration that is reflected in the Synthesis Report of AR6 (IPCC, 2023). The most direct use was in WGI, where ScenarioMIP climate model simulations formed the backbone of the assessment (IPCC, 2021). The use in WGII (IPCC, 2022b) was more limited because of a lag in production of literature on impacts and adaptation based on ScenarioMIP results. In WGIII, ScenarioMIP results made an indirect but fundamental contribution via the calibration of SCMs that allowed characterization of probabilistic global temperature projections and the resulting classification of a large set of baseline and mitigation scenarios produced by Integrated Assessment Models that were not run by ESMs/GCMs (IPCC, 2022a). There were some difficulties related to the process. This includes the relatively long time period from data production (IAM model runs and harmonisation) until final climate model runs (from 2015 to 2020). This means that impact studies were further pushed back given the common need for additional downscaling and bias adjustment, but also that climate model output was somewhat outdated by the time it was available. The end date of the historical simulations and the start date of the scenarios was significantly in the past by that time. Also, over time, critiques emerged about the plausibility of the most extreme scenarios (SSP5-8.5 and its precursor, RCP8.5; SSP1-1.9) (Hausfather and Peters, 2020; Engels et al., 2024).

2.2 General design principles

In view of the multiple aims of the ScenarioMIP scenarios, the experimental design was created with a set of general principles in mind:

- The scenarios form illustrative descriptions of future emissions and land use
- The scenario set covers a wide and plausible range
- Most scenarios will be emission-driven mode (for CO_2)
- The scenarios cover the period up to 2100 AD, and long-term extensions are developed beyond that as stylized pathways.

We discuss these general principles below.

The scenarios form illustrative descriptions of future emissions and land use

The primary purpose of the ScenarioMIP scenarios is to provide emissions and land use pathways to drive ESMs. ScenarioMIP will produce these pathways based on plausible, internally consistent socio-economic and technological scenarios[2]. It should be noted, however, that there are many different scenarios that could produce similar emissions and land use outcomes. The particular storylines and quantitative drivers constituting the ScenarioMIP scenarios are therefore illustrative. In fact, the resulting ESM simulations are intended to be used in future studies in combination with many different pathways describing future socio-economic development (Van Vuuren et al., 2014). In this context, it is useful to note that even the regional patterns of emissions of short lived forcers and land use, found to have effects at a globally aggregated level within single model studies (Lau and Kim, 2017; Lin et al., 2018) do not necessarily translate to a unique climate change pathway, since they have been shown to lack a robust regional climate signal in a multi-model context (Westervelt et al., 2020; Tebaldi et al., 2023).

In CMIP6, the Shared Socioeconomic Pathways (SSPs) provided the socio-economic and technological storylines and drivers underlying the emissions and land use pathways in ScenarioMIP (Riahi et al., 2017). The SSPs continue to be in wide use and recently the demographic and economic drivers for these scenarios have been updated. However, other storylines and drivers could be adopted or created as a basis for the ScenarioMIP emissions and land use pathways. In this proposal, we remain agnostic about the socio-economic pathways ultimately used in producing the emissions and land use pathways with IAMs. We point to particular SSPs that might provide a useful starting point, but there is no requirement that they be used.

The scenario set covers a wide and plausible range

The scenarios should encompass a wide range of policy-relevant emission trajectories considered to be plausible (i.e. that have a non-negligible likelihood of occurring; see Box 1 for a definition of a plausible scenario and other related terms). As a set, the ScenarioMIP scenarios should thus cover plausible outcomes ranging from high levels of climate change (in case of policy failure) to low levels of climate change resulting from stringent policies. This range might be smaller than assessed before: on the high-end of the range, the plausibility of the CMIP6 high emission levels (quantified by SSP5-8.5) has been questioned (Hausfather and Peters, 2020). At the low end, some of the CMIP6 emission trajectories modeled over the period 2020-2030 have become implausible, when not altogether impossible.

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[2] We use the term scenarios here for internally consistent, comprehensive descriptions of the future. The term pathways is sometimes used to refer to specific scenario elements (such as socio-economic development). We adopt this use of the term pathways here. In other literature, the term pathways is sometimes used to refer to goal-oriented scenarios or the terms scenarios and pathways are sometimes used interchangeably.

We recognise that plausibility is a subjective judgment. Moreover, in several cases our plausibility judgments are conditional on assumptions that are themselves hypothetical. For example, in all scenarios we assume that there are no climate change impacts (see further in this document). This can be justified by the overall scenarios framework in which impact analyses will be carried out by impact models using ScenarioMIP ESM simulations (and human drivers) as inputs. In other words, the ScenarioMIP scenarios are judged to be plausible conditional on the assumption of no climate change impacts. This conditionality is most consequential for the high climate change scenarios, in which impacts would be largest. The medium scenarios make subjective assumptions on current policies (see further). For low scenarios, we take into account geophysical and techno-economic limits, particularly regarding ramp-up rates of mitigation and CDR technologies, and technology and policy trends/constraints in the short-run. Views on plausibility evolve over time, as evidenced by the changing scenarios assumptions in successive IPCC WGIII assessment reports. It should therefore be acknowledged that there might be potential futures outside the ScenarioMIP scenario range.

Box 1: Terms characterizing scenario likelihood

There are a number of terms commonly used to describe the likelihood of a scenario. Strictly speaking, the likelihood of a scenario exactly predicting the realised future is near zero, given the immense number of potential futures. We refer here instead to the likelihood of a scenario approximating reality for a number of key output variables (such as forcing).

A plausible scenario encompasses a range of outcomes that have a non-negligible likelihood of occurring (see (Carter et al., 2007:)) thus implausible scenarios have a negligible likelihood of occurring. Plausibility is a subjective judgment that can be based on a number of criteria. As such it is useful to compare it to the related concept of feasibility. Feasibility is typically used to describe the potential for an action to occur and is therefore more closely associated with scenarios deriving from a given course of action. However, despite the subtle differences between the two terms, when making judgments about plausibility we can borrow as criteria the multiple dimensions of feasibility identified in IPCC assessments: geophysical, technological, economic, socio-cultural and institutional (Brutschin et al., 2021; Riahi et al., 2022; Jewell and Cherp, 2023; Ju et al., 2023; Allen et al., 2018b). In other words, for a scenario to be plausible, it should be feasible based on the 5 dimensions mentioned above.

Other scenario descriptors sometimes used in the literature include a possible scenario, which encompasses a range of outcomes that have a non-zero likelihood of occurring and therefore may or may not be plausible. A likely (or probable) scenario has a relatively high probability of occurring based on knowledge of current trends and common expectations about future developments and actions

One aspect of the future also concerns elements of equity and justice. Given the focus of the ScenarioMIP scenarios (i.e. to explore the broad relationships between the main drivers of climate change and the resulting climate outcomes), the scenarios described here do not explicitly address a range of justice assumptions. However, as ScenarioMIP outcomes are intended to be used with a range of IAM scenarios (with similar climate outcomes), it is critically important that the wider scenario literature pays more attention to equity and justice issues. This is discussed further in Box 2.

Most scenarios will be run in emission-driven mode for CO_2

Up to now, ScenarioMIP experiments were driven by concentrations. As this does not account for uncertainty in the carbon cycle response to climate, the decision was made for CMIP7 to run most simulations preferably in emission-driven mode (Sanderson et al., 2024). This means that for Earth System Models (ESMs), their carbon-cycle representation determines the concentration of CO_2 in the atmosphere that ensues from the prescribed emissions. This may lead to a wider concentration range as processes related to carbon cycle-climate feedbacks are newly involved in the scenario simulations, with their uncertainties. While the wider range may lead to some challenges in interpretation, it will better represent the uncertainty range resulting from both the carbon cycle and the climate system. The climate model simulations would also take better advantage of current ESM capabilities, especially regarding the outcomes of land-based mitigation solutions, which are heavily dependent on feedbacks that are not represented in concentration-driven experiments.

Concentration data will also be provided for ESMs/GCMs that can only run in concentration-driven mode (without an active carbon cycle; see (Hajima et al., 2024; Séférian et al., 2020) for a discussion of the current capabilities of state-of-the-art ESMs). For the concentration-driven simulations, the median values of the concentrations as estimated by the carbon cycle emulators calibrated to CMIP6 included in Simple Climate Models (SCMs) can be used. This means that the concentration-driven models will likely have a narrower outcome space compared to the emission-driven set, which will have consequences for interpretation and use of certain variables. Regarding CDR options, only afforestation and reforestation will be based on endogenous representation of land-based mitigation solutions in ESMs. For all other CDR options we will include their emission impact within the IAM emission output (see Section 5).

To better assess the impact of running in emission-driven mode over the range of climate system outcomes produced by the multi-model ensemble, we also propose that modeling groups run one scenario in both emission-driven mode and in concentration-driven mode, for comparison.

While we encourage the research and modeling community to experiment with full emission-driven runs, it is proposed that under the ScenarioMIP protocol models be run in emission-driven mode for CO_2 only and not for all GHGs. Including non-CO_2 would require a more detailed representation of relevant chemistry, significantly reducing the number of models that could participate. Moreover, too little experience has been built up with such simulations. The use of concentration-driven data for non-CO_2 GHGs and air pollutants will require an intermediate step in which a limited set of models are run with full representation of atmospheric chemistry to create the concentration data. This could include the use of emulators and an atmospheric chemistry model. While the proposal is to use one consistent method for all scenarios in ScenarioMIP, it might be interesting to research the relevant uncertainty by adding more atmospheric chemistry models and even use the output as forcing for ESMs (e.g. in AerChemMIP or in other research projects).

Finally, it should be noted that models running emission-driven simulations can have different temperatures and concentration levels in the start year of the experiments. The ESM teams are strongly encouraged to keep deviations from observations in the historical period to a minimum. Moreover, it is expected that the analysis of future projections will focus on deviations compared to the start year of the simulations (see (Sanderson et al., 2024)).

The scenarios cover the period 2025-2100 (AD) with long-term extensions up to 2500 (AD)

The expectation is that the CMIP results will inform the process of the upcoming IPCC Seventh Assessment Report and the 2028 global stocktake as well as future research and assessments in subsequent years. It is therefore proposed that IAM emissions are harmonized up to 2025. Historical emissions data is expected to be available through 2023, which is a major update compared to CMIP6 that had historical data up to 2015, and means that several critical periods (Covid pandemic, trends in natural gas use) will be included. The 2024-2025 period would be a hybrid of observed and extrapolated emissions. It is also expected that differences among emission scenarios would remain within a relatively narrow plausibility range until 2030 (see Box 1 for a definition of plausibility).

There are important reasons to investigate long-term dynamics beyond the end of the century thus serving the needs of communities studying long-term changes and (ir)reversibilities over multi-century time scales (e.g., ice sheet, sea level rise, and species extinction researchers). For CMIP7, the IAM model runs will provide data up to 2100 AD and the period after 2100 AD will be covered by long-term extensions that extend to 2500 AD based on simple extension rules (See Section 4). The ESM models are requested to run all runs at least to 2150 AD, using the 2100-2150 AD forcing from the extension protocol (see Section 4).

Box 2: The Role of Equity and Justice Considerations

In recent years, questions have been raised regarding how justice issues have been addressed in the scenarios used by the climate research community (e.g. Zimm et al., 2024; Kanitkar et al., 2024; Hickel and Slamersak, 2022). These authors highlight that in many scenarios used in the IPCC assessments, global inequalities in parameters such as income and energy use persist through time and that equitable sharing of emissions reductions efforts, carbon dioxide removal and adaptation implementation between countries is often insufficiently considered. While these concerns are very important, the type of scenarios discussed in this paper do not address equity and justice explicitly. The overall goal here is to explore the broad relationships between the main drivers of climate change and the resulting climate outcomes, covering a wide range of plausible futures and connecting various research communities. The climate models using the scenarios are sensitive to parameters such as global emission levels and land use, but are not very responsive to underlying assumptions related to equity and justice, which may only partially influence the regional or sectoral distribution of emissions or economic growth (see (Bauer et al., 2020)). Also, so far, no robust difference, in a multi-model context, has been identified between climate outcomes driven by different regional patterns of emissions of short lived forcers and land use (see Section 2.2, main text). While the ScenarioMIP experiments described in this paper refrain from exploring equity and justice assumptions explicitly, they include a regional differentiation of mitigation effort in the first decades, motivated by plausibility considerations of the role various parties are currently playing.

The ScenarioMIP scenarios are expected to be used in combination with a range of socio-economic pathways. It is important that questions related to equity and justice are addressed prominently in future research on mitigation and impact analysis (as has been done to some degree in the past). Research on just transitions will complement the work of ScenarioMIP by combining the climate outcomes (directly or based on emulators) with a range of socio-economic development and policy information. We strongly recommend that both the mitigation and impact research communities consider a wide range of socio-economic scenarios and policy assumptions that are consistent with equity and justice considerations in their research. This can be seen as a subsequent phase of scenario development - both to inform policy making and assessment.

Another aspect of justice concerns the development process of the ScenarioMIP protocol (IPCC, 2023b). To enhance transparency and inclusiveness, we have expanded the ScenarioMIP scientific steering committee to better represent relevant regions and disciplines. We also established a broader advisory group consisting of over 70 people from different parts of the world. Finally, the proposal, before this paper was submitted, underwent two rounds of review, one of which was public, to gather extensive feedback. The choice of a journal with open review also enhances the openness and transparency of ScenarioMIP activities.

2.3 Scenarios

Based on the design principles and interactions with all relevant communities, the following scenarios are proposed. First, there is a need for a high-end scenario to explore risks in case the world does very little to combat climate change, reversing even current trends towards mitigation. A pair of medium scenarios could explore the impact of current policies remaining 'frozen', or delayed mitigation action. On the low side of the temperature spectrum, it is important to explore the temperature range that has been associated with the Paris climate goals. We explicitly take no position on Paris-consistency of the low emission scenarios in this protocol. This leads to the following proposal (see further details in Section 3):

- *High emission scenario*: A scenario based on assuming developments that could lead to high emissions, including, e.g., high demographic growth and slow development of mitigation technologies and diffusion. This high emission scenario is, however, expected to result in forcings below SSP5-8.5.
- *Medium emission scenario:* A middle scenario exploring consequences of continuing current policies without modification.
- *Medium-Low scenario:* A medium-low scenario exploring a delayed increase in mitigation efforts, short of the Paris temperature goals but achieving net-zero CO2 emissions by the end of century, with a period of net negative CO2 emissions thereafter to achieve 1.5°C on a multi-century timescale.
- *Low emission scenarios:* Scenarios at the low-end informing policies consistent with the Paris Agreement. One of the scenarios should remain as low as plausible given feasibility constraints. This scenario is thus relevant for the low end of the Paris range (staying as close as can still be plausible to 1.5°C at the time of

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peak warming and limiting warming to 1.5°C by the end of the century). The second trajectory would be a scenario with a higher overshoot of the 1.5°C goal, followed by stringent climate policies (including Carbon Dioxide Removal) to return to lower levels, thus supporting research into the reversibility of climate outcomes and their impacts. The last scenario would be consistent with the pursuit of holding warming to levels likely below 2°C at all times, without returning to 1.5°C before the end of the century.

The exact global mean temperature outcomes of the scenarios will only be known after the ESMs have been run with the emission scenarios. The above temperature levels that are considered in the scenario design will thus be approximated with SCMs, and final temperature outcomes of the ESMs might deviate from these assumptions. The overall logic of the current design shares key characteristics with the proposal of Meinshausen et al. (2024)

A summary of the scenarios is given in Table 1 while Fig 1 illustrates the possible outcomes. In Section 3, 4 and 5, we will further explore ideas and considerations relevant to the various scenarios.

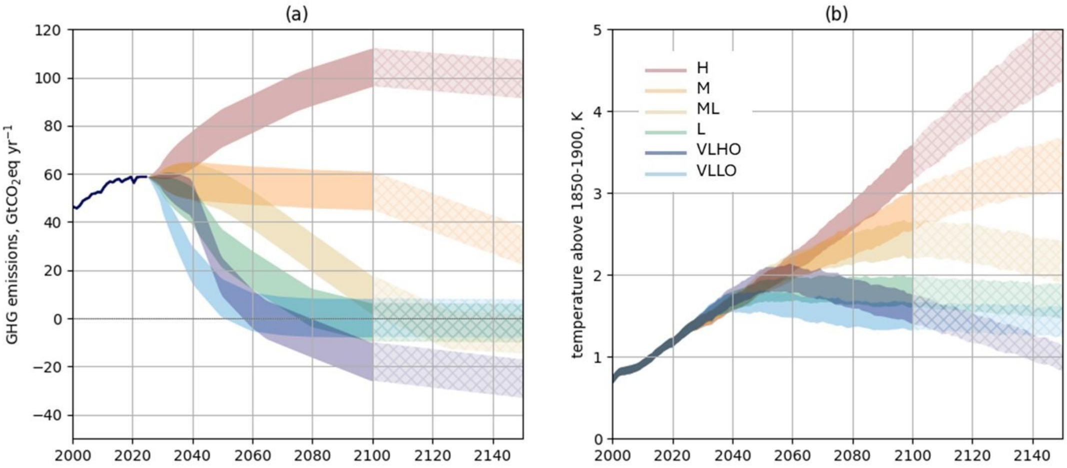

Figure 1: Draft scenarios for CMIP7 ScenarioMIP, showing (a) GHG emissions pathways as a function of time for each of the proposed scenarios (based on GWP-100) and (b) the expected global average temperature outcomes using the probabilistic FaIR ensemble used in IPCC AR6 (IPCC, 2021). Shaded regions for temperature outcomes show the 33-66 percentile range of the distribution while uncertainty bounds for emissions show +/-8 GtCO2 around the median. Scenarios are (H) High, (M) Medium, (ML) Medium-Low, (L) Low, (VLHO) Very Low after High Overshoot and (VLLO) Very Low with Limited Overshoot. The final emission trajectories will depend on IAM model runs and might differ from the illustrations provided here. The final temperature outcomes will be based on climate model runs, including, for instance, carbon cycle feedback. Textured regions are drawn for the 2100-2150 period (AD), where output is requested from Earth System Models, but emissions and forcings will be defined in the extension protocol.

The trajectories shown in Fig 1 are only meant for illustration as the exact emission trajectories depend on the quantification of the various scenarios using Integrated Assessment Models (IAMs), while the climate outcomes depend on the model runs by ESM and other climate models. It is produced using an ensemble of the FaIR simple climate model calibrated during the IPCC Sixth Assessment Report (AR6) (Smith et al., 2018; IPCC, 2021). FaIR is a reduced-complexity climate model useful for scenario assessment and idealised climate runs and a more detailed description can be found here (https://docs.fairmodel.net/en/latest/). Data on the figures is available at zenodo: DOI: 10.5281/zenodo.14382495. The figures include the extensions discussed in Section 4. The overall set of scenarios covers a plausible range of emissions, from around -10 to -20 GrCO$_2$ per year up to levels almost double today's emissions. The resulting, indicative, results for temperature range from 1.5 to almost 3.5 °C increase over the 1850-1900 level. The uncertainty ranges indicated are only meant to emphasize the illustrative nature of the figure and have no specific meaning.

Table 1: Scenarios, proposed naming, and their priority. These priorities are meant to be for models participating in emission-driven mode. We also request that these groups run, with high priority, the Medium scenario in concentration driven mode for comparison of the effects of the active carbon-cycle on the outcomes. Two more scenarios in concentration driven mode for these models have lower priorities. All the scenarios listed here will be provided as concentrations for models that want to run ScenarioMIP in concentration mode, and for which the high priority will include all 6 scenarios.

Scenario group	Scenario name	Brief description	Priority	Scenario-ID
High/Medium	High (H)	High emission scenario to explore potential high-end impacts	1	esm-scen7-h
	Medium (M)	Medium emission scenario consistent with current policies	1	esm-scen7-m
	Medium-Low (ML)	Scenario with delayed increase in mitigation effort, insufficient to meet Paris Agreement objectives	1	esm-scen7-ml
Low scenarios	Low (L)	Scenario consistent with staying likely below 2 °C	1	esm-scen7-l
	Very Low with Limited Overshoot (VLLO)	Scenario consistent with limiting warming to 1.5°C by 2100 AD with limited overshoot (as low as plausible) of 1.5 °C during the 21st century	1	esm-scen7-vllo
	Very Low after High Overshoot (VLHO)	Scenario with similar end-of-century temperature impact to VLLO, but with less aggressive near-term mitigation and large reliance on net negative emissions, resulting in a higher overshoot.	1	esm-scen7-vlho
Concentration-driven	*High, Concentration driven (HC)*	*Variant of H, concentration-driven for models that also run the emission-driven variant*	2	scen7-hc
	Medium, Concentration driven (MC)	*Variant of M, concentration-driven for models that also run the emission-driven variant*	1	scen7-mc
	Low,concentration driven (LC)	*Variant of L, concentration-driven for models that also run the emission-driven variant*	2	scen7-lc

2.4 Other design issues

Air pollution control

All scenarios include air pollution representation (Short Lived Climate Forcers (SLCFs), among which aerosols – including sulfur, BC and OC emissions) and assumptions related to air quality measures. Despite lack of agreement among different ESMs over the response of regional climate to aerosol forcings, and a low signal to noise ratio of these responses, aerosol emissions have been observed to shape regional climate and will be one of the major drivers to influence climate change in coming decades (Persad et al., 2022).

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In the low scenarios, sulfur and aerosol emissions will be low as a result of the reduction in fossil fuel use. While emissions in the high scenarios are likely to be higher, they could still be relatively low as a result of air pollution control (consistent with historic observations and also more recently trends in China). It should also be noted that assuming high aerosol emissions in this high scenario would dampen warming, lead to less precipitation and therefore a narrower range in precipitation between the high and other scenarios, which might be less useful for impact assessment (Shiogama et al., 2023). Thus, we propose to use relatively low aerosol levels in the high scenario based on air pollution control. A high aerosol variant could be run in AerChemMIP and RAMIP (Wilcox et al., 2023).

Ensembles

Recommendations on the use and size of initial condition ensembles are particularly relevant at the low end of the scenario range where the emergence of a climate signal is expected to require relatively larger ensembles but are also important to enable sampling of longer return period events (rarer events) at all levels of forcing. For CMIP7, we encourage running ensembles for each scenario ideally, but prioritizing the three low scenarios if necessary of 5 members or more, according to modeling centers capacities, to quantify the role of initial condition/internal variability uncertainty in scenario outcomes.

IAM model runs

With the - mostly qualitative - formulation of the six scenarios in this document as guidance, ScenarioMIP asks the IAM community to provide a database of alternative (i.e., ideally more than one) quantitative interpretations of each of the scenarios (see also Box 3). The Scenario Working Group of IAMC will be the conduit through which the plan and its timeline will be vetted and finalized, but submission of scenarios is open to the full science community. Subsequently, specific scenarios will be selected for ScenarioMIP based on a process that will involve the IAM community and will be documented in further publications. The full database of alternative scenarios will provide context and flexibility for users other than ScenarioMIP models (e.g. scenario analysts), particularly if key parameters are varied (such as underlying socio-economic assumptions, climate policy and equity considerations and CDR use). The alternative scenarios could also include variants with and without climate change impacts (see below under "*Impacts and adaptation*" for a discussion of this particular issue).

Box 3: Different emission reduction and carbon dioxide removal strategies

Strategies of emission reduction and carbon dioxide removal measures can differ in timing, geographic location and underlying socio-economic assumptions. For instance, climate impacts can be different for carbon dioxide removal originating from bio-energy-with-carbon-capture-and- sequestration (BECCS) or from afforestation and reforestation. The same can be the case for different underlying socio-economic assumptions. Emission reduction and carbon dioxide removal can also differ in terms of the contribution of various sectors and countries, strongly related to justice issues. The latter will be further explored in mitigation research, assessed in subsequent IPCC WGIII reports. In ScenarioMIP, the focus is on the climate response of different forcing trajectories. It will be interesting to further research whether differences in strategies lead to clearly identifiable physical responses in climate model runs, even if the existing literature is unable to draw robust conclusions in a multi-model context. Continuing to address this research question can further inform the exchangeability of climate model simulations for different impact studies. It should be noted that solar radiation management is not included in these experiments as it is covered in a separate MIP (GeoMIP) (Visioni et al., 2024).

Impacts and adaptation

ScenarioMIP requests that the IAM teams produce simulations that do not include climate change impacts on managed systems (e.g. agriculture, energy use, or economic growth). At this point in time, there are two main reasons for this. First, one of the main uses of the scenarios and their climate outcomes is to drive impacts estimation by the impact modeling community, which uses both the climate projections and the direct human drivers (such as land use and agricultural systems changes) as input to their analyses. If the IAM scenarios (and therefore the climate projections based on them) already include impacts, further impact modeling based on these scenarios would lead to double counting. Second, IAMs currently do not represent a full range of possible impacts and generally lack the

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required detail needed to represent many regional impacted systems and adaptation strategies. Including impacts in the IAM scenarios would therefore only provide a partial and somewhat arbitrary accounting of possible climate effects. The IAM and ESM scenarios are therefore not intended to provide complete pictures of potential future worlds. Rather, they must be augmented by impact and adaptation studies that complete that picture so that it includes climate shifts, mitigation, impacts, adaptation, and development. At the same time, demand for fully consistent scenarios is growing. It is, therefore, encouraged that IAM modelers undertake research projects to produce additional scenarios in which impacts are accounted for. This work may also lead to different scenario protocols for future ScenarioMIP exercises.

Modeling assumptions

The modeling paradigms and assumptions underlying IAM implementations relate to questions of socio-economic development, technological progress, mitigation preferences and climate justice. Exploring the implications of these assumptions, and alternative implementations, is of critical importance to provide policy relevant science to inform the deliberations on mitigation efforts and their regional distribution. These important questions, however, are outside the scope of ScenarioMIP, an exercise of CMIP that is focused on providing scenario forcing data for ESMs (see Box 2). The use of IAMs within ScenarioMIP is limited to providing emissions and land use forcing time series that allow for the exploration of different global climate futures. An exploration of alternative implementations of the ScenarioMIP scenario narratives using different modeling paradigms and normative assumptions is explicitly encouraged. Meanwhile, our working assumptions, from a climate modeling perspective, are that the regional distribution of carbon emissions do not matter to ESM outcomes, having long been characterized by their “well-mixed” nature, and therefore do not produce regional responses linked to the location of the sources of emissions. Regional distributions of land use, aerosols and other localized forcers have been shown to produce local responses that are however model dependent and result in non-robust patterns of climatic changes in a multi-model context, such as CMIP-type ensemble experiments (Westervelt et al., 2020; Tebaldi et al., 2023).

The role of complex climate models vs emulators

Some further exploration is needed of the role of different tools at different levels of the modeling hierarchy, especially ESMs vs emulators of climate model output. By emulators we here refer to computationally efficient tools that, when driven by a scenario, are able to provide impact-relevant variables akin to climate model output in spatial resolution and time frequency, bypassing the need to run ESMs. Their use can be attractive both to fill gaps in the design and to accelerate the uptake of some of the outcomes of new scenarios by the wider research community. Thus, it is useful to consider how emulators can further reduce the computational load on climate models for scenario exercises and the expectation is that, given the rapid developments in the emulation space of the last few years, especially with the deployment of machine learning, the use of emulators to substitute for ESM output may become better feasible in the not-so-distant future (Eyring et al., 2024). As of now, however, no emulator can address the provision of all outputs from an ESM and for all types of scenarios. High frequency (e.g. daily) output, jointly simulated variables (respecting correlations between them), and more generally variables other than average temperature and precipitation still present a challenge to emulators. In the scenario space, overshoot/peak-and-decline scenarios constitute particularly open questions, given the scarcity of this type of scenario simulations by ESMs on which emulators could be trained. At this point in time, therefore, it is envisioned that all ScenarioMIP scenarios will be run using ESMs. However, we do not exclude the possibility that, for specific projects utilizing specific climate variables and specific scenarios that have been shown to be emulated with fidelity, emulation could be a viable substitute, and will accelerate the penetration within the impact research communities of larger numbers of newly developed scenarios.

Input variables for ESMs and impact models

ScenarioMIP will provide data as external forcing for Earth system model simulations and additional information on possible socio-economic development and related parameters for the Impacts, Adaptation and Vulnerability research community. Table 2 illustrates what type of data could be made available, although further parameters are possible. We note here that some variables, such as gridded population and urban land cover, require dedicated efforts by the larger research community, rather than being simply a byproduct of IAM simulations.

Table 2: Input data for ESMs and IAV community (illustrative list)

	Climate models	Vulnerability, Impact and adaptation community
Data provided during CMIP6	CO_2 emissions (fossil + land use) + concentrations (harmonised with historical data) Land cover change (harmonised with historical data) CH_4, N_2O, CO, NOx, H_2, VOC, SO_2 halogenated gasses emission data (harmonised with historical data); concentrations of these gases, optical depth (particulate matter) and ozone concentrations (based on run via atmospheric chemistry model)	Gridded population Energy system parameters Gridded land use/crop data (in addition to land cover) Gridded water consumption and irrigation
Additional data	Gridded urban land cover Data on CDR activity (afforestation and reforestation areas; net-negative emissions) Gridded water consumption [gridded] Fertiliser use Crop yields Gridded energy consumption Other	Gridded urban land cover Income distribution and poverty/inequality Fertiliser use Crop yields Gridded energy consumption Air pollution

Further, the CMIP7 Forcings Task Team is in place to address some of these issues (required forcing input files, harmonization) and coordinate the provision of ESM forcings through the input4mip effort. This includes, for instance, harmonization of historical emission data and provision of consistent gridded land use data. For this, ScenarioMIP will work closely together with the Forcing Task Team.

Consistency with earlier scenario sets

In CMIP6, one of the scenario design's stated goals was to facilitate comparison with CMIP5 and some studies were published that quantified the relative contribution of different scenario composition versus different models to the changes in temperature range under comparable global radiative forcing pathways. It is assumed, however, that for the study of consistencies and differences due to model development, the experiments prescribed as part of CMIP's Diagnostics, Evaluation and Characterization of Klima (DECK) are more suitable. We do not exclude the possibility that one or more scenarios developed according to the new design choices will produce global forcings comparable to CMIP6 scenarios, but the choice was made not to use the principles of continuity and comparability to constrain the ScenarioMIP design.

2.5 Timeline

One of the goals of ScenarioMIP is to produce scenarios that can be useful to the 7th Assessment Report of IPCC. This means that studies forming the basis of the assessment and relying on the new scenarios outcomes need to start appearing in the peer-reviewed literature in the 2026-2027 time frame. We recognise that although the IPCC and CMIP7 timelines will facilitate a rigorous assessment of CMIP7 simulations by Working Group I, the research time available for the vulnerability, impacts and adaptation (VIA) research using CMIP7 data is quite constrained. Therefore, it is intended that the IAM scenarios based on this proposal are developed in the period September 2024 until June-August 2025, so that the climate model simulations can start after August 2025. This will possibly allow for prioritized scenarios to become available mid-2026.

3 Further elaboration of the design of the emission scenarios for CMIP7

3.1 Design of the high emission scenario (H)

The high emission scenario explores a plausible future world that weakens or even abandons mitigation policies and actions. It is important for addressing questions such as: what are the physical, socio-economic, and ecological impacts associated with a scenario in which climate policy largely fails? What is the risk of reaching possible tipping points in the Earth system over a wide range of future warming levels? How large might the climate change risks be to which society may have to adapt? Do non-linear responses alter the nature of extreme events as the world reaches higher warming levels? How far beyond current conditions are known adaptations viable? (When comparing to lower emission scenarios) how much might mitigation policies reduce risks relative to a future with high warming?

The scenario includes events and outcomes that may not be likely given current trends but are still plausible enough to occur. The world view it represents is consistent with policy roll-back, the lack of coordination and cooperation for addressing global environmental concerns, societies and industries depending on and even reverting to fossil fuel resources, the adoption of resource- and energy-intensive production technologies and lifestyles, and unforeseen technological barriers. This scenario is not meant to represent a "business-as-usual" or no-policy reference scenario for the other scenarios. The scenario is intended to explore the upper end of GHG emissions resulting from deep political, technological and structural deviation from current trends.

In this scenario, the rapid cost decrease in renewable energy of the past decade is followed by a period of slowdown of cost declines, possibly as a result of regional scarcity and limited tradability in materials for solar and wind technologies and EV batteries (Iea, 2021; Schlichenmaier and Naegler, 2022). This coincides with a rollback of climate policies given a lack of public support for the energy transition (e.g. local opposition to building new wind farms). The position of fossil fuel industries could remain strong related to concerns on jobs and national energy security. Such a scenario might be based on the high economic growth scenarios (e.g SSP5) or global competition scenarios (such as SSP3) or completely alternative cases. It would be useful to explore alternatives based on multiple storylines and then select a preferred, plausible high emission scenario.

In the high-economic growth case, one would need to assume that there is little effort to avoid global environmental concerns due to perceived tradeoffs with economic development, while local environmental impacts (e.g. aerosols related to air pollutant emissions) are addressed effectively by technological solutions. Technological progress and investments focus on fossil fuels while low investment in low-carbon technologies leads to relatively high barriers to development and dissemination in renewables and other low-carbon technologies. The strong reliance on fossil fuels and the lack of global environmental concern leads to ineffectiveness of international and national climate policies. Typically, high economic growth coincides with more rapid technology development; this could include mitigation technology – but could also lead in other directions (O'neill et al., 2017; Riahi et al., 2017).

In the competition scenario case, a resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or regional issues. Policies shift to become increasingly oriented toward national and regional security issues, including barriers to trade. A low international priority for addressing climate concerns leads to a collapse of international and national climate policies.

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In both cases, one could assume a steady roll-back of climate policy after 2026. Also, extreme events may lead to high emission futures, including climate or geopolitical shocks. However, the impact of such events are difficult to capture in a quantitative sense.

It should be noted that based on the scenario framework design, climate impacts are not included in the scenarios produced for ScenarioMIP. As discussed in section 2, this approach is taken to facilitate research by the impacts community and to avoid including only a partial accounting for impacts. It also implies that the judgment of plausibility of this scenario is conditional on the assumption of not including impacts.

An additional issue is the treatment of fossil fuel reserves and resources. The cumulative amount of fossil fuel use is likely to be considerably larger than the estimated total reserves (these are known deposits that are extractable at current prices and technologies) (Bauer et al., 2016; Rogner, 1997). Future technologies or market prices would make current resources (estimates of undiscovered deposits and/or those not recoverable at current prices) recoverable to some extent. The IAM models already include decision criteria about the use of such energy resources. How these play out in any particular version of the high scenario needs to be transparent.

It is clear that this scenario needs a strong storyline to motivate the techno-economic, political and socio-economic assumptions that drive the transformation as over the past decade several developments and trends have diverted away from very high-emission levels. In particular, progress in the fields of renewable energy technologies and electrification of end-uses have substantially eroded the competitive advantages of fossil fueled technologies.

3.2 Design of the medium emission scenario (M)

The medium emission scenario is a benchmark that shows the consequences of the current policy situation continuing over the century. In the scenario it is assumed that policy effort is frozen at the current level. It should not be considered as a “most likely” scenario. The scenario will be used to explore a future world in the case of continuing currently implemented regional climate policies and can be used to address questions such as: what future physical, socio-economic, and ecological risks are implied by current levels of climate change policy (Roelfsema et al., 2020; Rogelj et al., 2023)? (When comparing to lower scenarios) what are the relative benefits and costs of taking further mitigation actions? What are the needs for adaptation implied by current policy levels? What limits to adaptation would be encountered in future decades without additional mitigation actions?

To distinguish between the medium scenario and the lower mitigation scenarios, we make an assumption that mitigation actions in a medium scenario must be established in policy with some legislation to back them up, and ideally a plan for implementation. The scenario does not include announcements of future policy goals which come with no current basis in policy. This includes also the Nationally Determined Contributions (NDCs) pledges or net-zero announcements if they are not backed up by explicit policies. In line with current literature, the current policy scenario will not meet the NDCs. This still leaves a range of possible options based on the literature and ambiguity of interpreting current policies (Rogelj, 2023).

We consider several options for the treatment of policy assumptions that have a bearing on emissions over time for the medium scenario. In the IAM community already several rules are used to extend current policies beyond 2030 (Van Soest et al., 2021). There are various alternatives in terms of specific policies of countries, but the progression of policies in the real world is clearly unknown. We reflect this in the medium scenario by assuming no progression in mitigation policy beyond 2050. While this may be seen as making the scenario somewhat idealized, it does provide a clearer baseline against which the effect of new long-term policies can be evaluated in future studies.

Another complexity is whether to focus only on national policies, or to include corporate pledges, which is consistent with the need for public, private and citizen responses to the climate challenge. In the recommendation for initial scenarios for Earth system model simulations we take the pragmatic choice of focusing on national policies but recommend further work on the sensitivity of current policy outcomes to a broader interpretation of emission reduction pledges.

It would be interesting to explore these scenarios under a wider set of socio-economic assumptions. While we assume that climate policies remain at current levels, other policy areas could still develop. In addition, underlying technology assumptions are allowed to evolve and the sensitivity of results to these assumptions should be assessed. As a starting point for this scenario we recommend using an updated version of the reasoning from the "CurPol" scenario assumptions used in Working Group III of IPCC AR6 (IPCC, 2022a).

For consideration in the longer term, we would recommend exploration of the climate response to alternative IAM implementations of the current policy assumptions above, and potentially a wider consideration of other interpretations of current policy, including alternative views on policies around air quality.

3.3 Design of the medium-low emission scenario (ML)

This scenario (see Fig.1) describes a future in which strengthened mitigation efforts are delayed, falling short of the levels required to meet the objectives of the Paris Agreement. The scenario corresponds to emissions developments that gradually fall below the medium scenario after 2040. The scenario would be used to explore the impacts of temperature levels in between the Medium and Low scenarios. Moreover, after 2100 AD the scenario could explore the impacts of overshoot. It could plausibly be motivated by political constraints to rapid near-term action which lessen as the magnitude of observed climate impacts increases and mitigation costs decline with technological progress. The scenario represents a moderate action interpretation of a world that fails to implement the Paris Agreement. It would reach peak warming and net-zero CO_2 emissions at approximately the end of the century, with modest levels of net-negative CO_2 emissions thereafter. It would be based on the same socio-economic development pathway assumed for the medium scenario.

3.4. Design of the very low with limited overshoot emission scenario (VLLO)

We first discuss the lowest near-term emission pathway among the ScenarioMIP pathways as it partly also defines the other low scenarios. The very low with limited overshoot (VLLO) scenario should be designed such that the resulting temperature outcomes at the time of peak warming are as low as can still be plausibly achieved (see also Box 1 on plausibility). By now, some overshoot of the 1.5°C, at least in the median estimate, seems unavoidable. A key question therefore is to what level can an overshoot be constrained and how fast can warming be reduced (after an emission peak)? In the scenario, we assume that temperature levels come back to below 1.5°C by the end of the century (although it should be noted that the results are still relatively unknown when run in emission driven mode in climate models).

Critical design elements of the VLLO scenario are reducing CO_2 emissions rapidly and deeply and reaching net-zero CO_2 emissions as quickly as possible (possibly between 2045-2060), and net-zero GHGs soon thereafter. Also non-CO_2 emissions should be reduced deeply, including rapid CH4 emissions reductions in the near-term in order to limit peak warming levels as much as plausible. Aerosol emissions are determined by associated changes in energy and land use and assumptions about air pollution control policies. The scenario has ambitious assumptions about air pollution controls in line with sustainable development objectives. After the point of net-zero CO_2 emissions, the pathway will be designed to transition to sustained net-negative CO_2 emissions in order to increase the likelihood of limiting warming to 1.5°C in the second half of the century (initial assessments will be computed by SCMs/climate emulators). This should entail reaching net-zero GHG emissions in the second half of the 21st century. The scenario should also consider other Sustainable Development Goals (SDGs), including protecting biodiversity and reducing global inequalities, to the extent feasible. IAM teams should explore measures that minimize trade-offs and exploit synergies (e.g. dietary change for land use) when designing the emission scenarios. IAM teams are encouraged to explore VLLO emissions trends under different equity assumptions, e.g., by exploring implications of different regional and global socio-economic pathways.

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In order to achieve these outcomes, the VLLO scenario should consider a range of measures and underlying trends that would permit rapid emissions reductions based on plausible assumptions about the underlying pace of the system transformations (see e.g. (Brutschin et al., 2021), general characteristics of low-carbon technology innovation (Malhotra and Schmidt, 2020; Odenweller et al., 2022; Wilson et al., 2020), and the dynamics of socio-technical innovation (Jewell and Cherp, 2023). Achieving this low pathway is also strongly linked to sustainable land futures, including shifts towards low greenhouse gas emitting diets (e.g. the Lancet Planetary diet) (Humpenöder et al., 2024). This would result also in a more limited deployment of CDR in the VLLO scenario compared to the very low after a high overshoot (VLHO) scenario.

The IAM modeling teams will be asked to develop an ensemble of scenarios, representing alternative interpretations of each of the three low-emission ScenarioMIP scenarios (see also further in this document). Specifically for the lowest scenario, it is important to avoid assuming implausible reductions in the very near term. Modeling teams should constrain (very) near term developments in the scenarios as follows. First, until 2025 the scenario follows the same trajectory as all other scenarios. From 2025 to 2030, the IAM teams are asked to make their own judgment of "as low as plausible", mediating between (1) feasibility limits, (2) plausibility considerations with regard to how fast current technology and policy trends / constraints could change until 2030, and (3) stated policy objectives up to 2030 (including commitments beyond NDCs such as the Renewable Energy and Energy Efficiency pledge, the deforestation pledge, the Global Methane Pledge, etc.). The aim is to derive a VLLO scenario that can still represent a viable policy future in 2028-30 when the scenario will be assessed and used. After 2030, mitigation trends should be framed in terms of reducing peak warming and reaching the long-term climate target of limiting warming to below 1.5°C. This ambition is bounded by considerations of techno-economic feasibility of low carbon technology deployment and, where relevant, sustainable development goals.

For the development of the lowest plausible emissions trajectories, it is recommended that the modeling teams consider a wide portfolio of options that would enable rapid transitions towards low GHG emissions. The following design elements were identified (the list is non-exhaustive and can be amended by the modeling teams). These design elements broadly cover complementary levers (groups of measures) that are available to reduce emissions: 1) reduction in final energy demand, 2) rapid decarbonization of electricity supply (as measured by carbon intensity of electricity based on gross CO_2 emissions), 3) deep electrification of industry, transport and buildings, 4) deep decarbonization of residual non-electric fuel mix in industry, transport and buildings, 5) widespread behavioral changes in diet, transportation and consumption, 6) deep reduction of industrial process emissions, including also reducing Fluorinated greenhouse gases in line with Kigali amendment, 7) deep reduction of non-CO_2 gases, in particular methane, 8) elimination of net CO_2 emissions from land use and rapid deployment of land-based CDR measures (within sustainability limits) to move to net-negative Agriculture, Forestry and Other Land Uses (AFOLU) CO_2 emissions in the medium to long term and 9) deployment of CDR measures assuming plausible deployment rates, as well as keeping geological storage (or storage in materials) within technological and sustainability limits. Some of these levers (alternative fuels, AFOLU) may have implications for SLCF emissions and air pollution.

A number of particularly relevant scenario dimensions for ESMs were identified that could be explored in variants of the VLLO scenario in the future including: 1) land use and afforestation/reforestation policy, 2) land- and ocean-based CDR strategies, and 3) regionally defined renewable energy production. Future coupling on these dimensions between IAM and ESMs (beyond this ScenarioMIP round) could permit improved linkages in research.

3.5 Design of the very low after a high overshoot emission scenario (VLHO)

As of today, global greenhouse gas emissions continue to rise (Friedlingstein et al., 2024). Looking into scenarios with more substantial overshoot of the 1.5°C warming level is thus an important point of comparison to the VLLO emissions scenario discussed above. There are a number of key questions related to this scenario. The first is related to how reversible the climate system is (or whether a lot of hysteresis occurs). This provides information on the viability of such an approach. Second, the scenario can facilitate the assessment of the impacts of a larger temperature overshoot, compared to the more limited overshoot. This includes understanding the benefits, costs, and trade-offs of achieving declining temperatures in the long term. All in all, this means that the scenario can be used to gain a better understanding of the near- and long-term consequences of delaying emission reductions. This will help inform ongoing policy discussions around plausibility and implications of overshoot resulting from delayed actions.

There are several considerations in how the VLHO scenario should be designed:

- *Plausible levels of CDR.* In order to compensate for the high level of overshoot, this pathway will need to achieve temperature declines through measures that would reduce the forcing of different gases. This will imply higher CDR levels than the very low ScenarioMIP pathway. Despite the difficulty in assessing future CDR technologies, however, the attempted use of CDR should still be within the assessed plausible range in the literature.
- *Scenario differences. The* scenario needs to be sufficiently different from other scenarios in ScenarioMIP, in terms of resolving differences between ESM runs. Differences are measured not only in terms of IAM estimated temperature and concentration pathways, but also in terms of CDR measures implemented (volume and type) (leading possibly also to additional impacts).
- *Relevance to the Paris Agreement.*

In more practical terms, this translates to design choices affecting peak warming including the time by when and the speed by which the VLHO scenario falls below current trends as reflected in the M scenario and the decline in warming after the peak including the annual rate of net-negative CO_2 emissions and decisions regarding the type and amount of CDR and the level of residual GHG emissions in the second half of the century.

In order to see differences in climate outcomes above the noise of internal variability, separation amongst these lowest scenarios needs to be large enough. For CMIP6, a separation of 0.25-0.3 deg C was proposed (Tebaldi et al., 2015); it might be useful to explore whether lower differentiations might be possible (Mckenna et al., 2021) although the emission-driven mode might lead to an even larger overlap. We can illustrate the possible design of the scenario with a simple calculation. In terms of CO_2 emissions, a required temperature gap of 0.25-0.3 deg C equals about 400-600 $GtCO_2$, depending on the contribution of SLCFs and non-CO_2 gases. For the VLHO this thus means that emissions need to be clearly above the VLLO, followed by dropping rapidly to net-zero and then net-negative levels. The mechanisms and extent of attempted CDR deployment will have ESM-specific efficacies which will impact the degree to which the attempted high overshoot is realized in some members of the ESM ensemble. This may cause larger inter-model uncertainty for the VLHO scenario than for other scenarios of the ScenarioMIP set.

It might be desirable to consider dimensions in addition to peak warming to differentiate the VLLO scenario from the VLHO scenario. These dimensions may include among other factors, the policies targeting methane, and policies related to land use. The VLLO pathway may be linked to a sustainable land future in line with the SDG narrative including reduced pressure from agricultural land and considering environmental constraints. The VLHO scenario could contrast that, in line with a need for very large scale and rapid upscaling of CDR needs in such a scenario. At the same time, introducing too many differences would limit the capability to interpret the differences in terms of overshoot; that is, the ability to assign differences in climate outcomes to the occurrence of overshoot. As the scenarios are mostly interpreted in terms of overshoot, it is proposed to be careful about adding additional design criteria and only look into the additional demand for CDR in the VLHO scenario.

3.6 Design of the low emission scenario (L)

The third scenario in the low category is a scenario aimed at staying likely below 2°C at all times, comparable to the C3 category of IPCC (and is thus also relevant for discussions on the Paris Agreement). This scenario will have a slower emission reduction trajectory than the VLLO scenario. In 2030, emissions might be similar to the current emission pledges as captured by the NDCs for 2030. After that, emissions are projected to be reduced further and reach net-zero CO_2 emissions around 2070. Before 2070, some CDR use might compensate for hard-to-abate emission sectors. After 2070, emissions reductions continue to reach net-zero GHG emissions before 2100 AD and stay at that level in the long term. This design helps to better understand the long-term climate implications of sustained net-zero GHG emissions.

4. Scenario extensions beyond 2100 AD

Several climate science research communities expressed the desire to consider a set of scenario extensions going beyond the 21st century. The purpose of these extensions is twofold: to explore the long-term Earth System dynamics in response to warming at different stabilized levels, including the risk of breaching tipping points and triggering large scale irreversible changes, and also to explore reversibility of the system under different long term net-negative emissions pathways, exploring overshoots from different peak warming levels and different target long term climate states.

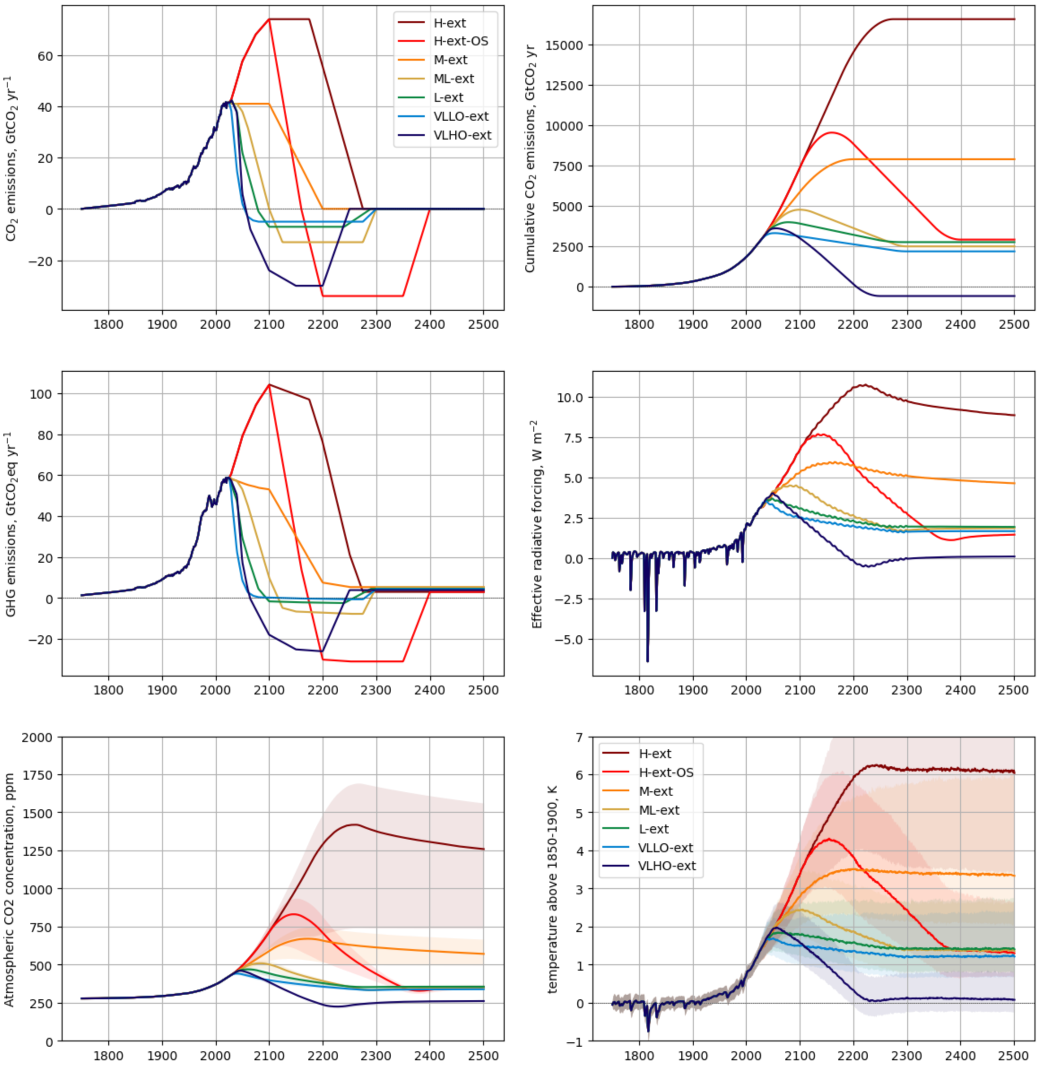

Figure 2: Preliminary extensions for ScenarioMIP in CMIP7. Top row shows CO$_2$ emissions and cumulative emissions. Second row shows GHG emissions (calculated using GWP100) and total radiative forcing. Bottom row shows

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atmospheric CO_2 concentrations and projected temperature outcomes. Simulations are conducted with the AR6 calibrated ensemble of the FaIR simple climate model, where solid lines show the 50th percentile outcome, while shaded regions show the 5-95 percentile range.

Table 3: Main characteristics of the scenario extensions

	H-ext	H-ext-OS	M-ext	ML-ext	L-ext	VLLO-ext	VLHO-ext
	Esm-scen7-h-ext	Esm-scen7-h-ext-os	Esm-scen7-m-ext	Esm-scen7-ml-ext	Esm-scen7-l-ext	Esm-scen7-vllo-ext	Esm-scen7-vlho-ext
Branches from	H	H	M	ML	L	VLLO	VLHO
Tier	1	2	2	2	2	1	2
Purpose	Assessment of risk of large irreversible changes in slow components of the Earth system	Assessment of reversibility from a very high warming state to achieve 1.5°C on a multi-century timescale before 2500.	Assessment of long-term implications of current policy, including large overshoot and reversibility	Assessment of potential to stabilize temperatures at 1.5°C Paris target on a multi-century timescale given insufficient action for 2 °C in 21st century	Assessment of potential to stabilize temperatures at 1.5°C if 21st century mitigation is "well below 2°C"	Assessment of long-term response to net-zero GHG emissions, following highly ambitious 21st century mitigation	Assessment of reversibility following ambitious 21st century mitigation, with a target of climate restoration back to pre-industrial temperatures
Storyline	Constant CO_2 emissions from 2100 to 2175, linear reduction reaching net-zero CO2 by 2275 and zero CO2 emissions thereafter.	Radical emissions reductions after 2100 with net zero CO2 in 2160, reaching negative emissions floor of -36GtCO2 in 2200 continuing until 2400	CO_2 emission reduction begins in 2100, net zero CO_2 by 2200.	Net zero CO2 in 2100, net negative thereafter with maximum removals of -13GtCO2/yr achieved in 2125, maintained until 2275 and phased out by 2300	Removals maintained at -7GtCO2/yr from 2100 until 2240, phased out by 2300.	Continued long term net-zero GHG (under GWP100) until 2300, net-zero CO2 after 2300	Continue negative CO_2 emissions, returning to preindustrial forcing by 2300

Note: All dates mentioned in the Table refer to AD.

As has been the case under the CMIP6 ScenarioMIP design, the scenario extensions will consist of emission and concentration trajectories to 2500 AD that are idealized, rather than being the outcome of IAM simulations. While IAMs are useful in generating plausible evolution of greenhouse gas emissions in the shorter-term, beyond about a century's time the uncertainties that increasingly affect the socio-economic drivers of these trajectories end up limiting the usefulness of IAMs for scenario design. The longer time period of the extensions (relative to the 2300 AD time horizon in CMIP6) is proposed to allow for a simulation of climate stabilization at different warming levels, and to provide sufficient time to allow for a range of diverse overshoot trajectories.

Forcings will be harmonized to the end year of the IAM scenarios (2100 AD) and will then follow stylized trajectories with a coherent narrative (e.g., constant positive CO_2 emissions, zero or negative CO_2 emissions, declining CO_2 emissions, with additional simplified assumptions about non-CO_2 forcing, land cover change, etc.). The idealized nature of these extensions also means that the current proposal can be easily adapted to further input or rationales, not requiring the same time commitment by the IAM groups as the 21st century scenarios described in the previous sections.

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The rationale and proposed GHG emissions trajectories for the extensions of the main scenarios (Fig. 2) are described here, and summarized in Table 3. Again, it should be noted that the results shown in Fig. 3 are only meant for illustration and are calculated using the FAiR small climate model based on the descriptions provided here. The actual emission trajectories depend on the IAM model runs (before 2100 AD) and the subsequent application of the extension rules.) (Smith et al., 2018; IPCC, 2021). Data shown in the figure is available at zenodo: DOI: 10.5281/zenodo.14382495. The results presented in Fig. 2 are discussed further for the individual scenarios.

We propose two high priority tier 1 extensions, to the high (H) and very low with limited overshoot (VLLO) scenarios. The high scenario extension (H-ext) simulates the multi-century implications of the highest plausible emissions levels, while the very low with limited overshoot scenario extension (VLLO-ext) simulates a long-term future in line with the Paris agreement. The other scenarios are requested with lower priority (tier 2): the (H-ext-OS) also branches from the high scenario in 2100 AD, but then rapidly reduces emissions and sustains net-negative emissions for multiple centuries, simulating climate response to a very large (and idealized) overshoot. The medium-low extension (ML-ext) is designed to likely achieve the Paris 1.5°C goal on a multi-century timescale following only modest mitigation efforts in the 21st century. The long-term extensions are designed to achieve temperature stabilization post-2300 AD. All scenarios ultimately reach net-zero CO_2, which results in temperature stabilisation on multi-centennial timescales ((Allen et al., 2018a)). Three of the extensions (H-ext-OS, ML-ext, L-ext) achieve likely 1.5°C stable warming, but on different timescales and with different levels of peak warming. VLHO-ext is designed to achieve pre-industrial warming levels following ambitious 21st century mitigation, and VLLO-ext is designed to simulate long-term gradual temperature reductions under net-zero greenhouse gas emissions.

4.1a High extension (H-ext)

It is proposed to have two extensions for the high scenario. The highest extension (H-ext), will explore the risk of long-term changes in slow components of the Earth system, also helping to assess the linearity of the transient climate response to cumulative emissions (TCRE) under high levels of CO_2 emissions. It will keep emissions constant at their 2100 AD level until 2175, then emissions would follow a moderate linear reduction, reaching net-zero CO2 by 2275. The scenario would ensure that total cumulative emission will be within the known fossil resources (Rogner, 1997), and is expected to ultimately stabilize temperatures at between 4°C and 10°C above pre-industrial post 2300 AD, with a central estimate of stable warming of 6°C.

4.1b High overshoot extension (H-ext-OS)

The high overshoot extension (H-ext-OS) is an idealised long term extreme overshoot, which simulates rapid reduction in emissions post 2100 AD from the high scenario with highly ambitious net-negative GHG emissions levels achieved by the late 22nd century and sustained for more than two centuries. This extension will explore the risk of irreversibility/hysteresis in slow components of the Earth system (e.g., ice sheets) beyond 2100 AD. It will also help to assess whether the relationship between global warming and net-negative emissions (Matthews et al., 2009) is robust under high levels of negative CO_2 emissions. The long-term temperature objectives would be to reach likely 1.5°C warming levels by 2400 AD.

4.2a Medium extension (M-ext)

The medium extension (M-ext) will assess the long-term implications of continued current policy making no assumption of net-negative emissions deployment in the long term. The medium scenario would be extended beyond 2100 AD with strong linear emissions reduction, reaching net-zero CO_2 by 2200 AD which is maintained thereafter. This scenario is expected to stabilize temperatures post 2200 AD at warming levels between 2°C and 6°C above pre-industrial, with a central estimate of about 4°C.

4.2b Medium-Low extension (ML-ext)

The medium-low extension (ML-ext) will explore the potential to meet Paris targets on a multi-century timescale from a current policy scenario, after modest but insufficient efforts during the 21st century. Net-negative emissions in 2100 AD will be sustained until 2300 AD with net-zero CO_2 emissions thereafter, with stable warming levels likely below 1.5°C after 2300 AD.

4.3 Low extension (L-ext)

The low extension (L-Ext) will serve the purpose of assessing the long-term climate and Earth system commitments if 21st century mitigation efforts are sufficient to keep temperatures likely below 2°C, but insufficient to keep temperatures below 1.5°C. The low scenario extension would sustain net-negative CO_2 emissions until 2200 AD, ramping down removals to net-zero CO_2 by shortly after 2250 AD. The design would be for long-term warming to stabilize at likely 1.5°C above the preindustrial level.

4.4 Very Low with Limited Overshoot extension (VLLO-ext)

The very low with limited overshoot scenario extension (VLLO-ext) will explore a future consistent with the language of the Paris Agreement which calls for "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century". We interpret this as net-zero greenhouse gas emissions as measured through GWP100, which are achieved in the latter half of the 21st century in the VLLO scenario. Net-zero GHG, when non-CO_2 emissions remain positive, requires continued net-negative CO_2 emissions, which in VLLO-ext are sustained until 2300 AD. This results in a gradual decline in temperatures such that expected warming in 2300 AD is likely below 1.5°C.

4.5 Very Low after High Overshoot extension (VLHO-ext)

The very low after high overshoot scenario extension (VLHO-ext) supports an assessment of complete climate reversibility under overshoot, including exploring the potential for climate restoration, i.e. aiming to return temperatures near pre-industrial conditions by 2300 AD. The extension would sustain very high negative emissions levels from 2100 until 2250 AD, such that the expected temperature post-2300 AD would be at pre-industrial levels. As for the 21st century scenarios in ScenarioMIP, emission-driven simulations are favored for the extensions to allow carbon-climate dynamics to be simulated in the Earth System Models, with prescribed CO_2 emissions, prescribed land cover change, and prescribed non-CO_2 concentrations. The specifics of the extensions of non-CO_2 forcings, land use cover and CDR (see Section 5) will be finalized once the IAM-produced scenarios are developed up to 2100 AD, the rationale being to have the forcings of the extensions harmonized to the 2100 values, with a 2100-2500 AD evolution consistent with the overall storyline of the scenario extension, noting that non-CO_2 emissions will probably remain positive for most extensions (see Fig. 2).

5 Representation of carbon dioxide removal

Carbon dioxide removal (CDR) methods are an important component of climate action and mitigation plans and have a unique role in reducing greenhouse gas concentrations via their potential to enable net-negative emissions. How these methods are deployed will affect both land use and land management, as well as energy system compositions, impacting broader sustainable development and biodiversity considerations (Mace et al., 2021). Currently, a broad range of CDR methods is being discussed within the policy communities and considered as part of climate action plans, however IAMs only represent a subset of these approaches. The main CDR methods represented in IAMs are Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Capture and Storage (DACCS), and afforestation and reforestation. In addition, IAMs are exploring new CDR methods such as biochar, soil carbon sequestration, enhanced weathering, and ocean-based CDR, although only a subset of those are expected to be included in most scenarios for ScenarioMIP as part of CMIP7. CDR methods will be investigated in

ScenarioMIP scenarios, as well as within other related MIPs such as CDR-MIP, LUMIP, and geoMIP. Discussions and coordination with these other MIPs is underway, as well as coordination with the CMIP Forcings Task Team and its sub-team focused on harmonization of forcings datasets. The CDR methods used in these scenarios are intended to be plausible but do represent a wide range of uncertainty and assumptions about underlying drivers (e.g. socio-economic and technological conditions).

An important need across this modeling process is for as much consistency as possible between models (from IAMs to harmonization to use within ESMs) for areas of land-use change as well as emissions and reductions resulting from CDR activities. In addition, to provide a clear understanding for the community about how to use ScenarioMIP runs in an impacts model or other studies to understand the impacts and trade-offs of CDR, full transparency and clarity are necessary about:

a) which processes are included in models (and the related intentions and considerations of IAMs),
b) the steps involved in translating this information between models, and
c) how processes are implemented in ESMs

This includes details on which type of CCS is used, and assumptions about total life-cycle emissions. When possible, underlying information on drivers of land-use change (especially food production vs bioenergy crop production) should also be provided, even if only at regional scales (and can potentially be downscaled either within the harmonization process or within ESMs themselves). IAM future scenario data will be harmonized to ensure continuity with historical datasets and to ensure a consistent data format for all scenarios. IAMs should attempt to calibrate their models to the same historical forcing datasets used for CMIP historical simulations. Both IAMs and ESMs should report gross as well as net emissions for each sector to help with analysis of each scenario.

For CMIP7, many ESMs are not yet ready to compute the carbon emissions and carbon storage associated with BECCS. Therefore, we suggest that ESM teams run in emissions-driven mode but directly use the BECCS emissions (or resulting concentrations) provided by IAMs, rather than computing these emissions within their own models, as described in more detail below, along with some context for this decision. In the longer term, it would be interesting to simulate BECCS activities within the ESMs capturing the possible climate feedbacks; however, for now, these experiments are currently best handled as research projects. ScenarioMIP calls for continued research on the best approaches for IAMs to provide BECCS-related data for use in emission-driven ESMs and for ESMs to use that data in a way that is consistent with the original IAM intentions. Some areas for future research and next steps towards this are highlighted in the section on BECCS below.

5.1 Direct Air Capture and Storage (DACCS)

DACCS (and comparable flows) will be directly reported from IAMs to ESMs. The proposal is to report the DACCS flow separately (and harmonize and downscale separately) from total emissions. The total CO_2 emissions would be still reported including DACCS activity. The effects of other types of novel CDR that do not depend on plant productivity, such as enhanced rock weathering, could also be included within these types of regional emissions/reductions flows, whenever they are being simulated within IAMs.

5.2 Reforestation and Afforestation

For reforestation and afforestation, IAMs already have gridded representations of where they intend trees to be planted (and protected) to store carbon as vegetation biomass. Since ESMs typically already have capabilities for modeling tree/forest growth and carbon storage, the IAM information on land cover change and hence a/reforestation should be relatively easily incorporated into ESM frameworks and hence ensure a process-based representation of the uptake and storage of carbon by these biomes. As a result, the proposal is for the net emissions associated with reforestation and afforestation in ESMs to be calculated within the land models of those ESMs using land-use data passed from IAMs (after harmonization). However, since forest growth rates, forest management, and potential biomass density will likely differ between ESMs and IAMs, there will still inevitably be differences between the carbon stored in trees/forests between these models (e.g. (Melnikova et al., 2022)). These differences could be better tracked if IAMs also provided the assumed carbon content in each grid cell, similar to the secmb (secondary mean biomass density) variable used in historical data for LUH2.

Afforestation and reforestation for carbon dioxide removal will be provided as gridded areas of land-use for new forested area plantations in previously non-forested locations (afforestation) and/or previously forested areas (reforestation). This will be reported as two separate areas, along with existing forest areas (by both IAMs and ESMs), which will enable support for downstream biodiversity and impacts analysis. It is critical for a meaningful representation in ESMs that they can represent managed forests.

5.3 Bioenergy with Carbon Capture and Storage (BECCS)

Bioenergy is represented in IAMs from a variety of feedstocks, including bioenergy crops, forest biomass, and agricultural/forest residues. To accurately represent these processes in ESMs, IAMs and their land-use forcing datasets need to provide each of these feedstock types explicitly. Further, bioenergy in IAMs can be coupled with capture and storage processes (CCS) which removes carbon from the earth-based pools (atmosphere, ocean, and land). Accordingly, to accurately represent the carbon removal portion of bioenergy use (i.e., BECCS), ESMs need information on the fraction (at least globally) of carbon stored geologically via CCS that derives from each feedstock.

It is important to note that IAMs model BECCS energy consumption (and related removals) from a consumption perspective; i.e., BECCS is accounted for in the IAM region where it is used, not where the biomass is grown. However, IAMs still report the biomass growth in the original location. Therefore, biomass growth as a driver of carbon dioxide removal will be consistent with the underlying IAM, but any emissions flux field generated will necessarily be inconsistent because of biomass trade. ESM teams should take note when trying to compare negative carbon flux values between their land modules and what is reported in the IAM emissions forcing data.

Further inconsistencies may arise due to bioenergy crop representations between IAMs and ESMs. In particular, IAMs represent technological crop yield improvements which are not due to any physical process, but are assumed to be from human intervention via research, development, and innovation. From an ESM perspective, this means that the carbon content for a given plot of bioenergy crop can increase over time. At minimum, a global time series of these values needs to be provided by the IAM to the ESM in order to take on board this effect.

At the time of writing, many ESMs are not yet ready to simulate the specific crop types used for BECCS and to include the bioenergy crop management and harvest schemes needed to compute the associated emissions and storage. They also need data to help validate and tune their models for these processes. Table 4 (based on a recent survey of ESMs) summarizes the current readiness of ESMs to fully model BECCS emissions/reductions.

Table 4: Results of a survey among ESMs participating in CMIP7 on their capabilities of BECCS representation

BECCS processes needed within ESMs	**Percentage of ESMs ready to compute/model these processes (out of 19 ESM teams responding)**
BECCS-specific crop types	26%
Technological yield improvements	42%

Anthropogenic carbon storage pools	47%
Bioenergy generation	26%
Efficiency of carbon capture at bioenergy plants	11%
Geological carbon storage	33%

Owing to all these complexities (which are different from the processes that need to be modeled for afforestation and reforestation), the plan for ScenarioMIP is for the carbon storage and/or net emissions from BECCS to be provided to ESMs as part of the emissions data from IAMs. ESMs will still need to model the emissions and biogeophysical climate impacts associated with land-use change and management for bioenergy (and other) crops. To facilitate this, they will be provided with harmonized gridded areas of bioenergy crops from IAMs. However, since many ESMs are actually preparing to fully calculate the net BECCS emissions as well, as much information as possible will be transferred from IAMs to ESMs so that those analyses and experiments can be undertaken in separate MIPs or research projects that will take place over longer time periods than ScenarioMIP. In principle, the results of the ESM BECCS calculations can feed into future versions of IAMs to highlight areas of highest BECCS carbon uptake potential.

To relay key information around BECCS to ESMs, IAMs will need to report, at the gridded level, the land-use change areas associated with first and second-generation bioenergy crop deployment. Irrigation and fertilizer usage associated with bioenergy crops could also be provided. These data will enable ESMs to model the climate impacts of land-use change associated with increasing or decreasing areas of bioenergy crops, along with the climate impacts of managing these agricultural systems. In addition, regional BECCS-related emissions and removals will also be harmonized and reported to enable ESMs to capture the effects of the emissions from bioenergy that replace other emissions in the energy system and the emissions removed via carbon capture and storage. Table 5 summarizes the AFOLU processes associated with BECCS and whether the emissions/storage for each process will be provided by IAMs or computed by ESMs in ScenarioMIP.

Table 5: the role of IAMs and ESMs in representing individual processes associated with BECCS.

AFOLU process	**Emissions/storage computed by ESM or provided by IAM for ScenarioMIP**
Land-use change associated with BECCS	ESM
Management of land used for BECCS	ESM
Emissions from bioenergy	IAM
Storage of carbon from CCS	IAM

In summary, Table 6 summarizes the data passed between IAMs and ESMs for CDR. In addition to the required datasets that are passed from IAMs to ESMs, as much additional information as possible on the IAM intentions and assumptions associated with CDR should be provided for additional analysis by ESMs and impact models. Moving forward, our goal is for IAMs and ESMs to work towards enabling full calculations of land-based CDR emissions/storage within ESMs for future MIPs and research projects.

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Table 6. CDR data passed from IAMs to ESMs annually as part of ScenarioMIP in CMIP7, along with intended ESM usage of these data.

CDR Method	IAM data passed to ESMs (via harmonization)	ESM use of this data
DACCS	Regional net emissions associated with DACCS, as well as total emissions including DACCS.	Use DACCS net emissions along with other emissions data.
BECCS	Gridded areas of first and second generation bioenergy crops, regional net emissions associated with BECCS, regional carbon storage associated with BECCS.	Compute land-use change and management of bioenergy crops but do not remove and store carbon. Use BECCS net emissions or BECCS storage (depending on ESM needs), together with other emissions data inputs.
Afforestation/Reforestation	Gridded areas of afforestation and reforestation.	Plant, grow, and protect trees. Compute carbon emissions and storage associated with tree growth.

6. Discussion and conclusions

We have proposed a limited set of scenarios of emissions, concentrations, and land use that, once modeled by IAMs, would provide external forcings for ESMs participating in CMIP7. These scenarios with their climate system outcomes are intended to facilitate studies of climate processes; provide inputs to a wide range of studies of impacts, adaptation, and mitigation; and support climate policy development and communication. They cover a wide range of plausible outcomes, from a high scenario representing policy failure and strong drivers of greenhouse gas emissions, to a very low scenario with dramatic emissions reductions.

The implementation of these scenarios in IAMs and ESMs poses a number of challenges, not all of which can be addressed or fully explored within the ScenarioMIP process. As a result, in a number of cases it became necessary to make design choices on the basis of current literature. Throughout the text we have indicated where further research could advance the field, and summarize important directions here.

Explore climate (model) processes:

- **Explore the effect of carbon cycle uncertainty, including climate feedbacks, on climate system outcomes.** ESMs are encouraged to run all scenarios in CO_2 emissions-driven mode, so that the carbon cycle is modeled within the ESMs. The multi-model ensemble will then capture uncertainty in the carbon cycle across models. A complementary analysis could test uncertainties in the carbon cycle parameters in the emulators (derived from the behavior of the CMIP6 ESMs) by deriving high and low CO_2 concentration pathways for a given emissions scenario using emulators. These concentration variants could then be run with ESMs (in concentration-driven mode) in addition to the median concentration pathway recommended as part of the ScenarioMIP protocol, to investigate the sensitivity of the climate system to the emulators' implementation

- **Explore the effect of atmospheric chemistry uncertainty on climate system outcomes.** The ScenarioMIP design calls for non-CO_2 greenhouse gases and air pollutants to be incorporated primarily in the form of atmospheric concentrations, with a single atmospheric chemistry model providing concentration fields based on the emissions scenarios. A fuller representation of uncertainty would run emissions through additional atmospheric chemistry models and then run through ESMs to assess the sensitivity of climate outcomes to the representation of atmospheric chemistry
- **Produce high-end warming scenarios using higher climate sensitivity.** It has been argued that warming associated with RCP8.5 might emerge from lower emission trajectories combined with high climate sensitivity or high carbon-cycle climate feedbacks. Therefore RCP8.5 should still be useful to cover the high-end of the climate change range. It is preferred, however, for such purpose to identify model runs that actually are consistent with such conditions, i.e. plausible high emissions in combination with high climate sensitivity.

Produce wider set of IAM scenarios:

- **Produce idealized or counterfactual emissions and land use scenarios to complement the plausible scenarios proposed here.** The ScenarioMIP design is limited to scenarios judged to be plausible, but other scenarios could also provide useful insight. For example, scenarios that are higher or lower than those proposed here, or that imagine counter-factual historical outcomes (Meinshausen et al., 2024), can be of scientific interest or policy relevant.
- **Develop alternative implementations of the scenarios requested here from the IAM community using different modeling paradigms and normative assumptions.** There are a number of questions of wide interest to the scientific and policy communities that would be unlikely to imply forcing pathways different enough to substantially affect climate system outcomes, either regionally or globally. They therefore fall outside the scope of ScenarioMIP, but are worth pursuing through other means. For example, different normative bases for approaches to mitigation may lead to different regional or sectoral emissions pathways, within approximately the same global forcing pathway. Similarly, alternative socio-economic pathways such as sustainable development scenarios with rapid convergence of regional incomes and living standards are useful to pursue but, if coupled with a target of limiting warming to (for example) likely below 2 C, would lead to similar global forcing pathways to other 2 C scenarios.
- **Produce versions of the scenarios described here that account for climate change impacts.** The SSP-RCP scenario framework by design does not include impacts in community scenarios so that they are more useful to the impact research community. However, incorporating impacts in these scenarios would also be of interest, in particular to test whether this would substantially alter global emissions and land use pathways.
- **Consider options to better integrate adaptation and mitigation.** There are several interactions between impacts, adaptation and mitigation. At the moment, these are not considered given the way information is forwarded from one community to another. It will become increasingly important to see how this issue can be overcome.

Explore climate model sensitivities:

- **Further explore whether different mitigation strategies achieving approximately the same global forcing pathways would produce detectable differences in climate outcomes.** The overall SSP-RCP scenario framework is based on the premise that in a multi-model setting ESM projections resulting from a given pathway of global average forcing can be considered consistent with alternative emissions and land use scenarios producing a similar global forcing pathway (van Vuuren et al., 2017). In that way, ESM simulations based on one of the ScenarioMIP scenarios can be used in studies with alternative assumptions about socio-economic pathways or mitigation strategies, as long as global forcing is similar. Limited existing research supports this assumption, but further study of the degree to which variations in regional forcing due to short-lived climate forcers or land use could produce significantly different climate and impact outcomes would be useful.
- **Further explore what minimum difference in global forcing is required to produce significantly different climate system outcomes.** Global forcing pathways that are not sufficiently separated from each other may not produce multi-model ESM ensembles with statistically significant differences in important climate variables. It may be that a forcing difference sufficient to produce a difference of 0.25-0.3 C global

average temperature is required (Tebaldi et al., 2015), but further analysis with the latest generation of ESMs is desirable.

Foster ESM emulators' development:

- **Develop spatially explicit, multi-variable emulators that can emulate ESM outcomes, especially for temperature overshoot scenarios.** Progress is being made in the development of ESM emulators, but currently there are not enough overshoot scenarios run by ESMs to train these emulators and test their accuracy in overshoot conditions. Emulators can subsequently be used to explore the outcomes of a much wider range of scenarios.

Improve ESM representation of mitigation strategies:

- **Develop and explore methods for ESMs to be able to compute CDR-related emissions and storage (including BECCS).** Because the implementation of CDR directly in ESMs is not yet a widespread practice, the ScenarioMIP design calls for IAMs to estimate the emissions associated with these measures and pass these results to ESMs. In future CMIP activities it would be desirable to implement CDR measures directly in ESMs. This requires research on what CDR-related output it is important for IAMs to provide, and how ESMs can implement it in a way that is consistent with the original IAM intentions.

Progress on these research directions will provide a basis for a future CMIP scenario activity that can make further progress on understanding human-earth system interactions and feedbacks.

Code and/or data availability

Data on the figures is available at zenodo: DOI: 10.5281/zenodo.14382495

Author contribution

DvV, BCO and CT coordinated the development process of the manuscript and took a lead in the writing. LC, TH, KR, PF and BS coordinated subgroups in the writing process that worked on particular sections. All authors contributed to the writing and the design of the proposal.

Competing interests

At least one of the authors is a member of the editorial board of GMD.

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Appendix A: Acronyms

AerChemMIP Aerosol Chemistry Model Intercomparison Project
AFOLU Agriculture, Forestry and Other Land Use
BECCS Bioenergy with Carbon Capture and Storage
CCS Carbon Capture and Storage
CMIC Climate Model of Intermediate Complexity
CMIP Coupled Model Intercomparison Project
CDR Carbon Dioxide Removal
DAC Direct Air Capture
DACCS Direct Air Capture with Carbon Storage
DECK Diagnostics, Evaluation and Characterization of Klima
ESM Earth System Model
EV Electric Vehicle
GCM Global Circulation Model/Global Climate Model
GHG Green-house gas
GMST Global Mean Surface Temperature
GSAT Global-mean Surface Air Temperature
GWP100 Global Warming Potential over 100 years
H High scenario
H-ext High extension
H-ext-OS High overshoot extension
IAM Integrated Assessment Model
IAMC Integrated Assessment Modeling Consortium
IEA International Energy Agency
input4mip CMIP activity tasked with the processing and availability of input data for ESM experiments under CMIP
IPCC Intergovernmental Panel on Climate Change
L Low scenario
L-ext Low extension
LUMIP Land Use Model Intercomparison Project
M Medium scenario
M-ext Medium extension
ML Medium-Low scenario
ML-ext Medium-Low extension
MIP Model Intercomparison Project
MOS Medium scenario with Overshoot
NDC Nationally Determined Contributions
OS Overshoot
RAMIP Regional Aerosol Model intercomparison Project
RCP Representative Concentration Pathway
SCM Simple Climate Model
SDG Sustainable Development Goal
SLCF Short-Lived Climate Forcer
SSC Scientific Steering Committee
SSP Shared Socio-economic Pathways
TCRE Transient Climate Response to cumulative Emissions

VIA Vulnerability, Impacts and Adaptation
VIACCS Vulnerability, Impacts, Adaptation and Climate Services
VLLO Very Low with Limited Overshoot scenario
VLLO-ext Very Low with Limited Overshoot extension
VLHO Very Low after a High Overshoot scenario
VLHO-ext Very Low after a High Overshoot extension
WGI/II/II Working Group I/II/III

Figure and Table captions

Figure 1: Draft scenarios for CMIP7 ScenarioMIP, showing (a) GHG emissions pathways as a function of time for each of the proposed scenarios (based on GWP-100) and (b) the expected global average temperature outcomes using the probabilistic FaIR ensemble used in IPCC AR6 (IPCC, 2021). Shaded regions for temperature outcomes show the 33-66 percentile range of the distribution while uncertainty bounds for emissions show +/-8 GtCO2 around the median. Scenarios are (H) High, (M) Medium, (ML) Medium-Low, (L) Low, (VLHO) Very Low after High Overshoot and (VLLO) Very Low with Limited Overshoot. The final emission trajectories will depend on IAM model runs and might differ from the illustrations provided here. The final temperature outcomes will be based on climate model runs, including, for instance, carbon cycle feedback. Textured regions are drawn for the 2100-2150 period (AD), where output is requested from Earth System Models, but emissions and forcings will be defined in the extension protocol.

Figure 2: Preliminary extensions for ScenarioMIP in CMIP7. Top row shows CO_2 emissions and cumulative emissions. Second row shows GHG emissions (calculated using GWP100) and total radiative forcing. Bottom row shows atmospheric CO_2 concentrations and projected temperature outcomes. Simulations are conducted with the AR6 calibrated ensemble of the FaIR simple climate model, where solid lines show the 50th percentile outcome, while shaded regions show the 5-95 percentile range.

Table 1: Scenarios, proposed naming, and their priority. These priorities are meant to be for models participating in emission-driven mode. We also request that these groups run, with high priority, the Medium scenario in concentration driven mode for comparison of the effects of the active carbon-cycle on the outcomes. Two more scenarios in concentration driven mode for these models have lower priorities. All the scenarios listed here will be provided as concentrations for models that want to run ScenarioMIP in concentration mode, and for which the high priority will include all 6 scenarios.

Table 2: Input data for ESMs and IAV community (illustrative list)

Table 3: Main characteristics of the scenario extensions

Table 4: Results of a survey among ESMs participating in CMIP7 on their capabilities of BECCS representation

Table 5: the role of IAMs and ESMs in representing individual processes associated with BECCS.

Table 6. CDR data passed from IAMs to ESMs annually as part of ScenarioMIP in CMIP7, along with intended ESM usage of these data.