An evolving Coupled Model Intercomparison Project phase 7 (CMIP7) and Fast Track in support of future climate assessment

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Abstract. The Coupled Model Intercomparison Project (CMIP) coordinates community-based efforts to answer key and timely climate science questions, facilitate delivery of relevant multi-model simulations through shared infrastructure and support national and international climate assessments. Generations of CMIP have evolved through extensive community engagement from punctuated phasing into more continuous support for the design of experimental protocols, infrastructure for data publication and access, and public delivery of climate information. We identify four fundamental research questions motivating a seventh phase of coupled model intercomparison relating to: patterns of sea surface temperature change, changing weather, the water-carbon-climate nexus, and tipping points. Key CMIP7 advances include: expansion of baseline experiments; focus on CO_2-emissions-driven experiments; sustained support for community MIPs; periodic updating of historical forcings and diagnostics requests; and a collection of prioritized experiments, or "Assessment Fast Track", drawn from community MIPs to support climate research, assessment, and services goals across prediction and projection, characterization, attribution, and process understanding.

1 Introduction

The Coupled Model Intercomparison Project (CMIP) is an international research activity that develops coordinated experimental protocols within the World Climate Research Programme (WCRP) for global coupled atmosphere-ocean-land-ice climate and Earth System Models (ESMs) and facilitates the distribution and interpretation of simulation output. ESMs represent the statistical characteristics of the weather and time evolution of climate through the equations of motion, physics, and thermodynamics and the interactions between radiation, clouds, and aerosols within the coupled hydrosphere, geosphere, biosphere, and cryosphere. Preceding phases of CMIP (Meehl et al., 1997; 2000; 2007;Taylor et al., 2012; Eyring et al., 2016) have evidenced the evolution of ESMs for improved representation of the Earth system through testing, evaluation, and comparison of models across generational increases in spatial resolution (initially tens of degrees to now around a quarter of a degree), comprehensiveness (including carbon cycle, atmospheric chemistry, aerosols, biogeochemistry, ecosystems, cryosphere, land-hydrology interactions, sea level rise, and human drivers), and granularity (ensembles of models assessing structural uncertainty, detection and attribution, predictability, sensitivity to feedbacks, statistics of extremes, etc.) (Figure 1). In addition to representing water and energy cycles and associated dynamics, ESMs coupling chemistry and the carbon cycle with the physical climate system have broadened model utility and applicability, for example, allowing exploration of interactions between anthropogenic emissions, climate, and the biosphere as mediated by biogeochemical cycles (Sanderson et al., 2024a).

CMIP supports the WCRP 2019-2028 science objectives of “Fundamental understanding of the climate system”, “Prediction of near-term evolution of the climate system”, “Long term response of the climate system”, and “Bridging climate science and society.” The range of CMIP experiments are instrumental to the research community’s ability to build robust scientific literature underpinning mechanistic and process understanding of the complexities of climate change in the Earth system (Durack et al., 2025). Realistic historical and projection simulations also support quantification of change and application to a broad range of relevant societal impacts.

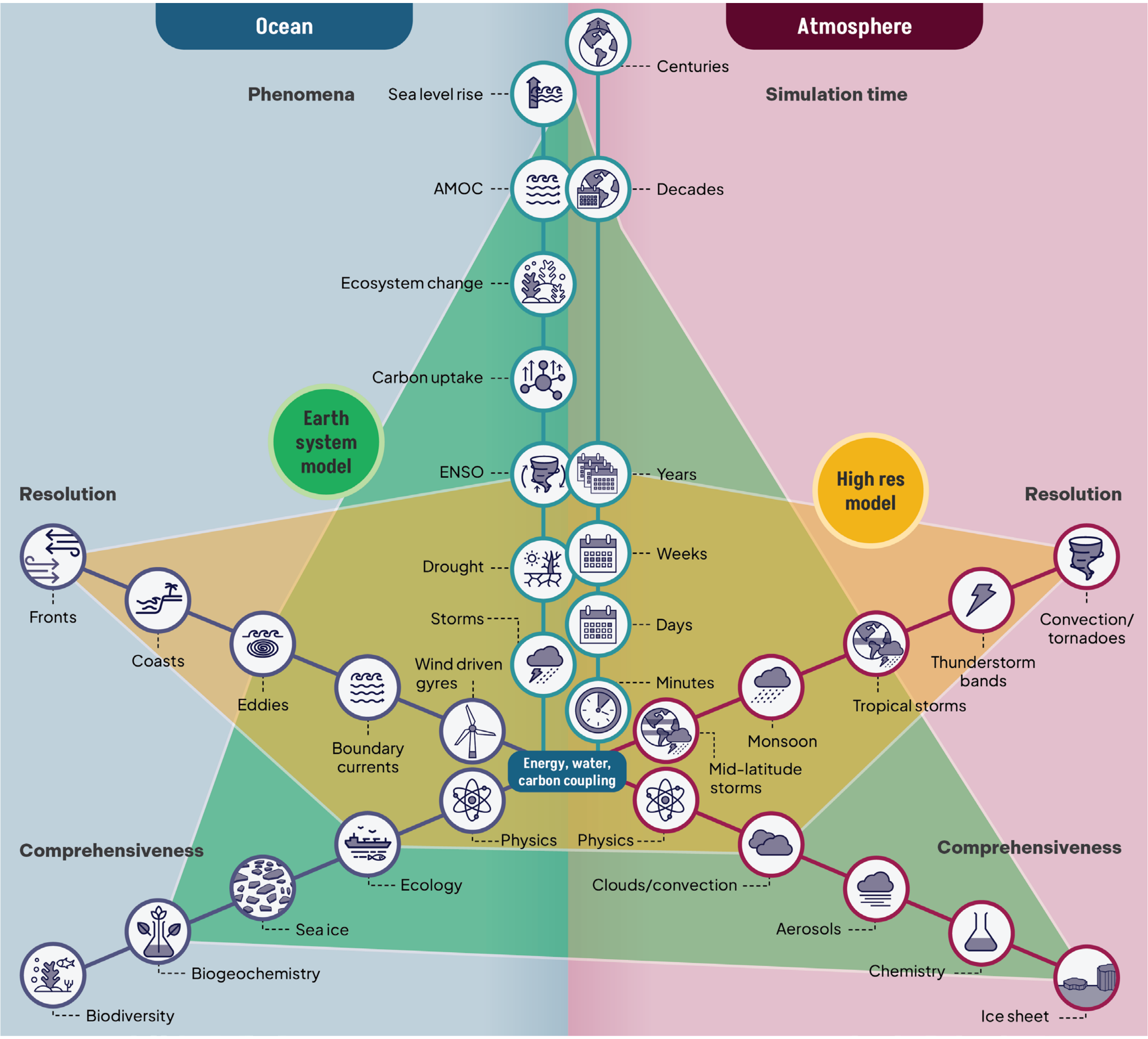

Figure 1: Earth system modeling as part of the multiverse of modeling approaches across resolution, comprehensiveness and simulation time. Atmospheric aspects are shown in red and ocean aspects in blue. Note that ensemble size, experiments/scenarios, precision, accuracy, availability and familiarity also come into play in the search for efficiency and robustness.

The public availability of CMIP ensembles has critically allowed the climate research community to explore ideas without having to design unique experiments and run simulations in house. The resulting intercomparisons have advanced understanding of climate's fundamental underlying physics in such examplars as tropical (Bellenger et al., 2014; Planton et al., 2021) and extra-tropical variability (Simpson and Polvani, 2016; Zappa and Sheppard, 2017), the behavior of temperature and precipitation extremes (Seneviratne and Hauser, 2020; Borodina et al., 2017), factors driving modeled climate sensitivity (e.g., Zelinka et al., 2020), and the connections between the representation of present-day climatology or processes and future projected change (e.g., Hall et al., 2019).

CMIP provision of climate responses to idealized and scenario-based projections of forcing has supported numerous national and international assessments (see **https://wcrp-cmip.org/cmip-use-in-policy/** for a partial list) and played a central role in every Intergovernmental Panel on Climate Change (IPCC) report since its inception (Meehl et al., 2007). Scenario projections include the response to changes in CO_2 and other greenhouse gases, aerosols, and ozone across a range of increasing and recovery trajectories via human perturbations to the carbon cycle and other aspects of the Earth system. Analysis has evolved from initial focus on the climatological response in temperature and precipitation to: climate modes such as El Niño Southern Oscillation, extremes such as drought, heat waves, monsoons and tropical storm statistics, a comprehensive suite of climate indicators such as snowpack, sea ice, ocean circulation, sea level rise, and ecosystems, and the implications across economic and societal sectors. Together, these activities support assessment and other climate services with increased understanding and projections across a suite of potential futures.

CMIP increasingly also provides the source of climate information for other large community research activities including the WCRP COordinated Regional Downscaling EXperiment (CORDEX; https://cordex.org/; Giorgi and Gutowski, 2015; Gutowski et al., 2016) , Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; Warszawski et al., 2013), Sea Level projections via FACTS (Kopp et al., 2023), the Copernicus Climate Data Store (Buontempo et al., 2022) and the Copernicus Interactive Climate Atlas (https://atlas.climate.copernicus.eu/atlas; Gutierrez et al., 2021).

The CMIP protocols and resulting ensemble archive thus serves at least four roles: testing, evaluating, and comparing coupled models; scientific inquiry across a range of idealizations; exploration of plausible futures for climate attribution, downscaling and impacts contributions to climate services; policy-relevant assessment of mitigation and adaptation options. Designing each CMIP phase as a research activity to balance the needs of evaluation, inquiry, service, and assessment applications is challenged by lack of alignment between the burden of investment falling mostly on the modeling community versus benefit for those credited for analysis in the subsequent scientific literature. Indeed, it has been argued that the assessment and service needs currently satisfied by CMIP might be better met by a more sustained application of ESMs (Schmidt et al., 2023a; Jakob et al. 2023; Stevens 2024). Unfortunately, the necessary ESM capabilities and associated infrastructure for such a sustained approach are not yet in place either at any individual modeling center nor the national or international levels. As a result, the experimental design for CMIP7 described here includes components that might fruitfully be taken up outside the research community in future phases of CMIP alongside those research aspects driven primarily for better process understanding.

The CMIP7 design provided here is informed both by cumulative participant experience obtained during CMIP6 and subsequent surveys and community feedback. Changes to the protocol and organization address community concerns by reducing contributor burdens of simulation and data provisioning, facilitating more nimble community-driven MIPs, and better supporting research, assessment, and service. The goals of CMIP7 are thus to: 1) continue the rich diversity of multi-scale research built in CMIP6, 2) enable episodic and punctuated participation and intercomparison and 3) facilitate more sustained participation with continuous and responsive support.

Given a backdrop of multiple existing CMIP generations of ESM simulations (Taylor et al., 2012; Eyring et al., 2026) and rapid development of alternative modeling approaches ranging from highly-resolved dynamical models to statistical emulators (Beusch et al., 2020; Mathison et al., 2024), the design presented here emphasizes the value obtained from new simulations by ESMs within the multiverse of models (WCRP. 2023). That value arises from three main developments. First is the accumulation of a longer, richer observational record encompassing a wider range of conditions and the accelerating emergence of change from climate variability. Second is the ongoing development and increasing comprehensiveness of ESMs aided by observational advances including increasingly diverse satellite observations of atmospheric composition, land characteristics, and ocean ecology affording new opportunities for these models to be evaluated, and their behavior understood. Third is the formulation of new questions, four of which are articulated in the next section, about the co-evolution of natural systems and human influence, especially as related to the trajectory of the coupled carbon-climate cycle.

This paper provides an overview of CMIP7 by first emphasizing four fundamental research questions (section 2) for which understanding is evolving rapidly and new ESM simulations have great promise to sharpen insight. The paper then describes guidance on protocols for the mandatory Diagnostics, Evaluation, and Characterization of Klima (DECK) and recommended “Assessment Fast Track” experiments (Section 3), distinguishing the more assessment and service focused prediction and projection experiments from those aimed at characterization, attribution and process understanding. It concludes with discussion of the evolving role of CMIP in the research community (Section 4) and Summary (Section 5).

2 Fundamental Research Questions motivating Coupled Model intercomparison

Four questions emerged during initial planning for CMIP7 as areas in which a new ensemble of ESM simulations holds promise for substantial progress through the comprehensive community engagement and wide range oft modeling approaches only CMIP can deliver. These questions are focused on the emergent capabilities of current ESMs — consistent with but narrower than the WCRP 2019-2028 Science Objectives described above — as a synthesis by the CMIP Panel based on a subset of experiments proposed by the broader community (section 3.3). While other pressing questions may be better addressed with different classes of models (e.g. cloud processes in global km-scale models, Merliset al., 2024), most experiments in the Assessment Fast Track (Section 3.4.5) address one or more of these questions. Underlying themes include the opportunity to confront the modeled representation of historical trends with the seven years of further observational record obtained since

CMIP6, enhanced capabilities in modeling coupled carbon-chemistry-climate systems, and targeted experimental designs that leverage the multiverse of modeling tools (Hewitt et al., 2021; WCRP, 2023).

2.1 Patterns of sea surface change: How will tropical ocean temperature patterns co-evolve with those at higher latitudes?

Description: The spatial pattern of sea surface temperature (SST) across the vast tropical Pacific has global implications through teleconnections and radiative feedbacks (e.g., Kang et al., 2020). SST evolution is intertwined with the fate of clouds which influence the global temperature response to increasing greenhouse gas concentrations (Armour et al., 2024) and feedback on local warming patterns (Myers et al., 2018; Erfani and Burls 2019; Rugenstein et al., 2023; Espinosa and Zelinka 2024). Growing evidence specifically suggests a two-way connection between trends in the Southern Ocean and those in the tropical Pacific (Dong et al., 2022; Kang et al., 2023), likely mediated by extratropical clouds (Kim et al. 2022) and unfolding over multi-year time scales. Models have helped elucidate some of the coupling mechanisms but struggle to reproduce important aspects of the historical SST patterns. Observed SST trends in both the tropical Pacific and the Southern Ocean are at the edge or outside the range of those simulated by CMIP6 models (Wills et al., 2022, Seager et al., 2022), raising concerns that models are able to capture neither the externally forced trend nor the magnitude of internal variability in these regions (Watanabe et al., 2024). Observations of enhanced warming in the western Pacific and slight cooling in the eastern Pacific oppose modeled patterns on average (Coats and Karnaukas, 2017; Seager et al., 2019).

Progress on this question will be facilitated by a longer observational record in which the forced signal has increased relative to internal variability, which will allow for more informative comparisons with observations (Schmidt et al., 2023a). Higher resolution and addition of new processes in ESMs, especially more refined treatments of mixing by ocean eddies (Yeager et al., 2023) and melt water input to the Southern Ocean (Dong et al., 2022, Schmidt et al, 2023b, Schmidt et al., 2025) from coupled ice sheet models, may mitigate model discrepancies and offer greater insight into local and teleconnecting mechanisms.

2.2 Changing weather: How will dangerous weather patterns evolve?

Description: Large scale patterns of climate play a critical role in establishing the conditions that trigger many weather extremes including hurricanes and other tropical storms, storm surges, tornadoes, floods, droughts, atmospheric and marine heat waves, wind droughts, and monsoons whose frequency and/or intensity may change. Understanding how these large-scale patterns and associated extremes will respond to climate change is key to providing actionable regional information for adaptation. Large ensembles following CMIP6 protocols have highlighted the role of internal climate variability and helped quantify discrepancies between model behavior and the historical record (e.g., Wills et al., 2022). The more active hydrological cycle projected under warming, for example, is expected to increase the potential for large storms (Holland and Bruyère, 2014). This is consistent with recent record-breaking storms such as the 2024 upper-tropospheric cut-off lows that produced severe floods in Spain, and rapid intensifying hurricanes, such as Otis in 2023 in the Eastern Tropical Pacific (Garcia-Franco et al., 2024) and Helene and Milton in 2024 in the southeastern United States (Clarke et al., 2024). Anticipating and adapting to changes in extremes will require better characterization of shifts in spatial and temporal distributions of dangerous weather patterns. As many extreme events occur when climatic thresholds are exceeded (e.g. tropical cyclones, ice melt, coral bleaching, etc.), improvements in ESMs to better match absolute historical temperatures as well as their changes will benefit simulation of extremes.

Insights into this question are expected across the multi-model ensemble whose wide anticipated range address questions of structural uncertainty and more specifically from contributions of both single-model ensembles of key experiments addressing internal variability uncertainty and regional detail via higher resolution than previously available (e.g., HighResMIP2; Roberts et al., 2024). The increasing proportion of models driven by CO_2 emissions rather than projected CO_2 concentrations will allow for novel investigation of future extremes under climate stabilization due to the demonstrated rigor of Transient Climate Response to Cumulative CO_2 Emissions (TCRE; Matthews et al., 2009) and climate stability under Zero Emissions Commitment (MacDougall et al., 2020).

2.3 Water-carbon-climate nexus: How will Earth respond to human efforts to manage the carbon cycle?

Description: State-of-the-art coupled carbon cycle–climate modeling lies at the intersection of climate science, ecosystems, hydrology, biogeochemistry, and socioeconomic systems. The future resilience of natural systems and human-modulated carbon sinks remains one of the key uncertainties in efforts toward climate stabilization and warming reversal. One of the main advances in CMIP7 is its focus on CO_2-emissions-forced models to explore dynamics climate-carbon coupling in idealized and realistic historical and future scenarios to quantify feedbacks (Sanderson et al., 2024a). Quantification of the land and ocean processes responsible for the historical carbon concentration response to CO_2 emissions constitutes an important step forward in demonstrating model robustness. As land carbon and water management are tightly coupled, exploration of each of these cycles has major implications for the other and have been only weakly constrained between projected forcing from Integrated Assessment Models and comprehensive ESMs across sectors of food, energy, and materials production sectors and biodiversity and sustainability goals. Quantifying vegetation responses to changing climate - how soils respond to warming, moisture, and thawing in the context of a changing microbial communities (e.g., Chase et al., 2021), and how vegetation growth interacts with soil microbial functioning (Lennon et al., 2024) - are critical to reducing uncertainty in future carbon budgets. However, the only CMIP6 model representing soil microbes explicitly (GFDL-ESM4) was among the most biased in representation of soil carbon (Ito et al., 2020), demonstrating that enhanced process representation can reveal other errors.

Exploration of the many proposed dimensions of Carbon Dioxide Removal (CDR) is another emerging research area critical to understanding vulnerabilities of ecosystems to natural and human drivers such as climate variability, ecosystem and water management, land use, fires, and pests. The societal context for understanding CDR is also rapidly changing: while previous carbon mitigation scenarios placed a large reliance on the viability of BioEnergy with Carbon Capture and Storage (BECCS; Arneth et al., 2019), there remain deep, multidimensional uncertainties such as competition for water and land use between BECCS, afforestation, biodiversity protection and agriculture. Because constraining historical land carbon uptake depends on knowledge of ocean carbon uptake, the large ocean discrepancy between current surface estimates based on pCO_2 observations and prognostic biogeochemical models (RECCAP2; Friedlingstein et al., 2023) limits our ability to confirm the effectiveness of prospective land or ocean CDR. Ocean CDR effectiveness, durability, vulnerability and overall additionality of proposed solutions such as iron fertilization, alkalinization, CO_2 injection, and carbon capture (e.g. seaweed) has only recently been explored. Also uncertain in the context of CDR is how ocean acidification will evolve.

Opportunities to address this question arise primarily from advances in 1) land process representation including the non-linear role of biogeography, land use, fires, permafrost and microbes, 2) improved representation of land and ocean biogeography though improvement in long standing climate biases such as double ITCZ, dry Amazon, and Southern Ocean warm bias, 3) new satellite CO_2, CH_4, land surface and other observational constraints, 4) the strength of TCRE and minimal ZEC as an emergent coupled carbon-climate property providing a rich field for climate stabilization research, and 5) new sets of experiments more explicitly targeting understanding of the carbon cycle in the context of carbon and water management across food, energy, and materials production sectors.

2.4 Tipping Points: What are the risks of triggering irreversible changes across possible climate trajectories?

Description: A tipping point is “a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly” (IPCC, 2021). Wood et al. (2023) recently provided framing of high impact/low likelihood outcomes and the need for research spanning their various dimensions. Potentially vulnerable tipping elements commonly cited in the climate system include collapse of Atlantic Meridional Overturning Circulation (AMOC), Amazon die-back, poleward migration of temperate forests, Sahel greening, sea level rise/ice sheet collapse, and Arctic warming with associated loss of permafrost and carbon release (Lee et al., 2021). Many tipping elements involve coupling between different components of the physical climate and/or the coupling of physical climate to biogeochemistry. Forest dieback and demographic shifts, for example, depend heavily on drought risk and related thermal and hydrological stressors (Drijfhout et al., 2015). This makes the representation of climate–vegetation interactions critical for robust assessments of potential change, especially in regions where resilience may already be declining such as the Amazon (Boulton et al., 2022).”. Wildfires are projected to increase over this century under enhanced CO_2 and associated vegetation growth (Allen et al., 2024). However, CMIP6 era models lack fidelity in these and other key processes - such as representation of the Antarctic slope current and land-ice interactions - needed to project Southern Ocean changes and Antarctic ice sheet collapse (Fox-Kemper et al., 2021). Mechanisms of irreversible and potential sudden change are manifold across different tipping elements with considerable remaining uncertainties (Lenton et al., 2008; Drijfhout et al., 2015). There is great societal value in identifying early signs of tipping points and in designing early warning systems as an adaptation to climate warming, particularly when they induce further climate impacts.

More robust insights can be expected with the shift to models forced by CO_2 emissions (allowing internally consistent carbon cycles and zero emission control experimentation) and by the coupling of more aspects of the climate system (e.g. ice sheets, biogeochemical processes). Additionally, provision of overshoot scenarios in the CMIP7 AFT from ScenarioMIP and Coupled Climate Carbon-Cycle (C4MIP) will provide new opportunities to explore the possibility of irreversible changes even with climate stabilization. CMIP7 also provides opportunities to explore process-driven storylines of how tipping points may occur through community paleoclimate studies such as exploration of the Green Sahara during the mid-holocene (Hopcroft and Valdes, 2021).

3. CMIP7 Experimental Design: Expanded Baseline Experiments and the Assessment Fast Track

The CMIP6 experiment design (Eyring et al., 2016) made great strides in decentralizing CMIP scientific leadership through a new process of endorsing MIPs while retaining responsibility for defining a small number of simulations to characterize the baseline behavior of each participating model through the mandatory Diagnostics, Evaluation and Characterization of Klima (DECK) and historical experiments. The resulting expansion of CMIP into new areas of science and new communities supported a wide range of groups working on climate process understanding (e.g. Zelinka et al., 2020) and impacts (e.g., through VIACS, Ruane et al., 2016). Despite efforts to harmonize requests for experiments and data across MIPs however, this rapid expansion also led to considerably increased burdens on participating modeling centers. Efforts to present the requirements of the new MIPs in a consolidated form led to a perception of a monolithic request. This pressure of requests coming from many independent MIPs was exacerbated by modeling center eagerness to produce all simulations early enough to be included in the IPCC's Sixth Assessment – conflating research, assessment, and service timelines. These and other issues were highlighted in feedback from the modeling community, including responses to a CMIP6 community survey (https://zenodo.org/records/11654909). This motivated an approach in CMIP7 planning of simultaneously less centralized coordination but more targeted recommendations on those experiments most likely to support the climate service and process understanding needs for assessment versus the more general application of models in community MIPs.

The CMIP7 protocol responds to these experiences by more clearly distinguishing among simulations intended to: 1) systematically characterize model behavior and provide robust control simulations for a wide range of sensitivity studies; 2) establish ranges for future climate change under different emissions trajectories; and 3) target high priority scientific questions (Section 2). To this end, the mandatory DECK is modestly expanded, community-driven and scientifically motivated MIPs are supported more broadly but encouraged to run on self-determined timelines, and assessments are supported by identifying and prioritizing a sub selection of simulations drawn from the MIPs of particular relevance to informing such reports (Figure 2). This section includes a description of the first such optional set, the CMIP7 Assessment Fast Track (AFT) that incorporates extensive community input and seeks to energize research inspired by emergent advances and modeling center priorities.

Rather than seeking to impose a single monolithic view from any single organizational perspective or stakeholder demand, each experiment within the AFT is explicitly optional - akin to participation in community MIPs. Acknowledging that details of the protocols described here are subject to modest change over time, the current (and all previous) versions, and the differences between them, will be made available as living documents through the CMIP website (https://wcrp-cmip.org/).

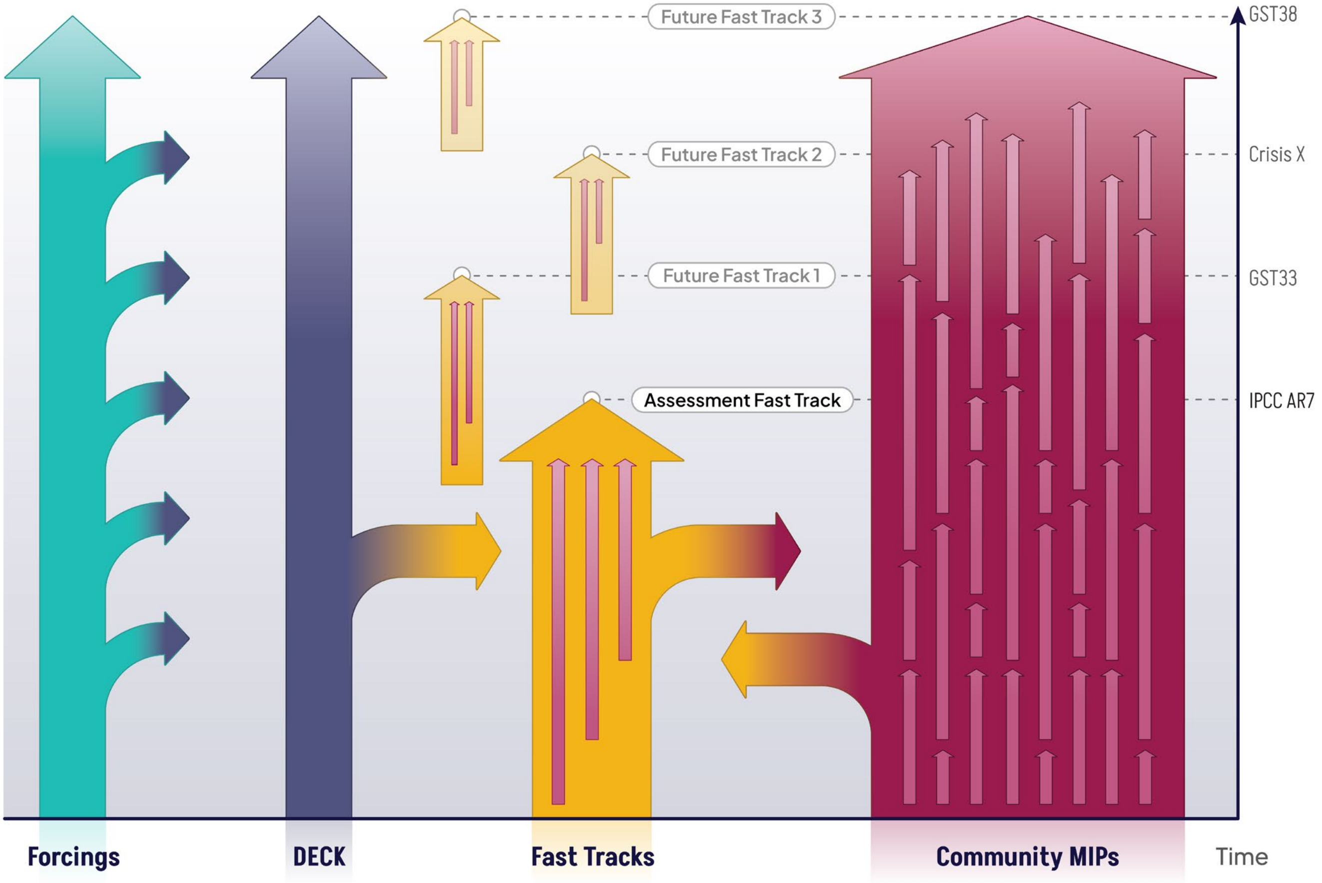

Figure 2: Schematic of the evolving CMIP design into an even more continuous approach with a continued DECK, regular updates and extensions of forcings, targeted "Fast Track" experiment sets starting with the "Assessment Fast Track", and CMIP infrastructure, standards, and tools also supporting ongoing science activities through community MIPs.

3.1 Diagnosis, Evaluation and Characterization of Klima (DECK) Experiments

CMIP6 introduced the set of mandatory baseline experiments aimed at the Diagnosis, Evaluation and Characterization of Klima (German for Climate), all of which were performed for CMIP5 and prior iterations of CMIP (Eyring et al., 2016) and serve as the nominal CMIP "entry card" for participation. The CMIP7 DECK is based on the same experiments (Table 1, short names in italics) but is expanded modestly by adding a) the historical simulation, b) a small set of "fixed-SST" experiments to characterize effective radiative forcing, and c) an expanded protocol to facilitate participation with ESMs that close the carbon budget and are capable of running with interactive CO_2 forced by emissions (including positive, zero, and negative scenarios) in addition to prescribed concentrations.

This expanded mandatory DECK is intended to allow for more complete description and characterization. Historical simulations (*historical* or *esm-hist*), which are most often interpreted in the context of more idealized experiments, are included in the DECK because they are key for characterizing model behavior over the observed historical record. Protocols remain formally unchanged from CMIP6 although more detailed guidance for models simulating biogeochemical mechanisms (and thus concentrations of CO_2 given emissions) and specifications of forcings are provided below (Table 1). One change in CMIP7 is the explicit recommendation that modeling centers provide at least 100 years of pre-industrial control (*piControl*) and/or *esm-piControl* from before the corresponding branching points for *1pctCO2*, *abrupt-4xCO2* and historical perturbations to allow users to better characterize drift. Because physical and compositional perturbations, whether specified as a forcing or computed internally, do not fully specify radiative perturbations driving climate change (e.g., Soden et al., 2018; Smith et al., 2020), the CMIP7 protocol modestly expands the DECK with experiments to characterize model-specific effective radiative forcing (increasing their priority from being "strongly encouraged" in CMIP6 to mandatory in CMIP7). These three atmosphere-only experiments with fixed model-specific pre-industrial SST and sea ice concentration (SIC) fields are added to the DECK following protocols developed for CMIP6 by the Radiative forcing Model Intercomparison Project (Pincus et al., 2016; Table 1). The *abrupt4xCO2* experimental protocol is further modified to recommend extending the simulation out to 300 years to provide a more robust estimate of the Equilibrium Climate Sensitivity than possible using only the first 150 years of simulation available in previous CMIP phases (Rugenstein et al., 2019; Dunne et al., 2020). While any size of ensemble is acceptable to meet the mandatory DECK compliance for submission to the Earth System Grid Federation (ESGF), submission of multiple ensemble members of *historical* and/or *esm-hist* simulations are highly encouraged as critical to a wide range of detection and attribution questions (see Sections 2.1, 2.2, and 3.3). Similarly, large ensembles of the Atmospheric Model Intercomparison Project (AMIP) simulations forced by SST and SIC are also encouraged.

Table 1: Overview of CMIP7 DECK with experiment short names, brief experiment descriptions, forcing methods, start and end year, and main purpose. Experiments start on 1 January and end on 31 December of the specified years. The recommended *piControl* minimum experiment length is defined below; however, to ensure broad simulation data use, *piControl* temporal coverage should extend across the equivalent period (after initialization) to that in the full historical and future scenario (with extension) periods. The plus (+) sign indicates that beyond meeting the basic DECK requirements, the total number of simulated years would depend on the number of ensemble members, whether the *piControl* will follow the Fast Track guidance of 150 year abrupt-4xCO2 extension to 300 years and whether the scenarios and their extensions are being run. Further information of anthropogenic forcing for CO_2 emission- and concentration- forcing is provided in Section 3.1.1. Simulations with an Atmosphere General Circulation Model (AGCM) rather than a fully coupled model are noted.

Experiment short name	Experiment description	Anthropogenic Forcing	Volcanic Forcing	Solar Forcing	Start Year	End Year	Main purpose
amip (AGCM)	Atmosphere with observed	Time-varying	Time-varying	Time-varying	1979	2021	Evaluation, SST/sea ice

	SSTs and SICs prescribed						forced variability
piControl and/or esm-piControl	Coupled atmosphere-ocean 1850 control	All 1850, CO_2 prescribed concentration or zero emissions	Fixed mean radiative forcing matching historical simulation (i.e. 1850–2021 mean)	Fixed mean value matching first two solar cycles of the historical simulation (i.e. 1850–1873 mean)	1	400+	Evaluation, drift, unforced variability
abrupt-4xCO2	CO_2 prescribed to four times pre-industrial	Same as piControl except CO_2 concentration prescribed to four times piControl	Same as piControl	Same as piControl	1 (branching from year 101 or later of piControl)	300+ (1000)	Equilibrium climate sensitivity, feedback, fast responses
1pctCO2	CO_2 prescribed to increase at 1% yr-1	Same as piControl except CO_2 prescribed to increase at 1% yr-1	Same as piControl	Same as piControl	1 (branching from year 101 or later of piControl)	150	Transient climate sensitivity
historical and/or *esm-hist*	Simulation of the recent past	All time varying, CO_2 prescribed concentration or emission	Time varying	Time varying	1850	2021	Evaluation, baseline for sensitivity studies and scenarios

piClim-Control (AGCM)	Pre-industrial conditions including SST and SIC prescribed	All 1850, CO_2 prescribed concentration	Same as piControl	Same as piControl	1	30	Baseline for model-specific effective radiative forcing (ERF) calculations
piClim-anthro (AGCM)	As *piClim-Control* except present-day anthropogenic forcing	All 2021, CO_2 prescribed concentration	Same as piControl	Same as piControl	1	30	Quantify present-day total anthropogenic ERF
piClim-4xCO2 (AGCM)	As *piClim-Control* except CO_2 set to four times 1850 concentrations	All 1850 except CO_2 prescribed at four times the 1850 concentration	Same as piControl	Same as piControl	1	30	Quantify ERF of 4 × CO_2

3.1.1 Spanning CO_2 concentration- and emission-based simulations

Given the increased prominence of science applications for coupled carbon-climate ESMs in climate stabilization and overshoot and the implications for carbon budgets (Sanderson et al., 2024a), the CMIP7 protocol has been re-designed to encourage participation with models driven with CO_2 emissions as well as specified CO_2 concentrations. The following guidelines seek to maximize comparability between the two sets of simulations:

For models running only with historical CO_2 concentrations (i.e. models that run *historical* only):

- run the *historical*, *abrupt-4xCO2*, and *1pctCO2* experiments, branching from year 100 or later of *piControl*.
- the requested length of *piControl* is enough to allow for comparison to all perturbations including future projections and extensions (if applicable). In other words, the *piControl* should extend as long as the longest perturbation experiment performed.

For models running with BOTH historical CO_2 concentrations and emissions (i.e. models that run *historical* and *esm-hist*):

- run the *esm-hist* experiment, branching from year 100 or later of *esm-piControl.*
- the requirements for concentration-driven experiments (*piControl*, *historical, abrupt-4xCO2 and 1pctCO2)* as above.

For models running with historical CO_2 emissions but NOT planning to run with historical CO_2 concentrations (i.e. models that run *esm-hist* only):

- run the *esm-hist* experiment, branching from year 100 or later of *esm-piControl.*
- run the *abrupt-4xCO2* and *1pctCO2* experiments, branching from year 100 (or later, as per modeling center preference) of *esm-piControl* with CO_2 concentrations as specified in Table 1, but using a pre-industrial value derived from the *esm-piControl* experiment (as discussed in the next paragraph). Note that a *piControl* simulation forced by the same CO_2 concentration is also encouraged to account for any carbon-climate coupling differences between esm-piControl.

Within these general guidelines to accommodate both CO_2 emission- and concentration- driven simulations within the same experimental protocol, the CMIP Panel acknowledges that some additional flexibility in implementation remains necessary. For example, one approach to specifying CO_2 concentrations for *piControl*, *abrupt-4xCO2* and *1pctCO2* would be to take the average of the 30 years (i.e. years 70-99) of esm-*piControl*, with *abrupt-4xco2* and *1pctCO2* CO_2 concentrations also defined relative to the same level. Another approach could be to preserve model 3-D diurnal to seasonal spatial and temporal variability when forced with CO_2 concentrations. Additionally, some modeling centers apply CO_2 concentration forcing as a restoring term to the internal atmospheric tracer with a 1/year time scale (Dunne et al., 2020). With respect to fidelity targets in models forced by CO_2 emissions, the CMIP6 historical CO_2 trend in the CMIP6 *esm-hist* ensemble was biased by -15 to +20 ppm CO_2 by 2014 (Gier et al., 2020). With the causes of these biases and strategies for reconciling models with observations the topic of much recent research (e.g. Hajima et al., 2025), our hope is that the CMIP7 ensemble will witness a substantial reduction in *esm-hist* biases to the point that these simulations can be used alongside historical simulations interchangeably.

3.1.2 Historical forcing data sets

Data used to drive simulations has been referred to within CMIP as “forcings” (Durack et al., 2018). This includes specified values of certain variables (e.g. greenhouse gas concentrations) and/or fluxes at domain boundaries (e.g. emissions of carbon dioxide), depending on the experimental protocol. CMIP7 forcing datasets for *historical* and *esm-hist* simulations are summarized in Table 2. Key changes with respect to CMIP6 include revisions of solar spectral partitioning and geomagnetic referencing (Funke et al., 2024), incorporation of revised volcanic aerosol model (Aubry et al., 2020), satellite (Kovilakam et al., 2020), ice core (Toohey and Sigl, 2017; Fang et al., 2023), and geological (Aubry et al., 2021) records of historical activity across both small and large volcanoes between the pre- and post- satellite era (Chim et al., 2023), comparability of regional emissions of short-lived climate forcers (i.e. aerosols, aerosol precursors, and greenhouse gases) to observations (Hoesly et al., 2023), and refined land-use harmonization (Chini et al., 2023; 2025). The end of the historical period for CMIP7 is 2021, driven by increased uncertainty in more recent estimates in emission of short-lived climate forcers. These and other forcing improvements will be described in the GMD Special Issue on Forcings (https://gmd.copernicus.org/articles/special_issue1307.html) as they become available. Models capable of interactive open biomass burning emissions of CO_2 are encouraged to run with these emissions interactively rather than prescribed from the available datasets except for CO_2 in all concentration-driven runs where CO_2 must be explicitly prescribed (*piControl*, *1pctCO2*, *4xabruptCO2*, and *piClim* experiments). Finally, while there is great interest in providing anomalous freshwater forcing (e.g. Schmidt et al., 2023b), possible datasets to provide such forcing were not able to be validated for formal recommendations at this time.

Table 2: Forcings for *historical, esm-hist* and *amip* experiments by dataset, provider, short description, temporal range, and documentation. Further details on forcings are provided in papers in a separate collection of GMD/ESSD special issue. Note that modeling centers can choose between CO_2 concentrations or emissions from the DECK suite of forcings depending on the simulations. Specification of all the other forcings remains the same between the two types of runs. See https://wcrp-cmip.org/cmip-phases/cmip7/cmip7-forcing-datasets/ for a general overview, https://input4mips-controlled-vocabularies-cvs.readthedocs.io/en/latest/dataset-overviews// for technical details, and https://github.com/PCMDI/input4MIPs_CVs for guidance on current versions of forcings.

Forcing dataset	**Documentation**	**Short description**	**Temporal range**
Anthropogenic short-lived climate forcers (SLCF) and CO_2 emissions	https://input4mips-cvs.readthedocs.io/en/latest/dataset-overviews/anthropogenic-slcf-co2-emissions/	Gridded monthly mean historical emission estimates by sector, and fuel for anthropogenic aerosol and precursor compounds, and CO_2, CH_4 and N_2O.	1750-2023
Open biomass burning emissions	https://input4mips-cvs.readthedocs.io/en/latest/dataset-overviews/open-biomass-burning-emissions/	Gridded monthly estimates of open biomass burning emissions (forests, grasslands, agricultural waste burning on fields, peatlands).	1750-2022
Land use	https://input4mips-cvs.readthedocs.io/en/latest/dataset-overviews/land-use/	Gridded annual estimates of the fractional land-use patterns, underlying land-use transitions, and key agricultural management information.	850-2023
Greenhouse gas historical concentrations	https://input4mips-cvs.readthedocs.io/en/latest/dataset-overviews/greenhouse-gas-concentrations/	Consolidated data sets of historical atmospheric (volume) mixing ratios of 43 greenhouse gases and ozone depleting substances.	1-2022
Stratospheric volcanic SO_2 emissions and aerosol optical properties	https://input4mips-cvs.readthedocs.io/en/latest/dataset-	Stratospheric volcanic SO_2 emissions and aerosol optical properties.	1750-2023

	overviews/stratospheric-volcanic-so2-emissions-aod/		
Ozone concentrations	https://input4mips-cvs.readthedocs.io/en/latest/dataset-overviews/ozone/	To be determined but expected to be - Gridded monthly mean 3-D ozone mixing ratios.	1850-2022
Nitrogen deposition	https://input4mips-cvs.readthedocs.io/en/latest/dataset-overviews/nitrogen-deposition/	To be determined but expected to be - Gridded monthly mean 2-D nitrogen deposition flux provided as dry/wet in the form of oxidised and reduced nitrogen species as in CMIP6	1850-2022
Solar	https://input4mips-cvs.readthedocs.io/en/latest/dataset-overviews/solar/	Daily and monthly mean reconstructed spectral solar irradiance (SSI) for spectral bins covering the wavelength range 10 – 100,000 nm.	1850-2023
Aerosol optical properties/MACv2-SP	https://input4mips-cvs.readthedocs.io/en/latest/dataset-overviews/aerosol-optical-properties-macv2-sp/	Anthropogenic aerosol optical properties for key plumes based on the MACv2-SP parameterization over the 1850-2022 period.	1850-2022
AMIP sea surface and sea ice boundary forcing	https://input4mips-cvs.readthedocs.io/en/latest/dataset-overviews/amip-sst-sea-ice-boundary-forcing/	Merged SST and sea ice concentration based on UK MetOffice HadISST and NCEP OI2	1870-2022

3.1.3 Pre-industrial control forcing

Forcings for the *piControl* experiment seek to establish a baseline climate against which the forced response can be assessed. The approach in CMIP7 follows CMIP6 although current forcing datasets are to be used. Greenhouse gases, anthropogenic and biomass burning aerosols, and land use forcing use constant 1850 values. Solar forcing uses a fixed mean over two solar cycles i.e. the average over 1 January 1850 to 28 January 1873 and volcano aerosol forcing for models that prescribe optical properties use the long-term historical 1850-2021 average values of the historical forcing dataset (Table 2). Averaging is motivated by the observation that multiannual discrepancies in volcanic or solar forcing between *piControl* and *historical* and/or *esm-hist* simulations can lead to drifts (Gregory et al., 2013; Fyfe et al., 2021). Files with the correctly averaged solar and volcanic forcing are provided. The prescribed climatology for stratospheric volcanic aerosol optical properties is characterized by a global annual mean stratospheric aerosol optical depth at 550nm of 0.0135.

3.2 Ocean and land spin-up

Prior to starting a control experiment, climate and Earth System models must be tuned (e.g. Hourdin et al., 2017) and integrated to a quasi-equilibrium initial state such that responses in historical and idealized forcing perturbation experiments can be easily distinguished from the *piControl*. Challenging to achieving quasi-equilibrium initialization of the *piControl* include uncertainties in the state and trends of the 1850 Earth system, model biases, and long timescales out to millennia involved. There are many diverse approaches to developing and spinning up pre-industrial simulations before finalizing the initial conditions for the *piControl* for both land (Sentman et al., 2011) and ocean (Irving et al., 2021; Séférian et al., 2016). While the CMIP7 protocol described here keeps with past precedent in providing no specific requirements for spin-up, previous phases of CMIP provide some guidance on the limits of what is feasible. This includes the C4MIP (Jones et al., 2016) global land and ocean carbon drift tolerance metric of 10 PgC/century for ocean heat content analysis from CMIP6 (Irving et al., 2021) for which GFDL-CM4 demonstrated the highest *piControl* drift of 0.3x10^{24} J/century, or 0.06 C century^{-1}, corresponding to 0.4 W/m2. Similarly, drift in surface temperatures would ideally be kept well below historical warming rates of 1 ^{o}C century^{-1}. Participants are encouraged to provide detailed descriptions of their spin-up methodology and to monitor global energy, water and salinity e.g. via the integrated metrics listed in Appendix 1 and/or save the monthly variables from the *piContro*l data request.

3.3 Support for community driven science

CMIP6 supported broad community engagement by soliciting proposals from self-organized MIPs, many of which had long histories. Twenty-two MIPs were eventually endorsed (https://wcrp-cmip.org/mips/cmip6-endorsed-mips/) and contributed to the CMIP6 request for data. As noted above, this centralized approach required synchronization of the diverse ensemble of MIP activities with forcings provision and data request harmonization on a single timeline.

CMIP7 also supports community driven model intercomparisons by providing forcing data sets, technical specifications, centralized and distributed infrastructure to access data, and standardized open data access to facilitate model simulation and comparison including ongoing logistical facilitation of novel community MIPs. Instead of endorsing entire MIPs as was done in CMIP6, CMIP7 is instead drawing on existing community MIP experiments to assemble compact, targeted ESGF collections of both the mandatory DECK and optional endorsed “fast track” simulations to address specific needs. This change is intended to reduce the burden on modeling centers and community MIPs to deliver experimental designs and simulations on any single timeline. At the same time, the CMIP Panel, the Working Group on Coupled Modelling (WGCM) Infrastructure Panel, infrastructure providers, and CMIP IPO remain committed to providing support for both existing and novel community MIPs to bring fresh questions, hypotheses, and insight for new experiments, constraints, and applications to enrich CMIP community science.

A broad spectrum of modes is available for community MIPs, which may be tightly coupled to CMIP7, for example submitting standardized data to the ESGF; or less tightly constrained by but compatible projects perhaps reusing standards or protocols, or activities which operate completely independently such as nationally and regionally supported research projects outside the auspices of WCRP. In the absence of centralized endorsement and harmonization of individual MIPs, the CMIP Panel and CMIP IPO play a community service role. This includes encouraging best practices in effective experimental design and execution through registration and offers guidelines on how best to develop and run MIPs to conform with CMIP Practices in Appendix 2.

3.4 Assessment Fast Track Experiments

The Assessment Fast Track (AFT) is a set of recommended CMIP7 simulations drawn from Community MIPs intended to support both the direct needs of the climate research community for synthesis and physical science assessment as well as downstream climate services applications. This focused set of priority (but optional) recommendations for CMIP7 simulations include: *near-term prediction and long-term projection* experiments that will provide information critical to satisfying the needs for both short- and long-term planning and for the impacts, mitigation and adaptation communities such as ISIMIP and VIACS as well as high temporal resolution forcing for regionally tailored information through dynamical and statistical downscaling such as CORDEX. CMIP7 goals also include the more classical aspects of systematic assessment with respect to *characterization* of model diversity, *attribution* of the quantitative role of specific mechanisms in driving the forced response, and *process understanding* as per the four Fundamental Research Questions described in Section 2 and listed in Figure 3. More information about the different experiments in Figure 3 is detailed below and in Table 3. Acknowledging that the CMIP7 DECK and Assessment Fast Track experimental protocol will be subject to updates during the project lifetime, a live version of the protocol can be found on the CMIP7 Guidance and Documentation webpages (https://wcrp-cmip.github.io/cmip7-guidance/). This guidance will be versioned, with the latest updates available via doi: 10.5281/zenodo.15704712.

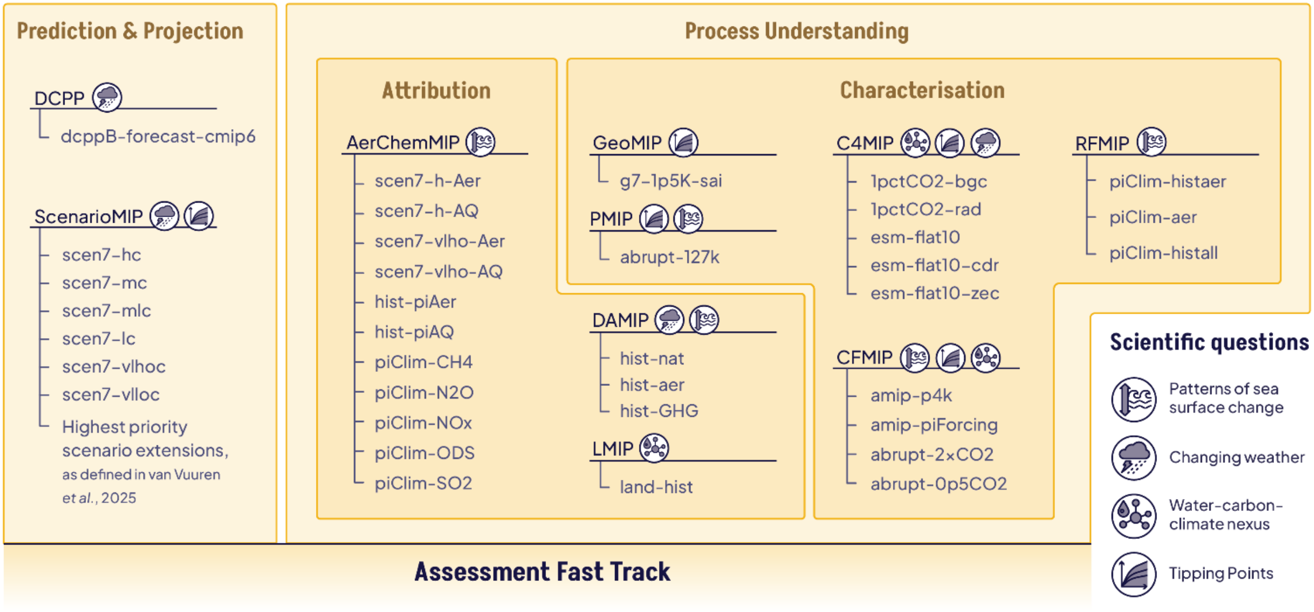

Figure 3: Schematic mapping the four Fundamental Research Questions (Patterns of sea surface warming, Changing weather, Water-carbon-climate nexus, and Tipping points) and four topical areas (Prediction and Projection, Attribution, Characterization, and Process Understanding) onto Assessment Fast Track experiments.

3.4.1 Harmonization to projections

As in previous phases of CMIP, attention to optimizing continuity, or "harmonization" of forcings is necessary across transition from the end of the historical forcing period heavily constrained by observations (Dec 2021 for CMIP7) into projected future scenarios from integrated assessment models through ScenarioMIP (van Vuuren et al., 2025). The Forcings Task Team's harmonization sub-group is working with the ScenarioMIP team on the details of this process, which will be finalized in 2025. The specification of natural forcings in ScenarioMIP simulations include a projected solar cycle (Funke et al., 2024) and a nine-year linear return to the constant prescribed climatology for stratospheric volcanic aerosol optical properties as in piControl, characterized by a global annual mean stratospheric aerosol optical depth at 550nm of 0.0135

3.4.2 Prediction and projection

Prediction experiments in the Decadal Climate Prediction Project (DCPP) and projections in ScenarioMIP provide important bounds on a range of possible near-term and future climate outcomes. Efforts aligned to DCPP exist as an ongoing effort outside of CMIP as the WMO Global Annual to Decadal Forecast (WMO Global Annual to Decadal Climate Update | 1 | World Meteorological Organization). However, there is great interest in generating a recent "snapshot" of decadal prediction ensembles that would include a comprehensive suite of model diagnostics consistent with CMIP data standards beyond the five variables currently made available through the World Meteorological Organization.

In each previous iteration of CMIP, the set of projection experiments included at least one high emissions scenario — initially the 1% idealized CO_2 increase (Washington and Meehl, 1989), then the Special Report on Emission Scenarios (SRES; Nakicenovic, et al., 2000) "business as usual", then an emissions-intensive scenario as part of the Representative Concentration Pathways (RCPs; van Vuuren et al., 2011) and Shared Socioeconomic Pathways (SSPs; Riahi et al., 2017; Meinhausen et al., 2020). Projection scenarios have been re-envisioned for the AFT by the ScenarioMIP community in close coordination with the CMIP Panel and WCRP to improve scenario practical viability and comprehensiveness (van Vuuren et al., 2025). For CMIP7, a medium (M) "current policy" scenario results in emissions roughly similar to present-day out to 2100, while aHigh (H) emissions "policy failure" scenario envisions the possible consequences of policy rollback. In contrast, Medium Low (ML), Low (L), Very Low after High Overshoot (VLHO), and Very Low with Limited Overshoot (VLLO) scenarios explore the results of various levels of emissions mitigation stringency. In prioritizing the running order of scenarios, CMIP7 follows previous CMIP guidance to allow "an adequate separation of the radiative forcing pathways in the long term in order to provide distinguishable forcing pathways for the climate models" (Moss et al., 2010). The CMIP Panel strongly encourages modeling centers to follow a running order of H and VLLO first to span the entire range of radiative forcing among likely futures. VLLO has a particularly important role in the AFT in providing the basis for interactive chemistry branching experiments (Table 3). Downstream modeling communities have expressed particular interest in H and M at the high end and L and VLLO at the low end. Emissions scenarios are produced with Integrated Assessment Models through 2100, while more idealized "Extensions" for each scenario continue to 2500. See van Vuuren et al. (2025) for a comprehensive discussion of these pathways and their technical implementation into scenario projections out to 2100 and extensions to 2500. Once these scenarios and their extensions are finalized, the CMIP Panel will survey coupled modeling centers and downstream modeling communities to issue further guidance on prioritization.

3.4.3 Attribution

One of the key aspects of ongoing CMIP efforts in systematic characterization of model behavior and its relationship to observations is in attributing the climate response to particular forcing changes, e.g., aerosol (AerChemMIP) and radiating forcing (RFMIP) for understanding how individual gases and aerosols affect the energy budget and Detection and Attribution MIP (DAMIP; Gillett et al., 2025) to quantify how different forcings influence climate. These experiments include a combination of single forcing changes and mechanism withdrawal experiments that allow for both the quantification of the impact of individual drivers and the combined responses to explore nonlinearity. From DAMIP, greenhouse gas only, aerosol only, and natural only experiments are prioritized given their broad use in prior assessment reports. These will provide the opportunity to examine model response to historical forcings between 2015-2021 as opposed to the projected forcings used in CMIP6. They will also provide the opportunity to examine the modeled response to updated forcings prior to 2014, since such differences in forcings can impact on the representation of the historical climate evolution in individual models (e.g., Fyfe et al., 2021; Holland et al., 2023; Chemke and Coumou, 2024). Comparison of coupled historical simulations with those in LMIP (and AMIP) allows for attribution of component level biases. The increasing use of models with fully interactive carbon cycles also facilitates attribution of historical changes to emissions (as opposed to concentrations) to understand the impact of individual forcings within the context of an interactive carbon cycle.

3.4.4 Characterization

This set of experiments similarly characterizes model ensemble systematic behavior towards understanding why models produce different outcomes and includes CFMIP for radiative feedbacks, C4MIP to assess carbon cycle-climate feedback strength, GeoMIP to assess geoengineering requirements and impacts of purposeful climate modification, and LMIP for the most direct comparison of land models with observations. As an example of the purpose and interconnectedness of all experiments, an example is provided for RFMIP that seeks to reduce the large uncertainty in effective radiative forcing due to aerosols in both observations (Bellouin et al., 2020) and across models (Smith et al. 2020). Experiment *piClim-aer* characterizes the model-specific effective radiative forcing at present-day (end of *historical*, or 2021 for CMIP7). Experiments *piClim-histall* and *piClim-histaer* are small ensembles of atmosphere-only simulations with fixed sea surface temperatures and sea ice concentrations, which characterize the time-varying effective radiative forcing over the course of the historical period from all natural and anthropogenic forcings and from the temporal evolution of aerosols alone. Further details on the motivation for each experiment and context within the MIP from which it is derived is provided in Table 3.

3.4.5 Process understanding

The AFT experiments (Table 3) were chosen as a practical balance among the number of participating models, and the complexity, resolution, and number of ensemble members for each model (Figure 1) to help distinguish the role of different processes and interactions and local versus remote drivers. Links between the research questions (Section 2) and DECK and AFT experiments include the following:

- Exploration of the *patterns of sea surface warming* and *changing weather* is supported through the updated and extended AMIP and historical experiments included in the DECK, set of projections and near-term predictions and associated diagnostics in Decadal Climate Prediction Project (DCPP), Cloud Feedback (CFMIP) and Radiative Forcing (RFMIP) experiments. The CFMIP and RFMIP experiments also allow exploration of atmospheric feedbacks and identify the role of SSTs in historical evolution and idealized response to forcing. Paleoclimate MIP (PMIP) *abrupt-127k* experiment allows exploration of SST responses to orbital forcing. The single forcing experiments proposed through DAMIP can also help in interpretation of the role of individual forcings in regional historical trends. The linearity of modeled responses to rising CO_2 and feedbacks can be also assessed through comparison of the CFMIP *abrupt-2xCO2* with *abrupt-0p5CO2* experiments. One particularly exciting application of the *esm-flat10-zec* (zero emissions) experiment is the ability to conduct long simulations under climate stabilization to develop better understanding of the statistics of climate extremes.

- The *Water-Carbon-Climate Nexus* can be explored through ScenarioMIP projections, Coupled Climate Carbon-Cycle (C4MIP) and Geoengineering (GeoMIP) experiments. Some of the most pressing societal questions include implications of coupled carbon-climate interactions under a variety of carbon emissions trajectories, particularly under scenarios of climate mitigation (e.g., Carbon Dioxide Removal), interactions of short-lived climate forcers under CH_4, H_2, and greenhouse gas and aerosol emissions trajectories, and advancing process understanding of Earth's radiation budget under purposeful climate modification (e.g., Solar Radiation Management). A series of idealized diagnostic "flat10" experiments in AFT will be used to derive emissions-driven estimates of Transient Response to Cumulative Emissions (TCRE; *esm-flat10*), Zero Emissions Commitment (ZEC; *esm-flat10-zec*) and climate reversibility under declining to negative emissions (*esm-flat10-cdr*; Sanderson et al. 2024b).
- *Tipping Points* can be explored through both the ScenarioMIP projections (*scen7-h*, *scen7-m*, scen7-mlc, *scen7-l, scen7-vlho, and scen7-vllo*) and extended suite of idealized response to constant (*esm-flat10*), zero (*esm-flat10-zec*), and declining to negative (*esm-flat10-cdr*) emissions. Another particularly exciting application of the *esm-flat10-zec* experiment to conduct ensembles of simulations under climate stabilization to develop better understanding of the likelihood of tipping points. The PMIP *abrupt-127k* experiment allows comparison to model response to last interglacial orbital parameters at which Arctic was free of sea ice and temperatures were close to present-day at pre-industrial CO_2.

3.4.6 Single model ensembles

Within the CMIP multi-model ensemble, the participation of single-model multi-member ensembles (e.g. Hawkins and Sutton, 2009) and even "large ensembles" (e.g. Kay et al., 2015) has been shown critical for detection and attribution, notably in DAMIP (Gillett et al., 2025). Note that the DAMIP component of the AFT involves the request for at least three *historical* simulations to compare with three *hist-nat* and *hist-aer*. For CMIP7, the CMIP Panel also strongly encourages the contribution of multiple ensemble members of *historical, esm-hist*, scenario projections and encourage modeling centers to adopt strategies for sampling *piControl* (and/or *esm-piControl*) states of low frequency climate variability (such as 20 year intervals) for the initial conditions of perturbation simulations as preferable to incremental perturbations or short intervals to avoid aliasing internal variability in the pre-industrial ensemble mean.

Table 3: Overview of the CMIP7 AFT experiments with experiment name, experiment primary goal, MIP short name from which it is derived, required model components, brief experiment overview description, primary goal of combined experiments in the MIP from which it is derived, minimum number of years per experiment, and its main purpose. Forcings include Greenhouse Gases (GHG), Short Lived Climate Forcers (SLCF), Aerosols (AER), and carbon BioGeoChemistry (BGC). Superscripts on the experiment short name represent 1) Prediction & Projection, 2) Attribution, 3) Characterization, and 4) Process Understanding. Superscripts on the MIP indicate applicability of the experiments to the synthesizing research questions (Section 2) of a) Patterns of sea surface warming, b) Changing weather, c) The Water-Carbon-Climate nexus, and d) Tipping points. The esm- prefix indicates

experiments are forced by CO2 emissions rather than CO2 concentrations. Note that for all AFT experiments that require a historical, present day, or scenarios, the CMIP7 protocol requires slight modification of the original CMIP6 experimental design to be updated to CMIP7 historical (Section 3.1.2) and ScenarioMIP (van Vuuren et al., 2025) forcing.

Experiment short name	**Primary Goal of Experiment**	**MIP short name and protocol paper**	**Required model components**	**Experiment overview**	**Years of simulation**
esm-scen7-h-AQ (esm-scen7-h-Aer for models without interactive chemistry)[2,4]	Quantifying the role of future mitigation actions on SLCFs for climate and air quality responses.	AerChemMIP[a] Collins et al., 2017	AOGCM AER (plus CHEM for -AQ experiments)	Future scenario esm-scen7-vllo/h with high aerosol and tropospheric non-methane ozone precursor emissions	= 79 x 3 = 237 fixed SST
esm-scen7-vllo-AQ (esm-scen7-vllo-Aer for models without interactive chemistry) [2,4]					79 x 3 = 237 AMIP
hist-piAQ (hist-piAer for models without interactive chemistry) [2,4]	Diagnosing climate and air quality responses to regionally inhomogeneous evolution of historical SLCF emissions to reduce uncertainty in our understanding of human-influenced climate change.		AOGCM AER CHEM	Historical simulation with pre-industrial aerosol and tropospheric non-methane ozone precursors	172 x 6 =1032 coupled

piClim-X (where X = CH4, N2O, NOX, ODS, SO2) [2,4]	Quantifying ERF climate feedback for individual SLCFs to assess their contributions to the radiation imbalance.		AGCM CHEM (except piClim-SO2 where AER required instead of CHEM)	Single forcing AMIP experiments with pre-industrial climatology with present-day CH_4, N_2O, NO_X, ODS, SO_2	43 x 6 =258 fixed SST
1pctCO2-bgc[3,4]	Idealized biogeochemical response to CO_2 concentrations	C4MIP[b,c,d] Jones et al., 2016; Sanderson et al., 2024a; Sanderson et al., 2024b	AOGCM BGC	Biogeochemically-coupled version of 1 percent per year increasing CO_2 experiment	150 coupled
1pctCO2-rad[3,4]	Idealized radiative response to CO_2 concentrations			Radiatively-coupled version of 1 percent per year increasing CO_2 experiment	150 coupled
esm-flat10[3,4]	Idealized coupled response to constant positive CO_2 emissions			10 PgC/yr constant CO_2 emissions experiment	100+ coupled
esm-flat10-cdr[3,4]	Idealized coupled response to reducing positive to negative CO_2 emissions after esm-flat10 to diagnose climate response and reversibility after all cumulative anthropogenic emissions are removed			10 PgC/yr constant CO_2 removal / negative emissions experiment	100+ coupled

esm-flat10-zec[3,4]	Idealized coupled response to zero CO_2 emissions after esm-flat10 to diagnose the Zero Emissions Commitment (ZEC) - the additional warming after the cessation of emissions required to inform remaining carbon budget estimates.			Zero-emissions commitment CO_2 experiment	100+ coupled
amip-p4k[3,4]	Atmospheric response to idealized ocean warming	CFMIP[a,c,d] Webb et al., 2017	AGCM	AMIP experiment with uniform 4K SST increase in ice-free regions	43 AMIP
amip-piForcing[3,4]	Atmospheric response to SST and SIC boundary conditions without corresponding forcings			AMIP experiment but from 1870 to the present with constant pre-industrial forcing levels (anthropogenic and natural).	153AMIP
abrupt-2xCO2[3,4]	Idealized coupled response to doubled CO2 - similar to 21st century – and in some cases very different from scaled 4x response.		AOGCM	Abrupt doubling of CO2 concentration relative to piControl	300 coupled
abrupt-0p5CO2[3,4]	Idealized coupled response to half CO2			Abrupt halving of CO_2 concentration relative to piControl	300 coupled

	concentration similar to LGM				
hist-aer[2,4]	Coupled response to anthropogenic aerosol forcing	DAMIP[a,b] Gillett et al., 2025	AOGCM	Time evolving historical and then medium scenario aerosol forcings while all other forcings held at piControl levels.	3 x 172 = 516 coupled
hist-GHG[2,4]	Coupled response to anthropogenic GHG forcing			Historical simulation with time evolving greenhouse gas forcing only and all other forcings at pre-industrial levels.	3 x 172 = 516 coupled
hist-nat[2,4]	Coupled response to natural solar and volcano forcing			Natural-only historical simulations (solar irradiance, stratospheric aerosol)	3 x 172 = 516 coupled
dcppB-forecast-cmip6[1]	Predicting and understanding forced climate change and internal variability up to 10 years into the future	DCPP[b] Boer et al., 2016	AOGCM	Forecast initialized from observations with forcing from ssp245 (2025-2036)	10 x 10 = 100 coupled
g7-1p5K-sai[3,4]	Coupled response to idealized stratospheric aerosol injection to arrest warming to better understand possible consequences of	GeoMIP[d] Visioni et al., 2024	AOGCM	Stratospheric Sulfur forcing held constant to stabilize climate at 1.5C warming starting from year 2035 of Medium Projection Scenario	50 coupled

	purposeful solar radiation modification				
land-hist[2,4]	Evaluate land processes in DECK simulations to identify systematic biases and their dependencies and estimate terrestrial energy/water/carbon variability	LMIP[c] Van den Hurk et al., 2016; D. Lawrence, personal communication	LAND	Land-only historical simulation from 1850 to 2022.	172 land only
abrupt-127k[3,4]	Coupled response to orbital changes associated with last interglacial leading to Arctic warming and sea ice loss and translation of high latitude climate forcing to lower latitudes	PMIP[a,d] Otto-Bleisner et al., 2017 Sime et al. (2023)	AOGCM	Abrupt orbit and greenhouse gases of 127 ka before present	100 coupled
piClim-aer[3,4]	Atmospheric response to present-day anthropogenic aerosols to attribute current warming and project committed future warming	RFMIP/ AerChemMIP[a]	AGCM	Effective radiative forcing by present-day aerosols	30 fixed SST
piClim-histaer[3,4]	Atmospheric response to historical changes in anthropogenic	RFMIP[a] Pincus et al., 2016 Smith et al., 2020		Historical and future transient effective radiative forcing from aerosols	251 fixed SST

	aerosols to attribute current warming and calibrate emulators				
piClim-histall[3,4]	Atmospheric response to historical changes in anthropogenic aerosols and WMGHG to assess why model warming differs from the observed record and estimate model forcing to compare with process models			Historical and future transient effective radiative forcing from all forcers	251 fixed SST
scen7-h, and/or esm-scen7-h[1]	Climate policy roll-back scenario with low renewable technology development and high emissions	ScenarioMIP[b,d] van Vuuren et al., 2025	AOGCM	Future projected simulations out to 2100 representing mitigation pathways of current policy, policy failure, policy success and overshoot.	79 coupled
scen7-m and/or esm-scen7-m[1]	Current policy scenario without further strengthening or roll-back				
scen7-ml, and/or esm-scen7-ml[1]	Modest mitigation policy scenario short of meeting Paris goals				
scen7-l and/or esm-scen7-l[1]	Scenario consistent with staying likely below 2 deg C				

scen7-vlho, and/or esm-scen7-vlho[1]	Delayed mitigation policy scenario with overshoot but rapidly intensifying CDR to return to 1.5 C				
scen7-vllo and/or esm-scen7-vllo[1]	Rapid near-term emissions reduction scenario to limit warming to about 1.5 C				
Scenario extensions[1]	Please refer to van Vuuren et al, 2025 for selection of extensions.			Future projected simulation extensions out to 2150-2500 representing pathways of current policy, policy failure, and mitigation.	Minimum 50 to maximum 400 coupled per extension

4. Evolving CMIP to meet changing needs and opportunities

4.1 The CMIP International Project Office and associated Task Teams

The process leading to the CMIP7 experimental design differs substantially from past iterations of CMIP. In light of CMIP's widening roles, and in response to the increasing demands of a growing user base, WCRP secured the establishment of a CMIP International Project Office (CMIP IPO) in 2020 through WMO Resolution 67 (https://www.wcrp-climate.org/images/modelling/WGCM/WGCM23/Presentations/5b_WGCM23-WMO-Res67_CMIP-IPO.pdf). The provision of full-time staff supports the development and delivery of CMIP consistent with the level of international investment and use. With the IPO in place, the CMIP process is institutionally organized and increasingly consistent with the professional standards of transparency, inclusiveness, and equity. The IPO also brings the capacity for full documentation of discussions and decisions, coordination of the various panels and task teams (https://wcrp-cmip.org/cmip7-task-teams/) allowing many more scientists (including early career researchers) to engage. Thus far, seven task teams each involving about a dozen people have contributed to the planning of CMIP7 to date. These include task teams on climate forcings, data access, data citation, data request, model benchmarking, model documentation, and strategic ensemble design as well as smaller working groups on spin-up, harmonization of historical and projection forcing datasets. Thematic diagnostic groups and sustained-mode initiatives are also being established, with teams focusing on the CMIP carbon footprint, controlled vocabularies, and quality control/assurance. The IPO has also facilitated broader community engagement and consultation.

4.2 Maturing infrastructure and support capabilities

Key CMIP7 efforts to improve the utility and interpretation of CMIP data have focused on open community consultation processes for revised standards for model documentation, output data request, and benchmarking. The widening use of CMIP data has underscored the uneven nature of model documentation. Downstream users in particular report frustration with descriptions diffused across model description and intercomparison journal articles, web sites, databases, and technical documents. To balance the needs of users with the limited resources at modeling centers for documentation, the CMIP7 Model Documentation Task Team has developed a protocol for Essential Model Documentation (EMD): a high-level description required of all participating models. Building from similar efforts in previous CMIP phases, it contains questions soliciting information and associated references on formulation to allow differences between models be easily compared and understood. The process of collating and reviewing community input into the model output data request has also extensively been revised. The CMIP7 Data Request starts from a set of 132 Earth System Model Baseline Climate Variables (Juckes et al., 2025) identified as being of high general utility. To enable broad access and scrutiny, scientific steering groups in five thematic areas (atmosphere, ocean & sea-ice, land & land-ice, impacts & adaptation, and Earth system) were convened with representation from 106 authors from 25 countries. These teams, working with the CMIP IPO, Data Request Task Team, and WGCM Infrastructure Panel, consolidated data requirements from MIPs and public consultation into a single comprehensive, or “harmonized” data request for the CMIP7 AFT issued in three major releases, starting with version 1.0 in November 2024 (see https://wcrp-cmip.org/cmip7/cmip7-data-request/), version 1.1 in January 2025, and version 1.2 in April 2025.

To better support automation of diagnostic evaluation, the Model Benchmarking Task Team has been working to incorporate available open-source evaluation and benchmarking packages into the Rapid Evaluation Framework (REF) and into ESGF to support more comprehensive assessment of model performance and simulation for various potential end users and applications. This community owned evaluation framework, built upon, and compatible with, existing community evaluation packages incorporates an application programming interface for executing metrics generation from a suite of community evaluation packages. The REF allows the full integration of the evaluation tools into the CMIP publication workflow, and their diagnostic outputs to be published alongside the model output on the ESGF through an easily accessible website (see https://wcrp-cmip.org/cmip-phases/cmip7/rapid-evaluation-framework/ for more information). Another dimension of expanded access and coordinated activity in CMIP7 is the Fresh Eyes on CMIP (https://wcrp-cmip.org/cmip7-task-teams/fresh-eyes-on-cmip/) - an early career researcher activity coordinated through the IPO.

5. Summary

CMIP7 continues the pattern of evolution and adaptation building from CMIP6, keeping minimal requirements of DECK and flexibility of infrastructure but switching from endorsing a broadly unconstrained suite of MIPs in favor of only a targeted set of experiments. As a means of clarifying some of the unifying science challenges motivating model intercomparison, CMIP7 science priorities are planned to address the following fundamental research questions (Section 2) relating to: 1) Patterns of sea surface warming, 2) Changing extremes, 3) The Water-Carbon-Climate nexus, and 4) Tipping Points which are well-aligned with the WCRP2019-2028 Science Objectives. The CMIP7 Assessment Fast Track (AFT) experiments (Table 3) are proposed to both help answer these guiding research questions and address the requirements of prediction and projection (3.7.1), attribution (3.7.2), characterization (3.7.3), and process understanding (3.7.4). While CMIP continues to sit at the heart of internationally coordinated climate and Earth system science within the WCRP, a significant part of the AFT and other aspects of the evolving activities also support the emerging communities focused on Climate Service activities.

CMIP has striven to meet increasing and broadening scientific and service demands while remaining responsive to the individual priorities and resource limitations of the modeling centers. The revised DECK and AFT recommendations (Section 3) are provided as guidance to modeling centers as they prioritize application of limited computational and human resources for CMIP7 participation. Particularly exciting among the CMIP7 opportunities is the ability to leverage growing model comprehensiveness and maturity of CO_2 emissions-forced ESMs to explore proposed carbon and climate mitigation solutions and the Earth system consequences of stabilization and overshoot and role of changing atmospheric composition, extremes and tipping points.

From consultations with modeling centers and forcings providers, the CMIP Panel anticipates the CMIP7 generation of forcings and models to have improved representation of historical climate changes in addressing some CMIP6 deficiencies. The inclusion in HighResMIP2 (Roberts et al., 2024) of models capable of representing tropical cyclones, mesoscale weather systems and eddying ocean interactions brings exciting new potential for characterization of extremes, while the re-characterization of future pathways into mitigation policy “success” and “failure” relative to “current policy” and highlighted experiments with models capable of running with CO_2 emissions provide paths for simplifying communication of the Earth system consequences under different policy options and answering emerging questions.

As the applications of CMIP data continues to widen into new contexts such as artificial intelligence and machine learning (AI/ML) and new communities including the private sector, the question of assuring “fitness-for-purpose” and the limitations of appropriate use of model contributions grows in importance. CMIP is working to address the growing pressure from stakeholders involved in adaptation and risk mitigation to provide guidance on appropriate use of individual models and the multi-model ensemble through the Rapid Evaluation Framework (REF; Section 4.2; Appendix 3; https://wcrp-cmip.org/rapid-evaluation-framework). As climate emulators based on AI/ML techniques mature and compete with classical physical-dynamical Earth system models to run large ensemble or downscale information to a more local scale, they may enable the construction of more structured ensembles from selected models such that a priori model pre-selection and sub-sampling (Appendix 3) become more viable in future phases of CMIP.

CMIP has evolved over its several phases to provide critical services to the broader scientific community through support for protocols including forcing/input data, output conventions, contributions from modeling centers, and mechanisms for data distribution. This chain of end-to-end solutions necessary for coupled model intercomparison is a facility useful for answering a multitude of questions for which CMIP standards, protocols, infrastructure, and experiments provide context. Given this established and ongoing importance of CMIP, it is important to recognize the ongoing challenges to sustainability of the CMIP process. While CMIP has benefited handsomely from the creation of the dedicated IPO, the lack of structural funding for forcings providers, modeling centers, infrastructure providers, and data users forces ad hoc participation based on national funding with diverse priorities. While this mode of funding has proven exceedingly successful in keeping research quality at the forefront, its highly episodic nature has proven challenging to transition to more continuous or sustained modes of information provision.

While the effort described above for CMIP in its 7th phase continues as a fundamentally research driven activity, efforts are also underway to build on aspects of CMIP into a more sustained mode. With the ever-increasing urgency of robust and actionable information for climate change assessment, adaptation and mitigation and predictions on seasonal to decadal timescales, the climate community in general (e.g. Schmidt et al., 2023a; Jakob et al., 2023; Stevens, 2024) and CMIP specifically (Hewitt et al., in preparation) have been pursuing ways to support sustained extension of historical forcings, applications of models, and their data provision. CMIP has also identified challenges in the transition of the research mode of funding, human and computational resources, cultures and reward systems along the path to sustained activity and seeks broad community engagement through WCRP and WMO to continue pressing forward on next generation solutions. These efforts include a recent workshop in October 2024 to explore a “Pathway to regular and sustained delivery of climate forcing datasets” (https://wcrp-cmip.org/event/forcings-workshop/).

Moving forward, CMIP is evolving to support the ever-increasing diversity of climate and Earth system questions that require a multiverse of models across resolution and comprehensiveness (Figure 1). As this diversity in model structure and applications expands, CMIP strives to offer a platform that enables intercomparison and hybridization of these approaches to support the international coupled modeling community to understand our present and future climate and their changes and impacts on the Earth system.

Appendices

Appendix 1

To characterize any model simulation performed before the initial year of piControl (spin-up; Section 3.2), it is recommended that modeling centers save model initial conditions as well as the following integrated annual metrics for provision to the CMIP IPO for public dissemination.

Metric	**Justification**
Top Of Atmosphere radiative imbalance and albedo [rsdt, rsut, rlut]	Interpretation of the evolving energy input into the system
Global mean SST [tos]	SST stability is essential
Ocean heat content – upper and lower if possible [thetaoga, bigthetaoga]	To first order, TOA and ocean heat content change should balance. Upper and lower ocean heat content is preferable – if not total.
Total ocean salt content [soga]	Check that the ocean is conserving salt
Total ocean mass and volume [masscello, volcello]	
Net surface heat flux (into ocean) [hfds, hfcorr]	Check with TOA and heat content (but need to think about ice)
Net surface freshwater flux into ocean and/or global mean precipitation	Check with ocean volume (but need to think about ice)
Northern and southern hemisphere sea ice volume/mass min and max [sivoln, sivols]	
AMOC [msftyrho, msftyz]	Maximum of MOC in Atlantic
Global mean albedo [rsdt, rsut]	
Snow cover – total area? [sncls]	
CO2mass	Integral of atmospheric CO2 concentration
net carbon flux atmosphere-ocean (global integral fgco2)	Understand if any remaining C relocation between the reservoirs is present at the end of spin-up, can be calculated from deltas from

	total land/ocean/permafrost carbon pools. This can be further detailed. e.g., Land carbon can be distinct between soil/vegetation/permafrost, ocean carbon can be distinct between DIC/DOC/POC/surface ocean/deep ocean, ...
net carbon flux atmosphere-land (nbp)	This may need to be derived if terms like fire and land use are treated separately
Net permafrost carbon flux	
Sediment weathering flux / riverine C flux (icriver, ocriver, fric, froc)	Necessary for mass balance within the ocean. There are separate terms for inorganic and organic carbon
Diagnosed CO_2 emissions	In case of CO_2 concentration or emissions driven spin-up, respectively, to assess the total C balance of the model.
intCVeg	Integral of Carbon in Vegetation (Three of these four land carbon metrics would be useful to track drift in stocks)
intCsoil *	Integral of Carbon in soil
intCLitter	Integral of Carbon in litter
intCLand	Integral of Carbon on Land
intdic	Integral dissolved inorganic carbon concentration
intCProduct	Integral of harvested Carbon from land use (cLand=cVeg+cLitter+cSoil+cProduct)
intAlk	Integral dissolved alkalinity concentration
intO_2	Integral dissolved oxygen concentration
intNO_3	Integral dissolved nitrate concentration
Total water storage	sum of snow water equivalent and soil moisture in all layers, useful to track drift in water budget

Appendix 2

General guidance on setting up a MIP

CMIP's long experience in coordinating model intercomparisons has helped identify a set of practices (up to date version can be found at https://doi.org/10.5281/zenodo.10572155) that allow broad participation and efficient use of resources, which are summarized here.

1. Articulate the hypothesis: Clearly define what new knowledge will be gained by the experiments. MIPs that define key metrics that can be calculated and compared with observed quantities are particularly useful in this regard.
2. Clarify the experimental design and data requirements: Experimental designs are most effective when they are able to distinguish areas of robust model agreement and inter-model differences. Clear design and description of individual experiments and data requirements is essential to ensure uniform conformance to protocols and production of comparable results. Targeted sizing of the experimental design (in terms of both runs and data requirements) helps limit the environmental footprint of performing the MIP simulations.
3. Leverage past experience: An awareness of previous model experiments and care in avoiding unnecessary duplication frees resources and focuses effort on novel questions. Designs explicitly taking into account the extent to which modestly different forcings, experiments, or model versions can provide compelling motivation for new experiments.
4. Develop prototype experiments: Performing prototype experiments with at least one model prior to proposing MIP experiments provides critical justification of why initial results are insufficient and need to be augmented with results from a multi-model ensemble. Identification of dependencies or links to existing (or proposed) experiments and associated available simulations provides a comprehensive perspective on the full requirements for participation.
5. Foster transparent and inclusive collaboration: MIPs co-designed by a wide range of individuals, communities, and institutions contributing ideas, simulations, results, or analysis help move the field forward. Reaching out early to modeling centers and/or other participants can help secure sufficient commitments to assure the experimental goals can be met. MIPs are encouraged to consider all aspects of diversity (e.g., geographical, gender, career stage) when building their leadership team in line with WCRP goals (see Section 6 WCRP Guidelines on Membership and Responsibilities)
6. Coordinate with other MIPs: Consider registering the MIP. This includes a brief description of initial plans and is meant to identify potential duplications and foster opportunities to coordinate across MIP activities. Such coordination is particularly helpful for avoiding naming clashes, which can create confusion for modelling teams and downstream data users alike.
7. Document the approach comprehensively: Description papers subject the MIP design to a process of peer review. Such papers provide the goals of the MIP and the rationale for each of the planned experiments. Defining the experiment protocols as clearly as possible helps avoid confusion and highlight possible areas of departure between modeling center implementations. "Living" experiment documentation on a website or other easily accessible platform can ensure that up-to-date information is readily available for those seeking to conduct the experiments.
8. Prioritize anticipated experiments: Explicit prioritization ("tiers") of experiments allows contributors to usefully participate at whatever level of effort best suits them for a spectrum of levels of engagement.
9. Support contributors and users: Anticipate how the data will be prepared and distributed so that the scientific findings can be published including testing diagnostics across models to assure data comparability.

10. Acknowledge contributions: Where MIP analysts are distinct from the groups contributing results encourage inclusion of data providers as co-authors (especially in early publications). Data citation is a further mechanism of acknowledgment.

Conforming with CMIP Practices

In addition to following the above “best practices”, a MIP may want to take advantage of the data standards and infrastructure that support the most recent phase of CMIP. In some cases, the CMIP panel and IPO may be able to provide additional input and services that may increase the potential scientific impact of a MIP. Insistence on the latest standards and adoption of the same controlled vocabularies used in previous CMIP phases can reduce the overhead on modeling group participation and facilitate community analysis of MIP results. While the CMIP7 technical specifications are still under development, they will rely heavily on the CMIP6 requirements which were discussed generally in Balaji et al. (2018) and were fully detailed on the CMIP6 website in the Guide to CMIP6 Participation.

Appendix 3: Model sub-selection

Noting that the number of models contributed to CMIP has grown substantially from CMIP3 to officially over 100 models in CMIP6 and that the computational, energy, and human resources available for CMIP-related activities is limited, the design phase for CMIP7 explored options for sub-sampling the ensemble by pre-selecting models for individual experiments with an eye towards optimizing computational efficiency. The final design, however, does not include a pre-selection of models. The reasons for this decision are laid out in this appendix.

Support for pre-selection of models comes from several bases, including the recent weighting of CMIP6 model output conducted in multiple studies and applications. One of the important departures of the IPCC 6th Assessment from those previous was a shift towards a synthesis of multiple lines of evidence to inform future climate uncertainty ranges (using a combination of ESM ensembles, observations and emulators). This was in part due to a subset of models which were deemed to exhibit historical warming inconsistent with observations (Hausfather et al., 2023). Potential mechanisms for direct model weighting on global warming response have been proposed by some authors (Massoud et al., 2023), while others propose multivariate weighting of models based on aggregate skill and independence (Sanderson et al., 2017, Brunner et al., 2020). It is also recognized in extensive literature (Knutti et al., 2013) that the diversity of current models arises from a smaller number of lineages which maintain dependency between them in the algorithmic structure and behavior (e.g., CESM to NorESM, E3SM, CCMC, BCC-CSM), which some studies have recommended as a strategy for weighting (Kuma et al., 2023).

There are also several strong arguments against pre-selection of models. In many cases, similarly structured models can behave very differently despite often common ancestry. For example, in CMIP6, the atmospheric component of NorESM2 is very close to that of CESM2, yet CESM2 had one of the highest equilibrium climate sensitivities at 5.2K and NorESM2-LM had one of the lowest at 2.5K (Meehl et al., 2020, Table 2). Results from Perturbed Parameter Ensembles also demonstrate that small changes in parameter tuning can yield strongly differing results from the same model (Yamazaki et al., 2021), which makes it challenging to determine how to balance ensuring independence with spanning as broad a range of uncertainty space as possible. While many models participating in CMIP include different configurations of the same trunk model (ESM, high resolution, alternative physics), this potential source of duplicity often provides valuable dimensions of diversity include not only the most comprehensive and high-resolution models but also more computationally efficient models which generally participate in targeted community science activities within CMIP. Further, even if it is feasible to choose the "best" models for a particular task, there are several benefits to a diverse ensemble which spans a wide range of plausible behavior. Insights into mechanisms and constraints on future projections such as "emergent constraints" benefit from the full range of responses that can allow linkages between aspects of the model representation and forced response to be identified. For example, Swaminathan et al. (2024) shows that many metrics of crucial interest are uncorrelated with Equilibrium Climate Sensitivity (ECS) such that many high ECS models in CMIP6 considered outside of the "probable" range have very good evaluation scores on many metrics and that having a lower ECS is not necessarily a measure of quality.

Model spread in future climate response cannot be not known in advance, and only in ensemble post-processing is it evident how process and technical improvements translate into ensemble performance and projection spread. While immensely valuable in combining multiple lines of evidence to constrain the global temperature response once the ensemble is mature, these approaches cannot be used a priori to select models to participate in CMIP experiments because model simulations are not yet available, making objective pre-selection of CMIP7 model variants effectively impossible. Further, such techniques are highly dependent on the metric chosen - two models may exhibit highly similar warming patterns, but different precipitation or carbon cycle responses - for example. Any attempt to pre-select independent models would require a highly multivariate approach. Studies such as Peatier (2024) and Sanderson (2017) also suggest that as the number of metrics included in an assessment increase, the ability to distinguish skill and similarity in that space weakens (even post-hoc) such that the more metrics are considered, the less significant the differences between models becomes in terms of overall performance and the more arbitrary the weighting. As such, it is not desirable to filter potentially useful and unique models until their historical performance and basic metrics of future climate response are known.

In contrast, post-selection and model weighting strategies have proven immensely useful for downstream and targeted community science activities which are able to select models based on simulations in the CMIP7 DECK and Assessment Fast Track in cases when desired diagnostic behavior is well defined. There are several examples of frameworks developed through CORDEX for sampling based on metrics for different regions (e.g., Grose et al., 2023, Nguyen et al., 2024). In many cases, however, these configuration-specific model variants are already effectively designed for specific parts of CMIP (e.g., high resolution for HighResMIP, interactive chemistry for AerChemMIP, interactive carbon cycle for C4MIP).

In the absence of pre-selection modeling centers might help fill uncertainty space by consulting results from the Rapid Evaluation Framework (REF), identifying gaps in model diversity across dimensions such as CO_2 and aerosol sensitivity, temperature and precipitation bias patterns, carbon response patterns, etc., and contributing simulations to fill uncertainty space towards yielding new information to robustly fill out the ensemble.

Data availability

The model output from the DECK and Assessment Fast Track simulations described in this paper will be distributed through the Earth System Grid Federation (ESGF). As in CMIP6, the model output with associated metadata and documentation will be freely accessible through data portals.

Author contribution

JD prepared the manuscript with contributions from all the co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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References

Armour, K. C., Proistosescu, C., Dong, Y., Hahn, L. C., Blanchard-Wrigglesworth, E., Pauling, A. G., Wills, R. C. J., Andrews, T., Stuecker, M. F., Po-Chedley, S., Mitevski, I., Forster, P. M., and Gregory, J. M.: Sea-surface temperature pattern effects have slowed global warming and biased warming-based constraints on climate sensitivity, Proceedings of the National Academy of Sciences, 121, https://doi.org/10.1073/pnas.2312093121, 2024.

Arneth, A., F. Denton, F. Agus, A. Elbehri, K. Erb, B. Osman Elasha, M. Rahimi, M. Rounsevell, A. Spence and R. Valentini: Framing and Context. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. https://doi.org/10.1017/9781009157988.003, 2019.

Aubry, T. J., Engwell, S., Bonadonna, C., Carazzo, G., Scollo, S., Van Eaton, A. R., Taylor, I. A., Jessop, D., Eychenne, J., Gouhier, M., Mastin, L. G., Wallace, K. L., Biass, S., Bursik, M., Grainger, R. G., Jellinek, A. M., and Schmidt, A.: The Independent Volcanic Eruption Source Parameter Archive (IVESPA, version 1.0): A new observational database to support explosive eruptive column model validation and development, Journal of Volcanology and Geothermal Research, 417, 107295, https://doi.org/10.1016/j.jvolgeores.2021.107295, 2021.

Aubry, T. J., Toohey, M., Marshall, L., Schmidt, A., and Jellinek, A. M.: A new volcanic stratospheric sulfate Aerosol Forcing Emulator (EVA_H): comparison with interactive stratospheric aerosol models, Journal of Geophysical Research Atmospheres, 125, https://doi.org/10.1029/2019jd031303, 2019.

Balaji, V., Taylor, K. E., Juckes, M., Lawrence, B. N., Durack, P. J., Lautenschlager, M., Blanton, C., Cinquini, L., Denvil, S., Elkington, M., Guglielmo, F., Guilyardi, E., Hassell, D., Kharin, S., Kindermann, S., Nikonov, S., Radhakrishnan, A., Stockhause, M., Weigel, T., and Williams, D.: Requirements for a global data infrastructure in support of CMIP6, Geoscientific Model Development, 11, 3659–3680, https://doi.org/10.5194/gmd-11-3659-2018, 2018.

Bellenger, H., Guilyardi, E., Leloup, J., Lengaigne, M., and Vialard, J.: ENSO representation in climate models: from CMIP3 to CMIP5, Climate Dynamics, 42, 1999–2018, https://doi.org/10.1007/s00382-013-1783-z, 2013.

Bellouin, N., Quaas, J., Gryspeerdt, E., Kinne, S., Stier, P., Watson-Parris, D., Boucher, O., Carslaw, K.S., Christensen, M., Daniau, A.L. and Dufresne, J.L.: Bounding global aerosol radiative forcing of climate change. Reviews of Geophysics, 58(1), https://doi.org/10.1029/2019RG000660, 2020.

Beusch, L., Gudmundsson, L., and Seneviratne, S. I.: Crossbreeding CMIP6 Earth system models with an emulator for regionally optimized land temperature projections, Geophysical Research Letters, 47, https://doi.org/10.1029/2019gl086812, 2020.

Boer, G. J., Smith, D. M., Cassou, C., Doblas-Reyes, F., Danabasoglu, G., Kirtman, B., Kushnir, Y., Kimoto, M., Meehl, G. A., Msadek, R., Mueller, W. A., Taylor, K. E., Zwiers, F., Rixen, M., Ruprich-Robert, Y., and Eade, R.: The Decadal Climate Prediction Project (DCPP) contribution to CMIP6, Geoscientific Model Development, 9, 3751–3777, https://doi.org/10.5194/gmd-9-3751-2016, 2016.

Borodina, A., Fischer, E. M., and Knutti, R.: Models are likely to underestimate increase in heavy rainfall in the extratropical regions with high rainfall intensity, Geophysical Research Letters, 44, 7401–7409, https://doi.org/10.1002/2017gl074530, 2017.

Boulton, C. A., Lenton, T. M., and Boers, N.: Pronounced loss of Amazon rainforest resilience since the early 2000s, Nature Climate Change, 12, 271–278, https://doi.org/10.1038/s41558-022-01287-8, 2022.

Brunner, L., Pendergrass, A. G., Lehner, F., Merrifield, A. L., Lorenz, R., and Knutti, R.: Reduced global warming from CMIP6 projections when weighting models by performance and independence, Earth System Dynamics, 11, 995–1012, https://doi.org/10.5194/esd-11-995-2020, 2020.

Buontempo, C., Burgess, S. N., Dee, D., Pinty, B., Thépaut, J.-N., Rixen, M., Almond, S., Armstrong, D., Brookshaw, A., Alos, A. L., Bell, B., Bergeron, C., Cagnazzo, C., Comyn-Platt, E., Damasio-Da-Costa, E., Guillory, A., Hersbach, H., Horányi, A., Nicolas, J., Obregon, A., Ramos, E. P., Raoult, B., Muñoz-Sabater, J., Simmons, A., Soci, C., Suttie, M., Vamborg, F., Varndell, J., Vermoote, S., Yang, X., and De Marcilla, J. G.: The Copernicus Climate Change Service: Climate Science in Action, Bulletin of the American Meteorological Society, 103, E2669–E2687, https://doi.org/10.1175/bams-d-21-0315.1, 2022.

Chase, A. B., Weihe, C., and Martiny, J. B. H.: Adaptive differentiation and rapid evolution of a soil bacterium along a climate gradient, Proceedings of the National Academy of Sciences, 118, https://doi.org/10.1073/pnas.2101254118, 2021.

Chemke, R. and Coumou, D.: Human influence on the recent weakening of storm tracks in boreal summer, Npj Climate and Atmospheric Science, 7, https://doi.org/10.1038/s41612-024-00640-2, 2024.

Chim, M. M., Aubry, T. J., Abraham, N. L., Marshall, L., Mulcahy, J., Walton, J., and Schmidt, A.: Climate projections very likely underestimate future volcanic forcing and its climatic effects, Geophysical Research Letters, 50, https://doi.org/10.1029/2023gl103743, 2023.

Chim, M. M., Aubry, T. J., Smith, C., and Schmidt, A.: Neglecting future sporadic volcanic eruptions underestimates climate uncertainty, Communications Earth & Environment, 6, https://doi.org/10.1038/s43247-025-02208-1, 2025.

Chini, L.P., Hurtt, G.C., Klein Goldewijk, K., Sitch, S., Rosan, T.M., Pongratz, J., Brasika, I.B.M. and Friedlingstein, P.: December. Global Land-Use Forcing Datasets for Carbon/Climate Models and Biodiversity Studies. In AGU Fall Meeting Abstracts (Vol. 2023, pp. GC11C-04), 2023.

Clarke, B., Barnes, C., Sparks, N., Toumi, R., Yang, W., Giguere, J., Woods Placky, B., Gilford, D., Pershing, A., Winkley, S., Vecchi, G.A., Arrighi, J., Roy, M., Poole-Selters, L., Van Sant, C., Grieco, M., Singh, R., Vahlberg, M., Kew, S., Pinto, I., Otto, F., Hess, V., Gorham, E., Rodgers, S., Philip, S., Kimutai, J.: Climate change key driver of catastrophic impacts of Hurricane Helene that devastated both coastal and inland communities. Report of the Grantham Institute for Climate Change, Faculty of Natural Sciences. doi: 10.25561/115024, 2024.

Coats, S. and Karnauskas, K. B.: Are simulated and observed twentieth century Tropical Pacific sea surface temperature trends significant relative to internal variability?, Geophysical Research Letters, 44, 9928–9937, https://doi.org/10.1002/2017gl074622, 2017.

Collins, W. J., Lamarque, J.-F., Schulz, M., Boucher, O., Eyring, V., Hegglin, M. I., Maycock, A., Myhre, G., Prather, M., Shindell, D., and Smith, S. J.: AerChemMIP: quantifying the effects of chemistry and aerosols in CMIP6, Geoscientific Model Development, 10, 585–607, https://doi.org/10.5194/gmd-10-585-2017, 2017.

Cubasch, U., Meehl, G.A., Boer, G.J., Stouffer, R.J., Dix, M., Noda, A., Senior, C.A., Raper, S.U. and Yap, K.S.: Projections of future climate change. In Climate Change 2001: The scientific basis. Contribution of WG1 to the Third Assessment Report of the IPCC (TAR) (pp. 525-582). Cambridge University Press, 2001.

Dong, Y., Pauling, A. G., Sadal, S., Armour, K. C. (2022) Antarctic Ice-Sheet Meltwater Reduces Transient Warming and Climate Sensitivity Through the Sea Surface Temperature Pattern Effect, *Geophys. Res. Lett.*, 49, e2022GL101249

Dong, Y., Pauling, A. G., Sadai, S., and Armour, K. C.: Antarctic Ice-Sheet meltwater reduces transient warming and climate sensitivity through the Sea-Surface temperature pattern effect, Geophysical Research Letters, 49, https://doi.org/10.1029/2022gl101249, 2022.

Drijfhout, S., Bathiany, S., Beaulieu, C., Brovkin, V., Claussen, M., Huntingford, C., Scheffer, M., Sgubin, G., and Swingedouw, D.: Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models, Proceedings of the National Academy of Sciences, 112, https://doi.org/10.1073/pnas.1511451112, 2015.

Dunne, J. P., Winton, M., Bacmeister, J., Danabasoglu, G., Gettelman, A., Golaz, J., Hannay, C., Schmidt, G. A., Krasting, J. P., Leung, L. R., Nazarenko, L., Sentman, L. T., Stouffer, R. J., and Wolfe, J. D.: Comparison of equilibrium climate sensitivity estimates from Slab Ocean, 150-Year, and longer simulations, Geophysical Research Letters, 47, https://doi.org/10.1029/2020gl088852, 2020

Dunne, J., Hewitt, H., Tegtmeier, S., Senior, C., Ilyina, T., Fox-Kemper, B. and O'Rourke, E.: Climate Projections in Next Phase of the Coupled Model Intercomparison Project. *WMO Bulletin*, 72, pp.7-13, 2023.

Durack, P., Taylor, K., Eyring, V., Ames, S., Hoang, T., Nadeau, D., Doutriaux, C., Stockhause, M., and Gleckler, P.: Toward standardized data sets for climate model experimentation, Eos, 99, https://doi.org/10.1029/2018eo101751, 2018.

Durack, P. J., Taylor, K. E., Gleckler, P. J., Meehl, G. A., Lawrence, B. N., Covey, C., Stouffer, R. J., Levavasseur, G., Ben-Nasser, A., Denvil, S., Stockhause, M., Gregory, J. M., Juckes, M., Ames, S. K., Antonio, F., Bader, D. C., Dunne, J. P., Ellis, D., Eyring, V., Fiore, S. L., Joussaume, S., Kershaw, P., Lamarque, J.-F., Lautenschlager, M., Lee, J., Mauzey, C. F., Mizielinski, M., Nassisi, P., Nuzzo, A., O'Rourke, E., Painter, J., Potter, G. L., Rodriguez, S., and Williams, D. N.: The Coupled Model Intercomparison Project (CMIP): Reviewing project history, evolution, infrastructure and implementation, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-3729, 2025.

Erfani, E. and Burls, N. J.: The Strength of Low-Cloud Feedbacks and Tropical Climate: A CESM sensitivity study, Journal of Climate, 32, 2497–2516, https://doi.org/10.1175/jcli-d-18-0551.1, 2019.

Espinosa, Z. I. and Zelinka, M. D.: The shortwave Cloud-SST feedback amplifies Multi-Decadal Pacific Sea surface temperature trends: Implications for observed cooling, Geophysical Research Letters, 51, https://doi.org/10.1029/2024gl111039, 2024.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geoscientific Model Development, 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016, 2016

Eyring, V., N.P. Gillett, K.M. Achuta Rao, R. Barimalala, M. Barreiro Parrillo, N. Bellouin, C. Cassou, P.J. Durack, Y. Kosaka, S. McGregor, S. Min, O. Morgenstern, and Y. Sun, 2021: Human Influence on the Climate System. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 423–552, doi: 10.1017/9781009157896.005.

Fang, S., Sigl, M., Toohey, M., Jungclaus, J., Zanchettin, D., and Timmreck, C.: The role of small to moderate volcanic eruptions in the early 19th century climate, Geophysical Research Letters, 50, https://doi.org/10.1029/2023gl105307, 2023.

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021: Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362, doi: 10.1017/9781009157896.011.

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C. E., Hauck, J., Landschützer, P., Quéré, C. L., Luijkx, I. T., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni, P., Barbero, L., Bates, N. R., Becker, M., Bellouin, N., Decharme, B., Bopp, L., Brasika, I. B. M., Cadule, P., Chamberlain, M. A., Chandra, N., Chau, T.-T.-T., Chevallier, F., Chini, L. P., Cronin, M., Dou, X., Enyo, K., Evans, W., Falk, S., Feely, R. A., Feng, L., Ford, D. J., Gasser, T., Ghattas, J., Gkritzalis, T., Grassi, G., Gregor, L., Gruber, N., Gürses, Ö., Harris, I., Hefner, M., Heinke, J., Houghton, R. A., Hurtt, G. C., Iida, Y., Ilyina, T., Jacobson, A. R., Jain, A., Jarníková, T., Jersild, A., Jiang, F., Jin, Z., Joos, F., Kato, E., Keeling, R. F., Kennedy, D., Goldewijk, K. K., Knauer, J., Korsbakken, J. I., Körtzinger, A., Lan, X., Lefèvre, N., Li, H., Liu, J., Liu, Z., Ma, L., Marland, G., Mayot, N., McGuire, P. C., McKinley, G. A., Meyer, G., Morgan, E. J., Munro, D. R., Nakaoka, S.-I., Niwa, Y., O'Brien, K. M., Olsen, A., Omar, A. M., Ono, T., Paulsen, M., Pierrot, D., Pocock, K., Poulter, B., Powis, C. M., Rehder, G., Resplandy, L., Robertson, E., Rödenbeck, C., Rosan, T. M., Schwinger, J., Séférian, R., et al.: Global Carbon Budget 2023, Earth System Science Data, 15, 5301–5369, https://doi.org/10.5194/essd-15-5301-2023, 2023.

Funke, B., Dudok de Wit, T. D., Ermolli, I., Haberreiter, M., Kinnison, D., Marsh, D., Nesse, H., Seppälä, A., Sinnhuber, M., and Usoskin, I.: Towards the definition of a solar forcing dataset for CMIP7, Geoscientific Model Development, 17, 1217–1227, https://doi.org/10.5194/gmd-17-1217-2024, 2024.

Fyfe, J. C., Kharin, V. V., Santer, B. D., Cole, J. N. S., and Gillett, N. P.: Significant impact of forcing uncertainty in a large ensemble of climate model simulations, Proceedings of the National Academy of Sciences, 118, https://doi.org/10.1073/pnas.2016549118, 2021.

García-Franco, J. L., Gómez-Ramos, O., and Domínguez, C.: Hurricane Otis: the costliest and strongest hurricane at landfall on record in Mexico, Weather, 79, 182–184, https://doi.org/10.1002/wea.4555, 2024.

Gier, B. K., Buchwitz, M., Reuter, M., Cox, P. M., Friedlingstein, P., and Eyring, V.: Spatially resolved evaluation of Earth system models with satellite column-averaged CO2, Biogeosciences, 17, 6115–6144, https://doi.org/10.5194/bg-17-6115-2020, 2020.

Gillett, N. P., Simpson, I. R., Hegerl, G., Knutti, R., Mitchell, D., Ribes, A., Shiogama, H., Stone, D., Tebaldi, C., Wolski, P., Zhang, W., and Arora, V. K.: The Detection and Attribution Model Intercomparison Project (DAMIP v2.0) contribution to CMIP7, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-4086, 2025.

Giorgi, F. and Gutowski, W. J.: Regional Dynamical Downscaling and the CORDEX initiative, Annual Review of Environment and Resources, 40, 467–490, https://doi.org/10.1146/annurev-environ-102014-021217, 2015.

Gregory, J. M., Bi, D., Collier, M. A., Dix, Hirst, A. C., Hu, A., Huber, M., Knutti, R., Marsland, S. J., Meinshausen, M., Rashid, H. A., Rotstayn, L. D., Schurer, A., and Church, J. A.: Climate models without preindustrial volcanic forcing underestimate historical ocean thermal expansion, Geophysical Research Letters, 40, 1600–1604, https://doi.org/10.1002/grl.50339, 2013.

Grose, M. R., Narsey, S., Trancoso, R., Mackallah, C., Delage, F., Dowdy, A., Di Virgilio, G., Watterson, I., Dobrohotoff, P., Rashid, H. A., Rauniyar, S., Henley, B., Thatcher, M., Syktus, J., Abramowitz, G., Evans, J. P., Su, C.-H., and Takbash, A.: A CMIP6-based multi-model downscaling ensemble to underpin climate change services in Australia, Climate Services, 30, 100368, https://doi.org/10.1016/j.cliser.2023.100368, 2023.

Griffies, S. M., Danabasoglu, G., Durack, P. J., Adcroft, A. J., Balaji, V., Böning, C. W., Chassignet, E. P., Curchitser, E., Deshayes, J., Drange, H., Fox-Kemper, B., Gleckler, P. J., Gregory, J. M., Haak, H., Hallberg, R. W., Heimbach, P., Hewitt, H. T., Holland, D. M., Ilyina, T., Jungclaus, J. H., Komuro, Y., Krasting, J. P., Large, W. G., Marsland, S. J., Masina, S., McDougall, T. J., Nurser, A. J. G., Orr, J. C., Pirani, A., Qiao, F., Stouffer, R. J., Taylor, K. E., Treguier, A. M., Tsujino, H., Uotila, P., Valdivieso, M., Wang, Q., Winton, M., and Yeager, S. G.: OMIP contribution to CMIP6: experimental and diagnostic protocol for the physical component of the Ocean Model Intercomparison Project, Geosci. Model Dev., 9, 3231–3296, https://doi.org/10.5194/gmd-9-3231-2016, 2016.

Gutiérrez, J.M., Jones, R.G., Narisma, G.T., Alves, L.M., Amjad, M., Gorodetskaya, I.V., Grose, M., Klutse, N.A.B., Krakovska, S., Li, J., Martínez-Castro, D., Mearns, L.O., Mernild, S.H., Ngo-Duc, T., van den Hurk, B., and Yoon, J.-H., 2021: Atlas. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L.Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K.Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. Interactive Atlas available from Available from http://interactive-atlas.ipcc.ch/

Gutowski, W. J., Jr, Giorgi, F., Timbal, B., Frigon, A., Jacob, D., Kang, H.-S., Raghavan, K., Lee, B., Lennard, C., Nikulin, G., O'Rourke, E., Rixen, M., Solman, S., Stephenson, T., and Tangang, F.: WCRP COordinated Regional Downscaling EXperiment (CORDEX): a diagnostic MIP for CMIP6, Geoscientific Model Development, 9, 4087–4095, https://doi.org/10.5194/gmd-9-4087-2016, 2016.

Hajima, T., Kawamiya, M., Ito, A., Tachiiri, K., Jones, C. D., Arora, V., Brovkin, V., Séférian, R., Liddicoat, S., Friedlingstein, P., and Shevliakova, E.: Consistency of global carbon budget between concentration- and emission-driven historical experiments simulated by CMIP6 Earth system models and suggestions for improved simulation of CO2 concentration, Biogeosciences, 22, 1447–1473, https://doi.org/10.5194/bg-22-1447-2025, 2025.

Hall, A., Cox, P., Huntingford, C., and Klein, S.: Progressing emergent constraints on future climate change, Nature Climate Change, 9, 269–278, https://doi.org/10.1038/s41558-019-0436-6, 2019.

Hausfather, Z., Marvel, K., Schmidt, G. A., Nielsen-Gammon, J. W., and Zelinka, M.: Climate simulations: recognize the 'hot model' problem, Nature, 605, 26–29, https://doi.org/10.1038/d41586-022-01192-2, 2022.

Hawkins, E. and Sutton, R.: The potential to narrow uncertainty in regional climate predictions, Bulletin of the American Meteorological Society, 90, 1095–1108, https://doi.org/10.1175/2009bams2607.1, 2009.

Hewitt, C. D., Guglielmo, F., Joussaume, S., Bessembinder, J., Christel, I., Doblas-Reyes, F. J., Djurdjevic, V., Garrett, N., Kjellström, E., Krzic, A., Costa, M. M., and St Clair, A. L.: Recommendations for future research priorities for climate modeling and climate services, Bulletin of the American Meteorological Society, 102, E578–E588, https://doi.org/10.1175/bams-d-20-0103.1, 2020.

Hoesly, R.M., Smith, S., Prime, N., Ahsan, H. and Suchyta, H.: A Global Anthropogenic Emissions Inventory of Reactive Gases and Aerosols (1750-2022): an Update to the Community Emissions Data System (CEDS). In AGU Fall Meeting Abstracts (Vol. 2023, pp. GC11C-05), 2023.

Holland, G., and Bruyère, C. L.: Recent intense hurricane response to global climate change. Climate Dynamics, 42, 617-627, 2014.

Holland, M. M., Hannay, C., Fasullo, J., Jahn, A., Kay, J. E., Mills, M., Simpson, I. R., Wieder, W., Lawrence, P., Kluzek, E., and Bailey, D.: New model ensemble reveals how forcing uncertainty and model structure alter climate simulated across CMIP generations of the Community Earth System Model, Geoscientific Model Development, 17, 1585–1602, https://doi.org/10.5194/gmd-17-1585-2024, 2024.

Hopcroft, P. O. and Valdes, P. J.: Paleoclimate-conditioning reveals a North Africa land–atmosphere tipping point, Proceedings of the National Academy of Sciences, 118, https://doi.org/10.1073/pnas.2108783118, 2021.

Hourdin, F., Mauritsen, T., Gettelman, A., Golaz, J.-C., Balaji, V., Duan, Q., Folini, D., Ji, D., Klocke, D., Qian, Y., Rauser, F., Rio, C., Tomassini, L., Watanabe, M., and Williamson, D.: The Art and science of climate model tuning, Bulletin of the American Meteorological Society, 98, 589–602, https://doi.org/10.1175/bams-d-15-00135.1, 2016.

Irving, D., Hobbs, W., Church, J., and Zika, J.: A mass and energy conservation analysis of drift in the CMIP6 ensemble, Journal of Climate, 34, 3157–3170, https://doi.org/10.1175/jcli-d-20-0281.1, 2020.

IPCC, 2021: Annex VII: Glossary [Matthews, J.B.R., V. Möller, R. van Diemen, J.S. Fuglestvedt, V. Masson-Delmotte, C. Méndez, S. Semenov, A. Reisinger (eds.)]. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 2215–2256, doi:10.1017/9781009157896.022., 2021.

Jakob, C., Gettelman, A., and Pitman, A.: The need to operationalize climate modelling, Nature Climate Change, 13, 1158–1160, https://doi.org/10.1038/s41558-023-01849-4, 2023.

Ito, A., Hajima, T., Lawrence, D.M., Brovkin, V., Delire, C., Guenet, B., Jones, C.D., Malyshev, S., Materia, S., McDermid, S.P. and Peano, D., 2020. Soil carbon sequestration simulated in CMIP6-LUMIP models: implications for climatic mitigation. Environmental Research Letters, 15(12), p.124061.

Jones, C. D., Arora, V., Friedlingstein, P., Bopp, L., Brovkin, V., Dunne, J., Graven, H., Hoffman, F., Ilyina, T., John, J. G., Jung, M., Kawamiya, M., Koven, C., Pongratz, J., Raddatz, T., Randerson, J. T., and Zaehle, S.: C4MIP – The Coupled

Climate–Carbon Cycle Model Intercomparison Project: experimental protocol for CMIP6, Geoscientific Model Development, 9, 2853–2880, https://doi.org/10.5194/gmd-9-2853-2016, 2016.

Juckes, M., Taylor, K. E., Antonio, F., Brayshaw, D., Buontempo, C., Cao, J., Durack, P. J., Kawamiya, M., Kim, H., Lovato, T., Mackallah, C., Mizielinski, M., Nuzzo, A., Stockhause, M., Visioni, D., Walton, J., Turner, B., O'Rourke, E., and Dingley, B.: Baseline Climate Variables for Earth System Modelling, Geosci. Model Dev., 18, 2639–2663, https://doi.org/10.5194/gmd-18-2639-2025, 2025.

Kang, S. M., Xie, S.-P., Shin, Y., Kim, H., Hwang, Y.-T., Stuecker, M. F., Xiang, B., and Hawcroft, M.: Walker circulation response to extratropical radiative forcing, Science Advances, 6, https://doi.org/10.1126/sciadv.abd3021, 2020.

Kang, S. M., Yu, Y., Deser, C., Zhang, X., Kang, I.-S., Lee, S.-S., Rodgers, K. B., and Ceppi, P.: Global impacts of recent Southern Ocean cooling, Proceedings of the National Academy of Sciences, 120, https://doi.org/10.1073/pnas.2300881120, 2023.

Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J. M., Bates, S. C., Danabasoglu, G., Edwards, J., Holland, M., Kushner, P., Lamarque, J. -f., Lawrence, D., Lindsay, K., Middleton, A., Munoz, E., Neale, R., Oleson, K., Polvani, L., and Vertenstein, M.: The Community Earth System Model (CESM) Large Ensemble Project: a community resource for studying climate change in the presence of internal climate variability, Bulletin of the American Meteorological Society, 96, 1333–1349, https://doi.org/10.1175/bams-d-13-00255.1, 2014.

Kim, H., Kang, S. M., Kay, J. E., and Xie, S.-P.: Subtropical clouds key to Southern Ocean teleconnections to the tropical Pacific, Proceedings of the National Academy of Sciences, 119, https://doi.org/10.1073/pnas.2200514119, 2022.

Knutti, R., Masson, D., and Gettelman, A.: Climate model genealogy: Generation CMIP5 and how we got there, Geophysical Research Letters, 40, 1194–1199, https://doi.org/10.1002/grl.50256, 2013.

Kovilakam, M., Thomason, L. W., Ernest, N., Rieger, L., Bourassa, A., and Millán, L.: The Global Space-based Stratospheric Aerosol Climatology (version 2.0): 1979–2018, Earth System Science Data, 12, 2607–2634, https://doi.org/10.5194/essd-12-2607-2020, 2020.

Kuma, P., Bender, F. a.-m., and Jönsson, A. R.: Climate Model Code genealogy and its relation to climate feedbacks and sensitivity, Journal of Advances in Modeling Earth Systems, 15, https://doi.org/10.1029/2022ms003588, 2023.

Lee, J.Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J.P., Engelbrecht, F., Fischer, E., Fyfe, J.C., Jones, C. and Maycock, A., 2021. Future global climate: scenario-based projections and near-term information. In Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change (pp. 553-672). Cambridge University Press.

Lennon, J. T., Abramoff, R. Z., Allison, S. D., Burckhardt, R. M., DeAngelis, K. M., Dunne, J. P., Frey, S. D., Friedlingstein, P., Hawkes, C. V., Hungate, B. A., Khurana, S., Kivlin, S. N., Levine, N. M., Manzoni, S., Martiny, A. C., Martiny, J. B. H., Nguyen, N. K., Rawat, M., Talmy, D., Todd-Brown, K., Vogt, M., Wieder, W. R., and Zakem, E. J.: Priorities, opportunities, and challenges for integrating microorganisms into Earth system models for climate change prediction, mBio, 15, https://doi.org/10.1128/mbio.00455-24, 2024.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H. J.: Tipping elements in the Earth's climate system, Proceedings of the National Academy of Sciences, 105, 1786–1793, https://doi.org/10.1073/pnas.0705414105, 2008.

MacDougall, A. H., Frölicher, T. L., Jones, C. D., Rogelj, J., Matthews, H. D., Zickfeld, K., Arora, V. K., Barrett, N. J., Brovkin, V., Burger, F. A., Eby, M., Eliseev, A. V., Hajima, T., Holden, P. B., Jeltsch-Thömmes, A., Koven, C., Mengis, N., Menviel, L., Michou, M., Mokhov, I. I., Oka, A., Schwinger, J., Séférian, R., Shaffer, G., Sokolov, A., Tachiiri, K., Tjiputra, J., Wiltshire, A., and Ziehn, T.: Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2, Biogeosciences, 17, 2987–3016, https://doi.org/10.5194/bg-17-2987-2020, 2020.

Massoud, E. C., Lee, H. K., Terando, A., and Wehner, M.: Bayesian weighting of climate models based on climate sensitivity, Communications Earth & Environment, 4, https://doi.org/10.1038/s43247-023-01009-8, 2023.

Mathison, C. T., Burke, E., Kovacs, E., Munday, G., Huntingford, C., Jones, C., Smith, C., Steinert, N., Wiltshire, A., Gohar, L., and Varney, R.: A rapid application emissions-to impacts tool for scenario assessment: Probabilistic Regional Impacts from Model patterns and Emissions (PRIME). EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-2932, 2024.

Matthews, H. D., Gillett, N. P., Stott, P. A., and Zickfeld, K.: The proportionality of global warming to cumulative carbon emissions, Nature, 459, 829–832, https://doi.org/10.1038/nature08047, 2009.

Meehl, G. A., Boer, G. J., Covey, C., Latif, M., and Stouffer, R. J.: Intercomparison makes for a better climate model, Eos, 78, 445–451, https://doi.org/10.1029/97eo00276, 1997.

Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F. B., Stouffer, R. J., and Taylor, K. E.: THE WCRP CMIP3 Multimodel Dataset: A new era in climate change research, Bulletin of the American Meteorological Society, 88, 1383–1394, https://doi.org/10.1175/bams-88-9-1383, 2007.

Meehl, G. A., Senior, C., Eyring, V., Flato, G., Lamarque, J.-F., Stouffer, R. J., Taylor, K. E., and Schlund, M.: Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models, Science Advances, 6, https://doi.org/10.1126/sciadv.aba1981, 2020.

Meehl, G. A., Washington, W. M., Ammann, C. M., Arblaster, J. M., Wigley, T. M. L., and Tebaldi, C.: Combinations of natural and anthropogenic forcings in Twentieth-Century climate, Journal of Climate, 17, 3721–3727, https://doi.org/10.1175/1520-0442(2004)017, 2004.

Meinshausen, M., Schleussner, C.-F., Beyer, K., Bodeker, G., Boucher, O., Canadell, J. G., Daniel, J. S., Diongue-Niang, A., Driouech, F., Fischer, E., Forster, P., Grose, M., Hansen, G., Hausfather, Z., Ilyina, T., Kikstra, J. S., Kimutai, J., King, A. D., Lee, J.-Y., Lennard, C., Lissner, T., Nauels, A., Peters, G. P., Pirani, A., Plattner, G.-K., Pörtner, H., Rogelj, J., Rojas, M., Roy, J., Samset, B. H., Sanderson, B. M., Séférian, R., Seneviratne, S., Smith, C. J., Szopa, S., Thomas, A., Urge-Vorsatz, D., Velders, G. J. M., Yokohata, T., Ziehn, T., and Nicholls, Z.: A perspective on the next generation of Earth system model scenarios: towards representative emission pathways (REPs), Geoscientific Model Development, 17, 4533–4559, https://doi.org/10.5194/gmd-17-4533-2024, 2024.

Merlis, T. M., Cheng, K.-Y., Guendelman, I., Harris, L., Bretherton, C. S., Bolot, M., Zhou, L., Kaltenbaugh, A., Clark, S. K., Vecchi, G. A., and Fueglistaler, S.: Climate sensitivity and relative humidity changes in global storm-resolving model simulations of climate change, Science Advances, 10, https://doi.org/10.1126/sciadv.adn5217, 2024.

Meinshausen, M., Nicholls, Z.R., Lewis, J., Gidden, M.J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N. and Canadell, J.G.; The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geoscientific Model Development, 13(8), pp.3571-3605, 2020.

Meinshausen, M., Schleussner, C.F., Beyer, K., Bodeker, G., Boucher, O., Canadell, J.G., Daniel, J.S., Diongue-Niang, A., Driouech, F., Fischer, E. and Forster, P.; A perspective on the next generation of Earth system model scenarios: towards representative emission pathways (REPs). Geoscientific Model Development, 17(11), pp.4533-4559, 2024.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T. and Meehl, G.A., 2010. The next generation of scenarios for climate change research and assessment. Nature, 463(7282), pp.747-756.

Myers, T.A., Mechoso, C.R. and DeFlorio, M.J.: Coupling between marine boundary layer clouds and summer-to-summer sea surface temperature variability over the North Atlantic and Pacific. *Climate Dynamics*, *50*, pp.955-969, 2018.

Nguyen, P. L., Alexander, L. V., Thatcher, M. J., Truong, S. C. H., Isphording, R. N., and McGregor, J. L.: Selecting CMIP6 global climate models (GCMs) for Coordinated Regional Climate Downscaling Experiment (CORDEX) dynamical downscaling over Southeast Asia using a standardised benchmarking framework, Geoscientific Model Development, 17, 7285–7315, https://doi.org/10.5194/gmd-17-7285-2024, 2024.

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6, Geoscientific Model Development, 9, 3461–3482, https://doi.org/10.5194/gmd-9-3461-2016, 2016.

Otto-Bliesner, B. L., Braconnot, P., Harrison, S. P., Lunt, D. J., Abe-Ouchi, A., Albani, S., Bartlein, P. J., Capron, E., Carlson, A. E., Dutton, A., Fischer, H., Goelzer, H., Govin, A., Haywood, A., Joos, F., LeGrande, A. N., Lipscomb, W. H., Lohmann, G., Mahowald, N., Nehrbass-Ahles, C., Pausata, F. S. R., Peterschmitt, J.-Y., Phipps, S. J., Renssen, H., and Zhang, Q.: The PMIP4 contribution to CMIP6 – Part 2: Two interglacials, scientific objective and experimental design for Holocene and Last Interglacial simulations, Geoscientific Model Development, 10, 3979–4003, https://doi.org/10.5194/gmd-10-3979-2017, 2017.

Peatier, S., Sanderson, B. M., and Terray, L.: Exploration of diverse solutions for the calibration of imperfect climate models, Earth System Dynamics, 15, 987–1014, https://doi.org/10.5194/esd-15-987-2024, 2024.

Pincus, R., Forster, P. M., and Stevens, B.: The Radiative Forcing Model Intercomparison Project (RFMIP): experimental protocol for CMIP6, Geoscientific Model Development, 9, 3447–3460, https://doi.org/10.5194/gmd-9-3447-2016, 2016.

Planton, Y. Y., Guilyardi, E., Wittenberg, A. T., Lee, J., Gleckler, P. J., Bayr, T., McGregor, S., McPhaden, M. J., Power, S., Roehrig, R., Vialard, J., and Voldoire, A.: Evaluating Climate Models with the CLIVAR 2020 ENSO Metrics Package, Bulletin of the American Meteorological Society, 102, E193–E217, https://doi.org/10.1175/bams-d-19-0337.1, 2020.

Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O. and Lutz, W.; The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global environmental change, 42, pp.153-168, 2017

Riahi, K., R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, E. Kriegler, R. Matthews, G.P. Peters, A. Rao, S. Robertson, A.M. Sebbit, J. Steinberger, M. Tavoni, D.P. van Vuuren, 2022: Mitigation pathways compatible with long-term goals. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.005

Roberts, M. J., Reed, K. A., Bao, Q., Barsugli, J. J., Camargo, S. J., Caron, L.-P., Chang, P., Chen, C.-T., Christensen, H. M., Danabasoglu, G., Frenger, I., Fučkar, N. S., Hasson, S. U., Hewitt, H. T., Huang, H., Kim, D., Kodama, C., Lai, M., Leung, L.-Y. R., Mizuta, R., Nobre, P., Ortega, P., Paquin, D., Roberts, C. D., Scoccimarro, E., Seddon, J., Treguier, A. M., Tu, C.-Y., Ullrich, P. A., Vidale, P. L., Wehner, M. F., Zarzycki, C. M., Zhang, B., Zhang, W., and Zhao, M.: High-Resolution Model Intercomparison Project phase 2 (HighResMIP2) towards CMIP7, Geoscientific Model Development, 18, 1307–1332, https://doi.org/10.5194/gmd-18-1307-2025, 2025.

Ruane, A. C., Teichmann, C., Arnell, N. W., Carter, T. R., Ebi, K. L., Frieler, K., Goodess, C. M., Hewitson, B., Horton, R., Kovats, R. S., Lotze, H. K., Mearns, L. O., Navarra, A., Ojima, D. S., Riahi, K., Rosenzweig, C., Themessl, M., and Vincent, K.: The Vulnerability, Impacts, Adaptation and Climate Services Advisory Board (VIACS AB v1.0) contribution to CMIP6, Geosci. Model Dev., 9, 3493–3515, https://doi.org/10.5194/gmd-9-3493-2016, 2016.

Rugenstein, M., Bloch-Johnson, J., Gregory, J., Andrews, T., Mauritsen, T., Li, C., Frölicher, T. L., Paynter, D., Danabasoglu, G., Yang, S., Dufresne, J., Cao, L., Schmidt, G. A., Abe-Ouchi, A., Geoffroy, O., and Knutti, R.: Equilibrium climate sensitivity estimated by equilibrating climate models, Geophysical Research Letters, 47, https://doi.org/10.1029/2019gl083898, 2019.

Rugenstein, M., Dhame, S., Olonscheck, D., Wills, R. J., Watanabe, M., and Seager, R.: Connecting the SST pattern problem and the Hot model problem, Geophysical Research Letters, 50, https://doi.org/10.1029/2023gl105488, 2023.

Sanderson, B. M., Booth, B. B. B., Dunne, J., Eyring, V., Fisher, R. A., Friedlingstein, P., Gidden, M. J., Hajima, T., Jones, C. D., Jones, C. G., King, A., Koven, C. D., Lawrence, D. M., Lowe, J., Mengis, N., Peters, G. P., Rogelj, J., Smith, C., Snyder, A. C., Simpson, I. R., Swann, A. L. S., Tebaldi, C., Ilyina, T., Schleussner, C.-F., Séférian, R., Samset, B. H., Van Vuuren, D., and Zaehle, S.: The need for carbon-emissions-driven climate projections in CMIP7, Geoscientific Model Development, 17, 8141–8172, https://doi.org/10.5194/gmd-17-8141-2024, 2024a.

Sanderson, B. M., Brovkin, V., Fisher, R., Hohn, D., Ilyina, T., Jones, C., Koenigk, T., Koven, C., Li, H., Lawrence, D., Lawrence, P., Liddicoat, S., Macdougall, A., Mengis, N., Nicholls, Z., O'Rourke, E., Romanou, A., Sandstad, M., Schwinger, J., Seferian, R., Sentman, L., Simpson, I., Smith, C., Steinert, N., Swann, A., Tjiputra, J., and Ziehn, T.: flat10MIP: An emissions-driven experiment to diagnose the climate response to positive, zero, and negative CO2 emissions, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-3356, 2024b.

Sanderson, B. M., Wehner, M., and Knutti, R.: Skill and independence weighting for multi-model assessments, Geoscientific Model Development, 10, 2379–2395, https://doi.org/10.5194/gmd-10-2379-2017, 2017.

Schmidt, G. A., Andrews, T., Bauer, S. E., Durack, P. J., Loeb, N. G., Ramaswamy, V., Arnold, N. P., Bosilovich, M. G., Cole, J., Horowitz, L. W., Johnson, G. C., Lyman, J. M., Medeiros, B., Michibata, T., Olonscheck, D., Paynter, D., Raghuraman, S. P., Schulz, M., Takasuka, D., Tallapragada, V., Taylor, P. C., and Ziehn, T.: CERESMIP: a climate modeling protocol to investigate recent trends in the Earth's Energy Imbalance, Frontiers in Climate, 5, https://doi.org/10.3389/fclim.2023.1202161, 2023a

Schmidt, G. A., Romanou, A., Roach, L. A., Mankoff, K. D., Li, Q., Rye, C. D., Kelley, M., Marshall, J. C., and Busecke, J. J. M.: Anomalous meltwater from ice sheets and ice shelves is a historical forcing, Geophysical Research Letters, 50, https://doi.org/10.1029/2023gl106530, 2023b.

Schmidt, G. A., Mankoff, K. D., Bamber, J. L., Carroll, D., Chandler, D. M., Coulon, V., Davison, B. J., England, M. H., Holland, P. R., Jourdain, N. C., Li, Q., Marson, J. M., Mathiot, P., McMahon, C. R., Moon, T. A., Mottram, R., Nowicki, S., Olivé Abelló, A., Pauling, A. G., Rackow, T., and Ringeisen, D.: Datasets and protocols for including anomalous freshwater from melting ice sheets in climate simulations, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-1940, 2025.

Seager, R., Cane, M., Henderson, N., Lee, D.-E., Abernathey, R., and Zhang, H.: Strengthening tropical Pacific zonal sea surface temperature gradient consistent with rising greenhouse gases, Nature Climate Change, 9, 517–522, https://doi.org/10.1038/s41558-019-0505-x, 2019.

Seager, R., Henderson, N., and Cane, M.: Persistent Discrepancies between Observed and Modeled Trends in the Tropical Pacific Ocean, Journal of Climate, 35, 4571–4584, https://doi.org/10.1175/jcli-d-21-0648.1, 2022.

Séférian, R., Gehlen, M., Bopp, L., Resplandy, L., Orr, J. C., Marti, O., Dunne, J. P., Christian, J. R., Doney, S. C., Ilyina, T., Lindsay, K., Halloran, P. R., Heinze, C., Segschneider, J., Tjiputra, J., Aumont, O., and Romanou, A.: Inconsistent strategies to spin up models in CMIP5: implications for ocean biogeochemical model performance assessment, Geoscientific Model Development, 9, 1827–1851, https://doi.org/10.5194/gmd-9-1827-2016, 2016.

Seneviratne, S. I. and Hauser, M.: Regional Climate sensitivity of climate Extremes in CMIP6 versus CMIP5 multimodel ensembles, Earth S Future, 8, https://doi.org/10.1029/2019ef001474, 2020.

Sentman, L. T., Shevliakova, E., Stouffer, R. J., and Malyshev, S.: Time scales of terrestrial carbon response related to Land-Use Application: Implications for initializing an Earth System model, Earth Interactions, 15, 1–16, https://doi.org/10.1175/2011ei401.1, 2011.

Sime, L. C., Sivankutty, R., Vallet-Malmierca, I., De Boer, A. M., and Sicard, M.: Summer surface air temperature proxies point to near-sea-ice-free conditions in the Arctic at 127 ka, Climate of the Past, 19, 883–900, https://doi.org/10.5194/cp-19-883-2023, 2023.

Simpson, I. R. and Polvani, L. M.: Revisiting the relationship between jet position, forced response, and annular mode variability in the southern midlatitudes, Geophysical Research Letters, 43, 2896–2903, https://doi.org/10.1002/2016gl067989, 2016.

Smith, C. J., Kramer, R. J., Myhre, G., Alterskjær, K., Collins, W., Sima, A., Boucher, O., Dufresne, J.-L., Nabat, P., Michou, M., Yukimoto, S., Cole, J., Paynter, D., Shiogama, H., O'Connor, F. M., Robertson, E., Wiltshire, A., Andrews, T., Hannay, C., Miller, R., Nazarenko, L., Kirkevåg, A., Olivié, D., Fiedler, S., Lewinschal, A., Mackallah, C., Dix, M., Pincus, R., and Forster, P. M.: Effective radiative forcing and adjustments in CMIP6 models, Atmospheric Chemistry and Physics, 20, 9591–9618, https://doi.org/10.5194/acp-20-9591-2020, 2020.

Soden, B. J., Held, I. M., Colman, R., Shell, K. M., Kiehl, J. T., and Shields, C. A.: Quantifying climate feedbacks using radiative kernels, Journal of Climate, 21, 3504–3520, https://doi.org/10.1175/2007jcli2110.1, 2008.

Stevens, B.: A perspective on the future of CMIP, AGU Advances, 5, https://doi.org/10.1029/2023av001086, 2024.

Stouffer, R. J., Eyring, V., Meehl, G. A., Bony, S., Senior, C., Stevens, B., and Taylor, K. E.: CMIP5 Scientific Gaps and Recommendations for CMIP6, Bulletin of the American Meteorological Society, 98, 95–105, https://doi.org/10.1175/bams-d-15-00013.1, 2016.

Swaminathan, R., Schewe, J., Walton, J., Zimmermann, K., Jones, C., Betts, R. A., Burton, C., Jones, C. D., Mengel, M., Reyer, C. P. O., Turner, A. G., and Weigel, K.: Regional impacts poorly constrained by climate sensitivity, Earth S Future, 12, https://doi.org/10.1029/2024ef004901, 2024.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design, Bulletin of the American Meteorological Society, 93, 485–498, https://doi.org/10.1175/bams-d-11-00094.1, 2011.

Toohey, M. and Sigl, M.: Volcanic stratospheric sulfur injections and aerosol optical depth from 500 BCE to 1900 CE, Earth System Science Data, 9, 809–831, https://doi.org/10.5194/essd-9-809-2017, 2017.

Van Den Hurk, B., Kim, H., Krinner, G., Seneviratne, S. I., Derksen, C., Oki, T., Douville, H., Colin, J., Ducharne, A., Cheruy, F., Viovy, N., Puma, M. J., Wada, Y., Li, W., Jia, B., Alessandri, A., Lawrence, D. M., Weedon, G. P., Ellis, R., Hagemann, S., Mao, J., Flanner, M. G., Zampieri, M., Materia, S., Law, R. M., and Sheffield, J.: LS3MIP (v1.0) contribution to CMIP6: the Land Surface, Snow and Soil moisture Model Intercomparison Project – aims, setup and expected outcome, Geoscientific Model Development, 9, 2809–2832, https://doi.org/10.5194/gmd-9-2809-2016, 2016.

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F. and Masui, T.; The representative concentration pathways: an overview. Climatic change, 109, pp.5-31, 2011.

van Vuuren, D., O'Neill, B., Tebaldi, C., Chini, L., Friedlingstein, P., Hasegawa, T., Riahi, K., Sanderson, B., Govindasamy, B., Bauer, N., Eyring, V., Fall, C., Frieler, K., Gidden, M., Gohar, L., Jones, A., King, A., Knutti, R., Kriegler, E., Lawrence, P., Lennard, C., Lowe, J., Mathison, C., Mehmood, S., Prado, L., Zhang, Q., Rose, S., Ruane, A., Schleussner, C.-F., Seferian, R., Sillmann, J., Smith, C., Sörensson, A., Panickal, S., Tachiiri, K., Vaughan, N., Vishwanathan, S., Yokohata, T., and Ziehn, T.: The Scenario Model Intercomparison Project for CMIP7 (ScenarioMIP-CMIP7) , EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-3765, 2025.

Visioni, D., MacMartin, D. G., Kravitz, B., Boucher, O., Jones, A., Lurton, T., Martine, M., Mills, M. J., Nabat, P., Niemeier, U., Séférian, R., and Tilmes, S.: Identifying the sources of uncertainty in climate model simulations of solar radiation modification with the G6sulfur and G6solar Geoengineering Model Intercomparison Project (GeoMIP) simulations, Atmospheric Chemistry and Physics, 21, 10039–10063, https://doi.org/10.5194/acp-21-10039-2021, 2021.

Visioni, D., Robock, A., Haywood, J., Henry, M., Tilmes, S., MacMartin, D. G., Kravitz, B., Doherty, S. J., Moore, J., Lennard, C., Watanabe, S., Muri, H., Niemeier, U., Boucher, O., Syed, A., Egbebiyi, T. S., Séférian, R., and Quaglia, I.: G6-1.5K-SAI: a new Geoengineering Model Intercomparison Project (GeoMIP) experiment integrating recent advances in solar radiation modification studies, Geoscientific Model Development, 17, 2583–2596, https://doi.org/10.5194/gmd-17-2583-2024, 2024.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., and Schewe, J.: The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework, Proceedings of the National Academy of Sciences, 111, 3228–3232, https://doi.org/10.1073/pnas.1312330110, 2013.

Washington, W. M. and Meehl, G. A.: Climate sensitivity due to increased CO2: experiments with a coupled atmosphere and ocean general circulation model, Climate Dynamics, 4, 1–38, https://doi.org/10.1007/bf00207397, 1989.

Watanabe, M., Kang, S. M., Collins, M., Hwang, Y.-T., McGregor, S., and Stuecker, M. F.: Possible shift in controls of the tropical Pacific surface warming pattern, Nature, 630, 315–324, https://doi.org/10.1038/s41586-024-07452-7, 2024.

WCRP. (2023). A WCRP vision for accessible, useful and reliable climate modeling systems. Report of the Future of Climate Modeling Workshop. WCRP Publication No.: 03/2023. Retrieved from https://www.wcrp-climate.org/WCRP-publications/2023/Final_Report_WCRP_FCM_Workshop.pdf

Webb, M. J., Andrews, T., Bodas-Salcedo, A., Bony, S., Bretherton, C. S., Chadwick, R., Chepfer, H., Douville, H., Good, P., Kay, J. E., Klein, S. A., Marchand, R., Medeiros, B., Siebesma, A. P., Skinner, C. B., Stevens, B., Tselioudis, G., Tsushima, Y., and Watanabe, M.: The Cloud Feedback Model Intercomparison Project (CFMIP) contribution to CMIP6, Geoscientific Model Development, 10, 359–384, https://doi.org/10.5194/gmd-10-359-2017, 2017.

Wills, R. C. J., Dong, Y., Proistosecu, C., Armour, K. C., and Battisti, D. S.: Systematic climate model biases in the Large-Scale patterns of recent Sea-Surface temperature and Sea-Level pressure change, Geophysical Research Letters, 49, https://doi.org/10.1029/2022gl100011, 2022.

Wood, R. A., Crucifix, M., Lenton, T. M., Mach, K. J., Moore, C., New, M., Sharpe, S., Stocker, T. F., and Sutton, R. T.: A Climate Science Toolkit for High Impact-Low Likelihood Climate Risks, Earth S Future, 11, https://doi.org/10.1029/2022ef003369, 2023.

Yamazaki, K., Sexton, D. M. H., Rostron, J. W., McSweeney, C. F., Murphy, J. M., and Harris, G. R.: A perturbed parameter ensemble of HadGEM3-GC3.05 coupled model projections: part 2: global performance and future changes, Climate Dynamics, 56, 3437–3471, https://doi.org/10.1007/s00382-020-05608-5, 2021.

Yeager, S. G., Chang, P., Danabasoglu, G., Rosenbloom, N., Zhang, Q., Castruccio, F. S., Gopal, A., Rencurrel, M. C., and Simpson, I. R.: Reduced Southern Ocean warming enhances global skill and signal-to-noise in an eddy-resolving decadal prediction system, Npj Climate and Atmospheric Science, 6, https://doi.org/10.1038/s41612-023-00434-y, 2023.

Zappa, G. and Shepherd, T. G.: Storylines of atmospheric circulation change for European Regional Climate Impact Assessment, Journal of Climate, 30, 6561–6577, https://doi.org/10.1175/jcli-d-16-0807.1, 2017.

Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., Klein, S. A., and Taylor, K. E.: Causes of higher climate sensitivity in CMIP6 models, Geophysical Research Letters, 47, https://doi.org/10.1029/2019gl085782, 2020.