The Detection and Attribution Model Intercomparison Project (DAMIP v2.0) contribution to CMIP7

Nathan P. Gillett[1], Isla R. Simpson[2], Gabi Hegerl[3], Reto Knutti[4], Dann Mitchell[5], Aurélien Ribes[6], Hideo Shiogama[7], Dáithí Stone[8], Claudia Tebaldi[9], Piotr Wolski[10], Wenxia Zhang[11], Vivek K. Arora[1]

[1]Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, Canada

[2]Climate and Global Dynamics, NSF National Center for Atmospheric Research, Boulder, CO, USA

[3]School of GeoSciences, University of Edinburgh, Edinburgh, UK

[4]Institute for Atmospheric and Climate Science, ETH Zürich, Universitätstrasse 16, 8092 Zürich, Switzerland

[5]School of Geographical Sciences, University of Bristol, Bristol, UK

[6]CNRM, Université de Toulouse, Météo-France, CNRS, Toulouse, France

[7]National Institute for Environmental Studies, Tsukuba, 305-8506, Japan

[8]National Institute of Water and Atmospheric Research, Wellington, 6021, New Zealand

[9]Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD, USA

[10]University of Cape Town, Cape Town, South Africa

[11]State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

Correspondence to: N. P. Gillett (nathan.gillett@ec.gc.ca)

Abstract. The first version of the Detection and Attribution Model Intercomparison Project (DAMIP v1.0) coordinated key simulations exploring the role of individual forcings in past, current and future climate as part of the Coupled Model Intercomparison Project, Phase 6 (CMIP6). The simulations have been used extensively in the literature for detection and attribution of long-term changes, constraining projections of climate change, extreme event attribution, and understanding drivers of past and future simulated climate changes. Attribution studies using DAMIP v1.0 simulations underpinned prominent assessments of human-induced warming in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report. Here we describe the set of DAMIP v2.0 simulations, proposed for the next phase of CMIP, CMIP7. Detection and attribution studies rely on preindustrial control simulations and historical simulations which will be part of the Diagnostic, Evaluation and Characterization of Klima (DECK) set of simulations for CMIP7. In addition, DAMIP v2.0 identifies three highest priority single forcing experiments for CMIP7 to be run as “Assessment Fast Track” simulations in support of the Seventh Assessment Report of the IPCC - namely simulations with natural forcings only, anthropogenic well-mixed greenhouse gases only, and anthropogenic aerosols only. Beyond this, the DAMIP v2.0 experimental design includes full column ozone-only simulations and land-use-only simulations, such that the set of individual forcings experiments, when considered together, represents the full set of historical forcings. While concentration driven simulations are prioritized for attribution of past changes, emissions-driven versions of the DAMIP experiments are also proposed to support understanding of the influence of carbon-cycle feedbacks on the simulated responses to individual forcings.

1 Introduction

Research on the detection and attribution of climate change aims to identify and quantify the influence of particular forcings or subsets of forcings on the climate system, with special focus on net human influence. Such research has underpinned progressively strengthening assessments on the role of human influence in driving observed climate change in successive Intergovernmental Panel on Climate Change (IPCC) reports, including the assessment in the most recent report that 'it is unequivocal that human influence has warmed the atmosphere, ocean and land' (Eyring et al., 2021). This research generally relies on climate model simulations of the response to individual forcings or subsets of external forcings, as well as observations (Eyring et al., 2021; Stott et al., 2004). In particular, such analyses generally require simulations of historical climate change including all major anthropogenic and natural influences (historical), long pre-industrial constant-forcing simulations to characterize the influence of internal variability alone (pre-industrial control), as well as simulations with subsets of forcing agents. This paper describes the coordinated set of climate model simulations designed to support detection and attribution research that are proposed under the Detection and Attribution Model Intercomparison Project v2.0 (DAMIP v2.0), part of the Coupled Model Intercomparison Project Phase 7. In CMIP7, historical and pre-industrial control simulations will be coordinated as part of the Diagnostic, Evaluation and Characterization of Klima (DECK, Dunne et al., 2024) set of simulations which all models must complete and which serve as a basis for model evaluation. Simulations with individual forcings or subsets of forcings are the focus of this paper.

2. Applications of DAMIP v1.0 CMIP6 simulations

DAMIP v2.0 follows from DAMIP v1.0 (Gillett et al., 2016), the coordinated set of detection and attribution simulations conducted under the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). CMIP6 included historical simulations driven with both anthropogenic and natural forcings (historical) as well as constant pre-industrial forcing simulations (piControl). DAMIP v1.0 complemented these with historical simulations driven by subsets of the historical experiment forcings. The highest priority Tier 1 simulations consisted of historical simulations driven with natural forcings only (hist-nat), historical simulations driven with well-mixed greenhouse gas changes only (hist-GHG), and historical simulations driven with aerosol and aerosol precursor emissions changes only (hist-aer). These simulations were supplemented with lower priority Tier 2/3 simulations including simulations driven with changes in stratospheric ozone only (hist-stratO3), volcanic aerosol only (hist-volc), solar irradiance only (hist-sol) and CO_2-only (hist-CO2). DAMIP v1.0 extended the individual historical forcing simulations up to 2100 using SSP2-4.5 (O'Neill et al., 2016) forcings to support analysis of the contribution of the different forcings to future changes (experiments ssp245-nat, ssp245-GHG, ssp245-aer and ssp245-

stratO3). Since the publication of the original experimental design (Gillett et al., 2016), some additional experiments were added to DAMIP v1.0, in particular: single forcing experiments with CMIP5 forcings to examine the effects of updates to the forcings from CMIP5 to CMIP6 (Fyfe et al., 2021), a simulation with ozone changes through the full atmospheric column (Shiogama et al., 2023), and a set of simulations to examine the response to COVID-induced changes in emissions (Jones et al., 2021).

Consistent with expectations, the Tier 1 simulations were carried out with the largest number of CMIP6 models, with hist-GHG simulations from 18 models, hist-aer simulations from 17 models, and hist-nat simulations from 17 models published on the CMIP6 data portal as of July 31st 2024 (Figure 1a). The simulations carried out with the fewest models were those added later in the CMIP6 cycle, namely the hist-GHG-cmip5, hist-aer-cmip5, hist-nat-cmip5, ssp245-cov-GHG and ssp245-cov-aer simulations, which were each only carried out with one model. Some modelling groups are now expanding their ensemble sizes through the Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP) (Smith et al., 2022), which is particularly focussed on attribution of multi-annual to decadal changes in climate, including the effects of updates to forcing datasets. While all DAMIP v1.0 experiments were referred to in at least one publication, the Tier 1 simulations (hist-GHG, hist-aer and hist-nat) were by the far the most cited, with hist-nat referred to in 245 publications (Figure 1b). The DAMIP v1.0 simulations were also used extensively in the Sixth Assessment Report (AR6) of Working Group I of the IPCC, with data from these simulations used in figures in five chapters of the report (Canadell et al., 2021; Doblas-Reyes et al., 2021; Eyring et al., 2021; Fox-Kemper et al., 2021; Szopa et al., 2021). Here also the Tier 1 simulations were by far the most used. DAMIP v1.0 simulations were, for example, used in two attribution analyses of warming since preindustrial times (Gillett et al., 2021; Ribes et al., 2021), which were two of the three main studies used to assess the anthropogenic contribution to observed warming (Eyring et al., 2021), which was a headline result in the Summary for Policymakers of the report (IPCC, 2021), and was also directly quoted in the Glasgow Climate Pact (UNFCCC, 2022). Since the publication of the IPCC AR6, a selection of key climate indicators have been updated on a yearly basis (Forster et al., 2024). This includes warming attributable to human influence, calculated using DAMIP v1.0 data.

Beyond assessments of global temperature change, DAMIP simulations have been used to explore a wide variety of Earth System Changes. They have been used to explore the role of individual forcings in modelled historical and projected future changes in the Atlantic Meridional Overturning Circulation (Menary et al., 2020). While the CMIP6 ensemble mean Atlantic Meridional Overturning Circulation response to forcings was rather linear in the forcing, this is not true of all models (Simpson et al., 2023). In addition, DAMIP simulations have been used to assess the relative roles of greenhouse gases and aerosols in historical changes in drought frequency, duration, and intensity (Chiang et al., 2021), the relative role of anthropogenic and natural forcings in contributing to increasing fire weather in the western United States (Zhuang et al., 2021), and the role of natural forcing, greenhouse gases and anthropogenic aerosols in historical changes in precipitation variability (Zhang et al., 2024b). They have been used to attribute the observed weakening of the summertime Eurasian jet stream in the historical record to anthropogenic aerosol forcing (Dong et al., 2022) and to isolate the relative role of greenhouse gases and aerosols to Northern Hemisphere summertime storm track trends (Kang et al., 2024). Despite this progress, we still do not adequately understand the relative role of forced changes and internal variability in observed circulation changes. Having now observed forced signals emerge for longer in observations and with continued improvements in process representation in Earth System Models, together with improved estimation of external forcings, further advances in this area may be achieved with the use of DAMIP v2.0 simulations of CMIP7.

As well as studies attributing long-term changes in climate, another application of DAMIP v1.0 simulations is in extreme event attribution, which aims to characterise how the probability of a single weather or climate event was altered by specific forcings, in particular anthropogenic forcing (Christidis et al., 2023; Herring et al., 2022; Lanet et al., 2024). This is an important use of DAMIP data, and allows for a wider global engagement in this field than those who have the capability to run climate model experiments tailored to the specific event under analysis. However, it also presents an additional potential challenge. Approaches for extreme event attribution sometimes require large ensembles of climate simulations, i.e., larger than the majority of DAMIP models will have (5-10 members), and up to thousands of ensemble members for very rare events (Schaller et al., 2014). Therefore when DAMIP simulations are used for extreme event attribution analysis, methods for increasing the sample size might sometimes be needed. Such methods could include using model years beyond that of the specific event, combining different climate models and their ensembles (King, 2017), increasing the sample size using extreme value theory (Sippel et al., 2015), or ensemble boosting (Fischer et al., 2023).

Increasingly, single forcing climate simulations are being used in hazard and impacts research. DAMIP data has been used very effectively in going most of the way to explaining the observed impact changes, for both trend-based impact attribution, and event-based impact attribution. In many of these studies, the authors are able to show a plausible explanation for the climate-influenced part of the observed impact. This has happened primarily in the areas of hydrology (e.g. Li et al., 2024a), and human health (e.g. Carlson, 2024; Chapman et al., 2022; Vicedo-Cabrera et al., 2021; Zhang et al., 2022). A challenge for impact detection and attribution research is to effectively integrate the relevant different socio-economic factors into the attribution framework, and this is particularly relevant in adaptation, loss and damage, and legal settings (James et al., 2019).

3 Experimental design of DAMIP v.2.0

In most respects DAMIP v2.0 follows the experimental design of DAMIP v1.0 (Table 1, Figure 2). As in DAMIP v1.0, we designate the highest priority experiments as Tier 1 experiments, with Tier 2 and Tier 3 representing successively lower priority experiments (see Figure 2). There are two primary designs for detection and attribution experiments - namely individual forcing simulations, and all-but-one simulations, in which all forcings except the one of interest are included (Gillett et al., 2016; Smith et al., 2022). All-but-one simulations, together with historical simulations, may offer some advantages for detecting the presence of one particular forcing in the observations, in particular from a causality theory point of view (Hannart et al., 2016; Naveau et al., 2020), and they can be used together with individual forcing simulations to test additivity (Marvel et al., 2015; Shiogama et al., 2013; Simpson et al., 2023). For example, aerosol-only simulations and all-but-aerosol simulations can be used together with simulations including all forcings to test whether the response to aerosols and the response to other forcings add to give the response to all forcings combined (e.g. Simpson et al., 2023). The Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP) proposed a comprehensive set of such simulations to investigate such questions (Smith et al., 2022). However, if the objective of an analysis is to characterize the response to one particular forcing, then individual forcing simulations will lead to reduced sampling uncertainties, because they do not require a difference between two sets of simulations to be taken, each of which has its own sampling uncertainties. For this reason, and for ease of comparison with previous CMIP generations, including DAMIP v1.0 experiments, DAMIP v2.0 largely follows DAMIP v1.0 in being primarily based on individual forcing simulations. That said, natural-only (hist-nat) simulations can be equivalently described and used as all-but-anthropogenic forcing simulations, and DAMIP v2.0 links with an AerChemMIP2 simulation with all forcings but aerosols (hist-piAer), which can be used to address particular questions relating to the dependence of the anthropogenic aerosol impact on the climate state and additivity of the aerosol response with the responses to other forcings (Marvel et al., 2015; Shiogama et al., 2013; Simpson et al., 2023).

Recognising the advances in modelling which are allowing a larger fraction of climate models to be run with interactive CO_2, the new science questions which may be addressed using interactive CO_2 simulations, as well as the interest in running many CMIP7 simulations with interactive CO_2 (Sanderson et al., 2024), DAMIP v2.0 is also proposing a set of individual forcing interactive CO_2 simulations (Section 3.3). Such simulations could for example be used to evaluate the effects of biogeochemical feedbacks on the responses to particular forcings, such as aerosols (e.g. Szopa et al., 2021), and could be used in studies attributing changes in atmosphere, land or ocean carbon pools to land use change, fossil CO_2 emissions and other GHG changes, and other factors. As in CMIP6, such interactive CO_2 simulations will have distinct experiment names from their corresponding prescribed concentration simulations (because the prognostic CO_2 concentration will generally differ from that prescribed in the corresponding concentration-driven experiments). Interactive CO_2 historical simulations will sample over uncertainties in the understanding and representation of the carbon cycle within ESMs, and will allow analysis of the effects of carbon cycle feedbacks on the responses to individual forcings, for instance testing the frequently-made assumption that the response to historical well-mixed GHG concentration changes is equivalent to the response to historical well-mixed GHG emission changes. However, given that direct and accurate observations of the evolution of atmospheric CO_2 exist, we recommend that prescribed-CO_2 simulations should continue to be used for detection and attribution studies of changes in the physical climate. For this reason, our highest-priority Assessment Fast Track simulations are concentration-driven, as are the other simulations described in Sections 3.1 and 3.2 (the Assessment Fast Track simulations are a subset of CMIP7 simulations to be carried out first in support of the IPCC Seventh Assessment Report (Dunne et al., 2024)). If modelling centres have the capacity and interest to carry out both prescribed-CO_2 and interactive-CO_2 simulations, we recommend that they carry out both, allowing the effects of carbon cycle feedbacks on the responses to individual sets of forcings to be isolated in each model.

Like the effects of an interactive carbon cycle, atmospheric chemistry also has the potential to modify the simulated response to individual forcings or sets of forcings. In a model with a full representation of atmospheric chemistry, methane and fluorinated gas concentrations influence tropospheric and stratospheric ozone concentration, solar and volcanic forcings influence stratospheric ozone concentrations, and aerosols and aerosol precursors influence ozone and methane concentrations, among other interactions. Such interactions would make DAMIP simulations from models with and without interactive chemistry not fully comparable. Because of such interactions, attribution of physical climate changes to changes in concentrations of radiatively active species is fundamentally different to attribution to emissions changes of such species. Typically detection and attribution studies of observed changes in climate attribute to concentration changes (e.g. Eyring et al., 2021), while emissions-driven individual forcing simulations may be used for bottom-up model-based estimates of the climate response to emissions of individual species (e.g. Szopa et al., 2021, Section 6.4). Like DAMIP v1.0, our focus here is mainly on supporting attribution to concentration changes, while AerChemMIP2 is proposing simulations to address attribution to emissions. While DAMIP v1.0 did propose an experimental design for hist-GHG and hist-aer for models with interactive chemistry to try to maintain comparability with other models, we note that this was never implemented because no modelling centres actually carried out the DAMIP v1.0 experiments with models with interactive chemistry. To simplify the experimental design and ensure comparability between outputs from different models, we therefore suggest that modelling groups carry out the DAMIP v2.0 experiments using model versions without gas phase chemistry if possible. While we note that aerosol microphysics and chemistry schemes may make simulated aerosol concentrations sensitive to simulated temperatures, winds, and possibly greenhouse gas concentrations, and therefore different in historical and hist-aer simulations, we note that the primary sensitivity of aerosol concentrations is to aerosol and aerosol precursor emissions, and that most modelling centres do not have the capacity to run their models with specified aerosol concentrations, and therefore we accept such small differences as a limitation of our experimental design.

If modelling centres plan to only submit simulations with interactive gas phase chemistry and are submitting historical simulations including this interactive chemistry, we request that they follow the DAMIP experimental design as indicated, but with the following modifications (see also Table 1). For hist-GHG and esm-hist-GHG they should specify emissions rather than concentrations of all well-mixed non-CO_2 greenhouse gases simulated interactively. hist-O3 and esm-hist-O3 simulations should not be carried out using models with interactive gas-phase chemistry. This is because ozone is simulated interactively in response to changes in ozone depleting substances, methane and other species in such models, and the concentrations of ozone depleting substances, methane and other species do not change in these simulations. All other simulations should be carried out as specified.

While hist-nat simulations in models with gas phase chemistry will include changes in stratospheric ozone which may modulate the response to solar and volcanic forcing, we expect the effects on surface climate to be small, and such output could probably be used together with historical simulations to attribute surface climate change to anthropogenic and natural forcings. Similarly hist-lu simulations from models with and without interactive chemistry are expected to be comparable. hist-GHG experiments are expected to differ between models with and without gas phase chemistry, because in models with interactive chemistry, methane emissions will increase tropospheric ozone, while halocarbon emissions will decrease stratospheric ozone. hist-aer experiments will also differ because emissions of NOx, NMVOCs and carbon monoxide (which are aerosol precursors) will all change tropospheric ozone and methane concentrations. Such experiments would not be directly comparable between models with and without gas phase chemistry, but analysis of the output could inform understanding of atmospheric chemistry feedbacks. To facilitate analysis of the results, we request that modelling centres flag output from models with interactive chemistry with the ‘f2’ flag, and indicate in their metadata and documentation that the model included interactive chemistry. We note that AerChemMIP2 also provides a dedicated framework for analysing the effects of such interactions systematically across models with interactive chemistry.

3.1 Historical simulations

3.1.1 Increased ensemble size for CMIP7 historical and Medium scenario simulations

While our focus is on historical experiments forced with single forcings or subsets of forcings, most detection and attribution analyses also use historical simulations with a complete set of forcings, and such analyses generally require an ensemble of such simulations, but only a single historical simulation is required as part of the DECK (Dunne et al., 2024). Therefore we request at least three ensemble members of the CMIP7 CO_2 concentration-driven historical simulations (historical), and the extension of those simulations to 2035 under the Medium scenario (scen7-mc, intended to represent a frozen policy scenario) proposed by ScenarioMIP for CMIP7 (van Vuuren et al., 2025). Given that actual anthropogenic forcings are expected to diverge only slightly from the Medium emissions scenario over the first decade or so (see Section 4), we request that these historical simulations and other DAMIP experiments are extended in this way. This will allow researchers to carry out attribution analyses based on contemporary data over the next decade, at least in the absence of a major volcanic eruption, and will likely ensure an overlap with the next phase of CMIP. DAMIP v1.0 simulations were extended in a similar way from 2015 to 2020, but in hindsight this was not long enough, since at the time of writing CMIP7 simulations are not yet available, but observations are available up to the end of 2024, well beyond the end of the DAMIP historical simulations. Such a need is particularly apparent for regularly updated attribution analyses (Forster et al., 2024). Modelling groups should publish the output data as CMIP7 historical simulations (1850-2021) and the Medium scenario simulations of ScenarioMIP (2022-2035). Note that we also request an ensemble size of at least three for all other DAMIP v2.0 historical simulations, though we encourage groups to run larger ensembles if possible. Also note that all DAMIP v2.0 simulations except historical-CMIP6 use forcings from the CMIP7 historical/esm-hist and Medium simulations described by Dunne et al. (2024). A larger ensemble of CMIP7 historical simulations will also make it easier to evaluate the consistency of simulated historical climate change with that observed, though any such analysis should account for the use of historical temperature change in the tuning of some models (Hourdin et al., 2017).

3.1.2 Simulations with a complete set of forcings

We are proposing a set of CO_2 concentration-driven historical simulations driven with subsets of forcings which together sum to give the full set of CMIP7 historical forcings. This set includes the hist-nat, hist-GHG and hist-aer experiments which are designated as Assessment Fast Track experiments here (Dunne et al., 2024) and also as Tier 1 experiments, based on the extensive use of the corresponding DAMIP v1.0 simulations in the literature and in support of IPCC assessment reports (Figure 1b). For this reason, we ask modelling groups to prioritize these simulations, and to consider running large ensembles of these simulations to support extreme event attribution and other applications (e.g. Smith et al., 2022), if time and resources allow. If the climate response to these forcings is additive, then the sum of the climate responses in this full set of historical simulations (hist-nat, hist-GHG, hist-aer, hist-O3 and hist-lu) will be equal to the response in the historical experiment. We note that the variance of this sum will in general be five times larger than the variance of the response in historical, which will need to be accounted for when identifying departures from additivity. This represents a minor adjustment relative to the DAMIP v1.0 experimental design in which land-use and land-cover change and tropospheric ozone changes were not included in any of the original DAMIP v1.0 simulations. All these simulations should be run from 1850 to 2021 using the CMIP7 historical forcings, and the Medium scenario (scen7-mc) from 2022 to 2035, and we request a minimum ensemble size of three for all historical experiments.

hist-nat: These natural-only simulations parallel the historical and Medium scenario simulations but instead are forced with only solar and volcanic forcings from the historical and Medium scenario simulations, similar to the CMIP6 hist-nat experiment. Such simulations, when compared with historical and Medium simulations, can be used for attribution of observed changes to anthropogenic influence, as they correspond to the counterfactual world in which human influence is removed. While much of the time evolution of biomass burning emissions has occurred as a result of human activity, the historical simulation includes observed year-to-year variations in biomass burning partly driven by natural variability. However, it is not easy to separate human-induced changes in biomass burning from naturally-induced changes. Therefore we request that modelling centres specify constant biomass burning emissions as in the piControl in this hist-nat simulation. In contrast with DAMIP v1.0, and consistent with our aim of ensuring a complete set of forcings across this simulation set and to simplify the experimental design, we are proposing that no ozone changes are specified in the hist-nat experiment, and that all ozone changes are included in the hist-O3 experiment.

hist-GHG: These greenhouse-gas-only simulations parallel the historical and Medium simulations but are forced by well-mixed greenhouse gas (carbon dioxide, methane, nitrous oxide and fluorinated gas) changes only from the historical and Medium scenario simulations, similarly to the CMIP6 hist-GHG experiment. Both stratospheric and tropospheric ozone should be held constant at piControl levels. Greenhouse gas changes are the dominant anthropogenic forcing, and these simulations will allow the response to this forcing to be quantified. Moreover, historical/Medium, hist-nat and hist-GHG will together allow the attribution of observed climate change to natural, greenhouse gas and other anthropogenic forcings (e.g. Gillett et al., 2021; Ribes et al., 2021).

hist-aer: These historical aerosol-only simulations parallel the historical/Medium simulations but are forced by changes in aerosol and aerosol precursor emissions changes only, as in historical and the Medium scenario. This includes changes in sulphur dioxide, black carbon, organic carbon, ammonia, NOx and VOCs, from biomass burning, industrial emissions and other sources.

hist-lu: These simulations parallel the historical and Medium simulations but are forced with prescribed land-use and land cover changes only from the historical and Medium scenario simulations, with all other forcings held constant at 1850 values. No such experiments were included in DAMIP v1.0, although they have since been proposed in LESFMIP (Smith et al., 2022), and historical experiments without land use change (hist-noLu) were included in CMIP6 in the Land Use Model Intercomparison Project (LUMIP, Lawrence et al., 2016). These experiments were used to investigate the effects of land use change on surface temperature and other variables in models (Luo et al., 2024; Zhang et al., 2024a), and to diagnose land use change emissions (e.g. Liddicoat et al., 2021). Note that hist-noLu is also a proposed LUMIP experiment for CMIP7, and hence hist-lu and hist-noLu could be used together to evaluate the additivity of the land-use change response and the response to other forcings. These experiments could also for example be used together to compare and contrast simulated historical land-use change emissions with atmospheric CO_2 held constant, and in the presence of CO_2 fertilisation with CO_2 changing through the historical period.

hist-O3: These simulations parallel the historical/Medium simulations but are forced by changes in ozone concentrations only from the historical and Medium scenario simulations. They will allow characterization of the response to combined tropospheric and stratospheric ozone changes, which have played an important role in driving circulation changes in the high-latitudes of the Southern Hemisphere and temperature changes in the stratosphere, as well as attribution studies of the response to ozone change (e.g. Gillett et al., 2013; Morgenstern, 2021). Since it is increasingly understood that ozone depleting substances influence ozone concentrations in the troposphere (e.g. Hassler et al., 2022; Li et al., 2024b), in CMIP7 we are requesting simulations forced by changes in ozone concentrations over the whole atmospheric column, as opposed to the stratospheric ozone changes only simulations proposed in CMIP6 (Gillett et al., 2016) (although experiments with ozone changes over the whole atmosphere were later proposed and carried out (Liu et al., 2022; Shiogama et al., 2023; Smith et al., 2022)). Moreover, this choice simplifies the experiment design, and avoids difficulties associated with specifying stratospheric ozone changes only, given that tropopause height can differ across models (although, we acknowledge that inconsistencies between tropopause height and ozone concentrations can still exist when prescribing ozone over the full column, which users should be aware could impact conclusions in certain circumstances (Hardiman et al., 2019)).

3.1.3 Other historical simulations

hist-volc: The hist-volc simulations parallel the hist-nat simulations except that the hist-volc simulations are driven by stratospheric aerosol changes only. The hist-volc experiments will allow the characterisation of and attribution to volcanic influence, separate from the poorly constrained response to variations in solar forcing. Such analysis can improve our understanding of the response to future volcanic eruptions.

historical-CMIP6: These are identical to CMIP7 historical experiments, but instead of using CMIP7 forcings, they use CMIP6 historical forcings to 2014 and ScenarioMIP SSP2-4.5 forcings from 2015 to 2035. CMIP simulations of past and future climate changes are key to attribution as well as projection of climate change, for example in IPCC assessments (Eyring et al., 2021; Lee et al., 2021), and it is important to be able to understand differences in results based on successive CMIP generations. Comparing historical CMIP6 and CMIP7 simulations will be complicated by the fact that both the models and the forcings will be different between the two CMIP generations, making it difficult to separate the influence of updates to the forcings versus changes to the models. By carrying out simulations with a subset of CMIP7 models using CMIP6 forcings, it will be possible to separate the influence of updates to the forcings. A similar approach was used to isolate the influence of updates to forcings between CMIP5 and CMIP6 and the impact of forcing changes has been shown to be an important contributor to differences between CMIP6 and CMIP5 simulations (Fyfe et al., 2021; Holland et al., 2024).

3.2 Future simulations driven with subsets of forcings

While ScenarioMIP simulations including scenarios of future changes in greenhouse gases, aerosols, ozone and land use change allow the simulation of possible future climate evolution, they do not directly allow the effects of particular forcings, or sets of forcings, to be isolated. Simulations of future climate change with subsets of forcings can help us understand the drivers of future climate change. Moreover, the Allen et al. (2000) and Stott and Kettleborough (2002) approach to constraining climate projections may be used to separately scale the future responses to well-mixed greenhouse gases and to aerosols, based on regressions over the historical period, since models may over- or under-estimate the climate response to greenhouse gases and aerosols by different factors. This kind of analysis requires future scenario simulations with subsets of forcings. DAMIP v1.0 included ssp245-nat, ssp245-GHG, ssp245-aer and ssp245-stratO3 simulations to address such needs (Gillett et al., 2016). Similarly, DAMIP v2.0 also includes future simulations with subsets of forcings following the Medium scenario from ScenarioMIP for CMIP7 (van Vuuren et al., 2025), which approximately corresponds to a continuation of current climate policies.

Medium-GHG: This is an extension of the hist-GHG simulations to 2100 using the Medium scenario well-mixed greenhouse gas concentrations, with other forcings kept at pre-industrial values.

Medium-aer: This is an extension of the hist-aer simulations to 2100 following the Medium scenario aerosol concentrations/emissions, with other forcings kept at pre-industrial levels. These simulations will also allow a more robust characterisation of the response to future aerosol changes, without conflating these changes with the responses to ozone and land-use changes, as would occur if the aerosol response were estimated from a difference between the Medium scenario and Medium-GHG.

Medium-O3: These simulations are extensions of the hist-O3 simulations to 2100 following the ozone concentrations specified for the Medium scenario. Stratospheric ozone is projected to recover following the successful implementation of the Montreal Protocol and its amendments (e.g. Hassler et al., 2022). These simulations will facilitate a robust multi-model assessment of the climate effects of this recovery on Southern Hemisphere climate and stratospheric temperature.

3.3 Interactive CO_2 experiments

Detection and attribution studies have typically attributed changes in the physical climate system to changes in concentrations of greenhouse gases and other species by regressing observed changes onto the simulated response to changes in concentrations of greenhouse gases and other species (e.g. Eyring et al., 2021), but an alternative bottom-up approach uses models directly to simulate the responses to changes in emissions of particular greenhouse gases or other species (e.g. Forster et al., 2021, Section 7.3; Szopa et al., 2021, Section 6.4). Such approaches can quantify the respective contributions of emissions of various chemical species, such as CO_2, methane, SO_2, and others. These approaches can account for feedbacks on the response to emissions of particular chemical species, based on their representation in models. IPCC (2021, Figure SPM.2) contrasted observationally-constrained attributable warming in response to changes in concentration of greenhouse gases among other factors, with estimates of the warming attributable to emissions of CO_2, methane and other species. These estimates included the simulated effects of tropospheric chemistry (Szopa et al., 2021), which strongly influence the responses to some forcings, but they omitted the effects of carbon-climate feedbacks which are also expected to influence the responses to such forcings (Szopa et al., 2021). In part to address this knowledge gap, we are proposing interactive-CO_2 versions of all the experiments described in Sections 3.1 and 3.2, with the exception of historical-CMIP6 (where our focus is on understanding differences in the concentration-driven historical experiments between CMIP6 and CMIP7). Such experiments should be carried out using Earth System Models (ESMs) with interactive carbon cycles, which can simulate atmospheric concentrations of CO_2 based on prescribed emissions. As noted above, we recommend that modelling centres carrying out these interactive CO_2 experiments also carry out the corresponding prescribed CO_2 experiments, allowing the effects of carbon-climate feedbacks on the response to each set of forcings to be quantified. These simulations should be run from 1850 to 2035, using the esm-hist CO_2 emissions and other forcings for the period 1850-2021, and the Medium scenario CO_2 emissions and other forcings for the period 2022 to 2035.

esm-hist-nat: These interactive-CO_2 simulations parallel esm-hist simulations, but with only solar and volcanic forcings varying, and all other forcings held fixed, including ozone. Such simulations can be used for example to evaluate the effects of carbon-climate feedbacks on the response to volcanoes (Kandlbauer et al., 2013; Rothenberg et al., 2012), or as a true counterfactual simulation reflecting the CO_2 evolution in the absence of anthropogenic influence.

esm-hist-GHG: These interactive-CO_2 simulations parallel the esm-hist simulations, but include only fossil CO_2 emissions and changes in the concentration of other well-mixed greenhouse gases (methane, nitrous oxide and fluorinated gas). No changes in land-use or emissions associated with land-use change should be prescribed.

esm-hist-aer: These interactive-CO_2 simulations parallel the esm-hist simulations, but include only changes in aerosol and aerosol precursor emissions. Changes in aerosols can perturb the carbon cycle not only through changes in the climate, but also through deposition of nutrients such as nitrogen, sulphur, iron and phosphorous, and through changes in solar irradiance and diffuse radiation at the surface (Szopa et al., 2021), and the response will depend on the representation of these mechanisms in each ESM.

esm-hist-lu: These interactive-CO_2 simulations parallel the esm-hist simulations but are forced with prescribed land-use and land cover changes only, with all other forcings held constant at 1850 values. Such experiments will include the simulation of CO_2 emissions based on prescribed land-use change, and will support the calculation of the net climate influence of land-use change (biogeophysical and carbon dioxide effects) (e.g. Intergovernmental Panel On Climate Change, 2022).

esm-hist-O3: These interactive-CO_2 simulations parallel the esm-hist simulations, but include only prescribed changes in tropospheric and stratospheric ozone concentration. Tropospheric ozone increases reduce terrestrial plant growth influencing land carbon uptake (Szopa et al., 2021). Early studies found a substantial role for stratospheric ozone in driving changes in the Southern Ocean carbon sink (Le Quéré et al., 2007), but more recent assessments find a weaker role (Garny et al., 2022). These simulations will support the investigation of the effects of such processes on atmospheric CO_2 concentration.

esm-hist-volc: These interactive-CO_2 simulations parallel the esm-hist simulations, but are driven with stratospheric aerosol changes only.

esm-Medium-GHG: Thes interactive CO_2 simulations are extensions of the esm-hist-GHG simulations to 2100, with CO_2 emissions and other well-mixed greenhouse gas concentrations following the Medium scenario.

esm-Medium-aer: Thes interactive CO_2 simulations are extensions of the esm-hist-aer simulations to 2100, with aerosol and aerosol precursor emissions following the Medium scenario.

esm-Medium-O3: These interactive CO_2 simulations are extensions of the esm-hist-O3 simulations to 2100, with tropospheric and stratospheric ozone concentration following the Medium scenario.

Figure 3 shows global mean surface CO_2 concentration and temperature in a subset of such simulations carried out with CanESM5.0 (Swart et al., 2019), compared with corresponding prescribed concentration simulations for reference. The simulated CO_2 in the esm-hist simulations of this model is within 15 ppm of that observed and that specified in the historical and hist-GHG simulations (compare the solid and dashed black lines in Figure 3a). As expected, esm-hist-GHG shows lower simulated CO_2 concentrations than esm-hist, because it includes only emissions of fossil CO_2 and omits land-use change emissions of CO_2. Because of this, esm-hist-GHG exhibits less warming than hist-GHG (Figure 3b). By contrast esm-hist-lu shows an increase in atmospheric CO_2 due to the interactively simulated effects of land-use change, and hence it is warmer than hist-lu, in which constant preindustrial CO_2 is specified (Figure 3b). In this model, atmospheric CO_2 increases slightly in esm-hist-aer. While the ocean takes up carbon in this simulation in response to the simulated cooling, this is more than compensated for by the land giving up carbon, likely due to reduced photosynthesis in response to the reduced solar irradiance. However, this model lacks a representation of the vegetation response to the change in diffuse irradiance associated with the increase in atmospheric aerosols (Szopa et al., 2021), and therefore this response might be different in other models. Because of this increase in atmospheric CO_2, the cooling in response to aerosols in esm-hist-aer is slightly weaker than in hist-aer, but overall these two experiments exhibit a comparable global surface temperature response in this model.

3.4 Updated forcing simulations

As noted in Section 3.1, for the purposes of detection and attribution analyses, we recommend extending CMIP7 historical simulations from 2022 to 2035 with the ScenarioMIP Medium scenario, and similarly to extend DAMIP single-forcing simulations from 2022 to 2035 with the individual forcings prescribed for this scenario. However, observed concentrations and emissions of forcing agents will at some point evolve differently from those specified in this scenario. While forcings have evolved broadly consistently with the SSP2-4.5 scenario used to extend DAMIP v1.0 simulations since 2015 (Matthews and Wynes, 2022), there have been some differences. For example, recent aerosol emissions from China have declined more strongly than those specified in the SSP2-4.5 scenario (Wang et al., 2021), a decline in marine sulphur emissions resulting from new International Maritime Organisation regulations was not included in the SSP2-4.5 simulations (Watson-Parris et al., 2022, 2024), the COVID-19 pandemic changed emissions temporarily in ways which were not included in the SSP2-4.5 scenario (e.g. Szopa et al., 2021), and the Hunga Tonga eruption in 2021 injected sulphur dioxide and water vapour into the stratosphere, influencing the climate (e.g. Jenkins et al., 2023). In the past such differences between forcings used to drive climate models simulations, and those which actually have transpired have been cited as reasons for differences between simulated and observed warming trends in the early 21st century (e.g. Eyring et al., 2021; Santer et al., 2014), and in the early 2020s (Rantanen and Laaksonen, 2024). For these reasons, LESFMIP proposed a set of individual forcing simulations using regularly updated forcing estimates, as part of CMIP6 (Smith et al., 2022), though at the time of writing such simulations have not yet been carried out and the protocols and process are not in place for the regular update of forcings which would support such experiments. If this could be achieved in the future, however, such simulations could be used to understand the influence of updates to particular forcing estimates in contributing to observed climate trends, particularly on interannual to decadal timescales, as well as to reduce uncertainties in attribution results associated with forcing changes after 2021. Given the uncertainty in whether future forcings over the next decade or so will diverge strongly from those specified in the Medium scenario, and if and when updated forcings datasets will be made available to the modelling community, we are not proposing additional named experiments here. However, we do note that the Earth System Grid Federation (ESGF) naming convention includes a forcing index which can be used to label different forcing variants for a given experiment. We recommend that this index is used to publish simulations with updated forcing variants if and when modelling centres perform them. For example, if the original version of hist-nat, using the Medium scenario forcings from 2022 to 2035 were published with the ‘f1’ forcing index, and were a major volcanic eruption to occur in 2027, and an updated stratospheric aerosol forcing datasets be published that year, a new version of the simulation using the updated forcings could be published with the ‘f2027’ forcing index. Such a simulation could cover only part of the time period covered by the original simulation (e.g. 2022-2035 only), as long as it is labelled appropriately. We suggest labelling such simulations with major updates to forcings with the year which historical forcings were extended to e.g. ‘f2027’. Alternatively a version number of the forcing dataset could be used. Any such effort would require additional community coordination and documentation if and when new forcing datasets were published, and would be most valuable if carried out in conjunction with updated all-forcing scenario simulations as part of ScenarioMIP or DCPP.

4. Synergies with other MIPs

In CMIP6, several DAMIP v1.0 experiments were coordinated with other MIPs in order to maximise synergies and support research to address a wide range of scientific questions (Gillett et al., 2016). For example, DAMIP v1.0 and the Radiative Forcing Model Intercomparison Project (RFMIP) (Pincus et al., 2016) proposed coordinated coupled and prescribed sea surface temperature simulations with natural-only and well-mixed GHG-only forcings, in order to estimate corresponding effective radiative forcings. For CMIP7, we have again coordinated with a broad range of MIPs to maximise scientific synergies.

As discussed above, all DAMIP v2.0 simulations extend beyond the end of the historical simulation in 2021, and we are recommending extending these simulations with the Medium scenario from ScenarioMIP. Our simulations which are extended to 2100 are also coordinated with ScenarioMIP to support understanding of the roles of individual forcings in driving future climate change in the Medium scenario. Similarly, we are coordinating our scenario choice with DCPP, such that both DAMIP simulations and DCPP simulations will use the same scenario, allowing the contributions of individual forcings to near-future climate change to be calculated and compared with initialised predictions under the same consistent set of forcings.

The AerChemMIP2 Assessment Fast Track hist-piAer experiments parallel the historical and Medium scenario simulations, except that aerosols are kept fixed at pre-industrial levels. Together with the hist-aer and historical experiments, these experiments will allow analysis of the extent to which the climate response to aerosols is additive with the response to other forcings. For this reason we encourage modelling centres participating in DAMIP to also carry out the hist-piAer simulations.

The RFMIP experiment piClim-histaer (which is an atmosphere-only simulation with fixed preindustrial SSTs and sea ice and transient aerosols) parallels hist-aer, except that it has fixed SSTs. This experiment can be used to diagnose the evolution of the effective radiative forcing of aerosols, while the DAMIP hist-aer experiment can be used to diagnose the climate response to that forcing.

High resolution climate model simulations are often able to better represent phenomena relevant to climate extremes, such as tropical cylones, atmospheric rivers, and heat waves and heavy rainfall in mountainous regions (e.g. Roberts et al., 2025). Such events are often the focus of extreme event attribution studies. The HighResMIP2 (Roberts et al., 2025) 1950s control (control-1950), and historical simulation beginning in 1950 (hist-1950), as well as its extension to 2100 with the Medium scenario will be valuable in supporting extreme event attribution for such variables, with allowance made for the fact that the 1950s control is not a preindustrial control. We also encourage modelling groups to carry out DAMIP experiments with high resolution models to the extent possible, but realize that computational constraints may prevent this. Finally, we note that the HighResMIP2 choice of the Medium scenario to extend historical simulations to 2100 aligns with our choice of the same scenario in DAMIP v2.0.

5. Variables requested by DAMIP

DAMIP has provided input to the process that is defining the harmonized data request for DECK and Assessment Fast Track experiments through the proposal of the "Detection and Attribution" opportunity. This opportunity contains basic variables that are needed for quantifying how the mean climate and its variability are changing over time, for understanding the mechanisms involved, and for comparing with the observational record with a view to detecting and attributing climate change signals. Many of these variables overlap with the proposed baseline variable set for Earth System Modeling (Juckes et al., 2024). These proposed variables include fields for assessing the different forcings that the climate system is experiencing, fields for assessing global mean temperature, hydrological, sea level, and circulation changes in both the atmosphere and ocean, as well as top of atmosphere and surface fluxes for diagnosing energy balances and fields for understanding the role of clouds in the climate system. With the move towards a greater role for emissions-driven simulations, we also request variables that would help us understand the origins of differences in CO_2 concentration among simulations when run in emissions-driven mode. A variety of daily fields are also requested to understand the time evolution of extremes and to diagnose synoptic features and daily surface fluxes that can be used to understand the drivers of those extremes. Finally, DAMIP requests zonal mean or 3D atmospheric temperature with a high vertical resolution extending deep into the stratosphere to allow the upper levels to be examined with sufficient resolution to be compared with Stratospheric Sounding Unit (SSU) observations (e.g. Mitchell, 2016; Santer et al., 2023). Stratospheric temperature trends are an important part of the climate change signal, and are also particularly insightful for assessing ozone recovery, volcanic aerosol, and solar signals (Mitchell, 2016; Santer et al., 2023).

We propose the "Detection and Attribution" variable groups be output for all DAMIP experiments and related experiments from the DECK and other MIPs shown in Figure 2. We also suggest that these be output for the pre-industrial control experiments to allow the uncertainties due to internal variability alone to be quantified as well as the AMIP experiments which can be used to explore the role of observed historical trends in SSTs in the evolution of the climate system and in potential differences between coupled models and observations. Since most of the variables proposed as part of the Detection and Attribution opportunity are basic fields needed to characterize the behaviour of the climate system, we also suggest that these variables be output for the more idealized experiments that are part of DECK and Assessment Fast Track that can be used to understand the behaviour of models and explore the direct effects of radiative forcings and the indirect effects of SST warming on the climate system. These include: 1pctCO2, 1pctCO2-bgc, 1pctCO2-rad, abrupt-4xCO2, piClim-anthro, hist-piSLCF, amip-p4k, and amip-piForcing. We also suggest that these variables are saved for the DCPP initialized predictions from 2025-2036 to compare simulated near term trends in these predictions with those in free-running coupled simulations, allowing for attribution of predicted trends in the climate system to external forcings as well as aspects of variability and change that are imparted to the models through the initial conditions in this particular experiment.

6. Summary

This paper describes the Detection and Attribution Model Intercomparison Project (DAMIP v2.0) which will form part of CMIP7 (Dunne et al., 2024) and is intended to underpin detection and attribution analysis informing the IPCC Seventh Assessment Report. DAMIP v1.0 simulations in CMIP6 were extensively used in the fields of attribution of climate trends, extreme event attribution and attribution of climate impacts, and they also underpinned the assessment of human-induced global warming in the IPCC AR6 (IPCC, 2021), which was reported in the Glasgow Climate Pact (UNFCCC, 2022).

DAMIP v2.0 again proposes hist-nat, hist-GHG and hist-aer simulations as high priority Assessment Fast Track simulations for CMIP7. These simulations were the most heavily used in CMIP6. We are proposing that they are extended to 2035 using the Medium scenario from ScenarioMIP. However, we also propose a set of historical simulations with forcings which together from the complete set of historical forcings (hist-GHG, hist-aer, hist-nat, hist-lu and hist-O3), allowing additivity to be easily tested, and ensuring all forcings are covered. Given that stratospheric and tropospheric ozone changes interact with each other, and to simplify the experimental design, we propose hist-O3 simulations which have prescribed ozone changes in the stratosphere and troposphere, rather than just in the stratosphere as was the case for CMIP6. To evaluate the effects of individual forcings on future climate evolution, we are proposing extension of key simulations to 2100 under the Medium emissions scenario. Finally, for CMIP7 we are proposing a new set of interactive-CO_2 simulations, which will among other things allow the net effect of land-use change on climate to be evaluated, and allow the effects of carbon-climate feedbacks on the simulated response to individual forcings to be evaluated.

Website of DAMIP: Updated details on the project and its progress will be available at https://wcrp-cmip.org/mips/damip/.

Code Availability: The full CanESM5 source code, used to run the simulation shown in Figure 3, is publicly available at https://gitlab.com/cccma/canesm (last access: 30 January 2025). The version of the code which can be used to produce all the simulations described in this paper, is tagged as v5.0.3 and has the associated DOI: https://doi.org/10.5281/zenodo.3251113 (Swart et al., 2019).

Data Availability: The model output from the DAMIP simulations described in this paper will be distributed through the Earth System Grid Federation (ESGF) with digital object identifiers (DOIs) assigned. The model output will be freely accessible through data portals after registration.

Author Contributions: As members of the Scientific Steering Committee of DAMIP v2.0, NPG, IRS, GH, RK, DM, AR, HS, DS, CT, PW and WZ together developed the experimental design for DAMIP v2.0. NPG prepared Figures 1 and 3, and IRS prepared Figure 2. VKA carried out the interactive CO_2 simulations shown in Figure 3. NPG led the writing of the manuscript, and all authors contributed to editing and revising the text.

Competing Interests: The authors declare that they have no conflict of interest.

Acknowledgments: CT was supported by the Office of Science, U.S. Department of Energy Biological and Environmental Research as part of the Water Cycle and Climate Extremes Modeling (WACCEM) project funded by the Regional and Global Model Analysis program area. Pacific Northwest National Laboratory is operated by Battelle for the U.S. Department of Energy under Contract DE-AC05-76RL01830. DS was supported by the Ministry of Business, Innovation and Employment (MBIE), Aotearoa New Zealand, through the Whakahura Endeavour Programme.

References

Allen, M. R., Stott, P. A., Mitchell, J. F. B., Schnur, R., and Delworth, T. L.: Quantifying the uncertainty in forecasts of anthropogenic climate change, Nature, 407, 617–620, https://doi.org/10.1038/35036559, 2000.

Canadell, J. G., Monteiro, P. M. S., Costa, M. H., Cotrim da Cunha, L., Cox, P. M., Eliseev, A. V., Henson, S., Ishii, M., Jaccard, S., Koven, C., Lohila, A., Patra, P. K., Piao, S., Rogelj, J., Syampungani, S., Zaehle, S., and Zickfeld, K.: Global Carbon and other Biogeochemical Cycles and Feedbacks, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 673–816, https://doi.org/10.1017/9781009157896.007, 2021.

Carlson, C. J.: After millions of preventable deaths, climate change must be treated like a health emergency, Nat Med, 30, 622–622, https://doi.org/10.1038/s41591-023-02765-y, 2024.

Chapman, S., Birch, C. E., Marsham, J. H., Part, C., Hajat, S., Chersich, M. F., Ebi, K. L., Luchters, S., Nakstad, B., and Kovats, S.: Past and projected climate change impacts on heat-related child mortality in Africa, Environ. Res. Lett., 17, 074028, https://doi.org/10.1088/1748-9326/ac7ac5, 2022.

Chiang, F., Mazdiyasni, O., and AghaKouchak, A.: Evidence of anthropogenic impacts on global drought frequency, duration, and intensity, Nat Commun, 12, 2754, https://doi.org/10.1038/s41467-021-22314-w, 2021.

Christidis, N., Mitchell, D., and Stott, P. A.: Rapidly increasing likelihood of exceeding 50 °C in parts of the Mediterranean and the Middle East due to human influence, npj Clim Atmos Sci, 6, 1–12, https://doi.org/10.1038/s41612-023-00377-4, 2023.

Doblas-Reyes, F. J., Sörensson, A. A., Almazroui, M., Dosio, A., Gutowski, W. J., Haarsma, R., Hamdi, R., Hewitson, B., Kwon, W.-T., Lamptey, B. L., Maraun, D., Stephenson, T. S., Takayabu, I., Terray, L., Turner, A., and Zuo, Z.: Linking Global to Regional Climate Change, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1363–1512, https://doi.org/10.1017/9781009157896.012, 2021.

Dong, B., Sutton, R. T., Shaffrey, L., and Harvey, B.: Recent decadal weakening of the summer Eurasian westerly jet attributable to anthropogenic aerosol emissions, Nat Commun, 13, 1148, https://doi.org/10.1038/s41467-022-28816-5, 2022.

Dunne, J. P., Hewitt, H. T., Arblaster, J., Bonou, F., Boucher, O., Cavazos, T., Durack, P. J., Hassler, B., Juckes, M., Miyakawa, T., Mizielinski, M., Naik, V., Nicholls, Z., O'Rourke, E., Pincus, R., Sanderson, B. M., Simpson, I. R., and Taylor, K. E.: An evolving Coupled Model Intercomparison Project phase 7 (CMIP7) and Fast Track in support of future climate assessment, EGUsphere, 1–51, https://doi.org/10.5194/egusphere-2024-3874, 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, Geosci. Model Dev., 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016, 2016.

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

Fischer, E. M., Beyerle, U., Bloin-Wibe, L., Gessner, C., Humphrey, V., Lehner, F., Pendergrass, A. G., Sippel, S., Zeder, J., and Knutti, R.: Storylines for unprecedented heatwaves based on ensemble boosting, Nat Commun, 14, 4643, https://doi.org/10.1038/s41467-023-40112-4, 2023.

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D. J., Mauritsen, T., Palmer, M. D., Watanabe, M., Wild, M., and Zhang, H.: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 923–1054, https://doi.org/10.1017/9781009157896.009, 2021.

Forster, P. M., Smith, C., Walsh, T., Lamb, W., Lamboll, R., Hall, B., Hauser, M., Ribes, A., Rosen, D., Gillett, N., Palmer, M. D., Rogelj, J., Von Schuckmann, K., Trewin, B., Allen, M., Andrew, R., Betts, R., Boyer, T., Buontempo, C., Burgess, S., Cagnazzo, C., Cheng, L., Friedlingstein, P., Gettelman, A., Gütschow, J., Ishii, M., Jenkins, S., Lan, X., Morice, C., Mühle, J., Kadow, C., Kennedy, J., Killick, R., Krummel, P. B., Minx, J. C., Myhre, G., Naik, V., Peters, G. P., Pirani, A., Pongratz, J., Schleussner, C.-F., Seneviratne, S. I., Szopa, S., Thorne, P., Kovilakam, M. V. M., Majamäki, E., Jalkanen, J.-P., Van Marle, M., Hoesly, R. M., Rohde, R., Schumacher, D., Van Der Werf, G., Vose, R., Zickfeld, K., Zhang, X., Masson-Delmotte, V., and Zhai, P.: Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence, https://doi.org/10.5194/essd-2024-149, 8 May 2024.

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

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, Proc. Natl. Acad. Sci. U.S.A., 118, e2016549118, https://doi.org/10.1073/pnas.2016549118, 2021.

Garny, H, Hendon, H, Abalos, M, Chiodo, G, Purich, A, Randel, W. J., Smith, K, and Thompson, D: Stratospheric ozone change and climate, in: World Meteorological Organisation Scientific assessment of ozone depletion: 2022, 271–323, 2022.

Gillett, N. P., Fyfe, J. C., and Parker, D. E.: Attribution of observed sea level pressure trends to greenhouse gas, aerosol, and ozone changes, Geophysical Research Letters, 40, 2302–2306, https://doi.org/10.1002/grl.50500, 2013.

Gillett, N. P., Shiogama, H., Funke, B., Hegerl, G., Knutti, R., Matthes, K., Santer, B. D., Stone, D., and Tebaldi, C.: The Detection and Attribution Model Intercomparison Project (DAMIP v1.0)contribution to CMIP6, Geosci. Model Dev., 9, 3685–3697, https://doi.org/10.5194/gmd-9-3685-2016, 2016.

Gillett, N. P., Kirchmeier-Young, M., Ribes, A., Shiogama, H., Hegerl, G. C., Knutti, R., Gastineau, G., John, J. G., Li, L., Nazarenko, L., Rosenbloom, N., Seland, Ø., Wu, T., Yukimoto, S., and Ziehn, T.:

Constraining human contributions to observed warming since the pre-industrial period, Nat. Clim. Chang., 11, 207–212, https://doi.org/10.1038/s41558-020-00965-9, 2021.

Hannart, A., Pearl, J., Otto, F. E. L., Naveau, P., and Ghil, M.: Causal Counterfactual Theory for the Attribution of Weather and Climate-Related Events, Bulletin of the American Meteorological Society, 97, 99–110, https://doi.org/10.1175/BAMS-D-14-00034.1, 2016.

Hardiman, S. C., Andrews, M. B., Andrews, T., Bushell, A. C., Dunstone, N. J., Dyson, H., Jones, G. S., Knight, J. R., Neininger, E., O'Connor, F. M., Ridley, J. K., Ringer, M. A., Scaife, A. A., Senior, C. A., and Wood, R. A.: The impact of prescribed ozone in climate projections run with HadGEM3-GC3. 1, JAMES, 11, 3443-3453, https://doi.org/10.1029/2019MS001714, 2019.

Hassler, Young, P., Ball, W., Damadeo, R., Keeble, J., Maillard Barras, E., and Sofieva, V.: Update on global ozone: Past, present and future, in: World Meteorological Organisation (WMO) Scientific Assessment of Ozone Depletion: 2022, vol. 278, 2022.

Herring, S. C., Christidis, N., Hoell, A., and Stott, P. A.: Explaining Extreme Events of 2020 from a Climate Perspective, Bulletin of the American Meteorological Society, 103, S1–S129, https://doi.org/10.1175/BAMS-ExplainingExtremeEvents2020.1, 2022.

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.

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, Bull. Am. Meteorol. Soc., 98, 589-602, https://doi.org/10.1175/BAMS-D-15-00135.1, 2017.

Intergovernmental Panel On Climate Change: Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems, 1st ed., Cambridge University Press, https://doi.org/10.1017/9781009157988, 2022.

IPCC: Summary for Policymakers, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 3−32, https://doi.org/10.1017/9781009157896.001, 2021.

James, R. A., Jones, R. G., Boyd, E., Young, H. R., Otto, F. E. L., Huggel, C., and Fuglestvedt, J. S.: Attribution: How Is It Relevant for Loss and Damage Policy and Practice?, in: Loss and Damage from Climate Change, edited by: Mechler, R., Bouwer, L. M., Schinko, T., Surminski, S., and Linnerooth-Bayer, J., Springer International Publishing, Cham, 113–154, https://doi.org/10.1007/978-3-319-72026-5_5, 2019.

Jenkins, S., Smith, C., Allen, M., and Grainger, R.: Tonga eruption increases chance of temporary surface temperature anomaly above 1.5 °C, Nat. Clim. Chang., 13, 127–129, https://doi.org/10.1038/s41558-022-01568-2, 2023.

Jones, C. D., Hickman, J. E., Rumbold, S. T., Walton, J., Lamboll, R. D., Skeie, R. B., Fiedler, S., Forster, P. M., Rogelj, J., Abe, M., Botzet, M., Calvin, K., Cassou, C., Cole, J. N. S., Davini, P., Deushi, M., Dix, M., Fyfe, J. C., Gillett, N. P., Ilyina, T., Kawamiya, M., Kelley, M., Kharin, S., Koshiro, T., Li, H., Mackallah, C., Müller, W. A., Nabat, P., Van Noije, T., Nolan, P., Ohgaito, R., Olivié, D., Oshima, N., Parodi, J., Reerink, T. J., Ren, L., Romanou, A., Séférian, R., Tang, Y., Timmreck, C., Tjiputra, J., Tourigny, E., Tsigaridis, K., Wang, H., Wu, M., Wyser, K., Yang, S., Yang, Y., and Ziehn, T.: The Climate Response to Emissions Reductions Due to COVID-19: Initial Results From CovidMIP, Geophysical Research Letters, 48, e2020GL091883, https://doi.org/10.1029/2020GL091883, 2021.

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, EGUsphere, 1–37, https://doi.org/10.5194/egusphere-2024-2363, 2024.

Kandlbauer, J., Hopcroft, P. O., Valdes, P. J., and Sparks, R. S. J.: Climate and carbon cycle response to the 1815 Tambora volcanic eruption, Journal of Geophysical Research: Atmospheres, 118, 12,497-12,507, https://doi.org/10.1002/2013JD019767, 2013.

Kang, J. M., Shaw, T. A., Kang, S. M., Simpson, I. R., and Yu, Y.: Revisiting the reanalysis-model discrepancy in Southern Hemisphere winter storm track trends, npj Clim Atmos Sci, 7, 1–10, https://doi.org/10.1038/s41612-024-00801-3, 2024.

King, A. D.: Attributing Changing Rates of Temperature Record Breaking to Anthropogenic Influences, Earth's Future, 5, 1156–1168, https://doi.org/10.1002/2017EF000611, 2017.

Lanet, M., Li, L., Ehret, A., Turquety, S., and Le Treut, H.: Attribution of summer 2022 extreme wildfire season in Southwest France to anthropogenic climate change, npj Clim Atmos Sci, 7, 1–10, https://doi.org/10.1038/s41612-024-00821-z, 2024.

Lawrence, D. M., Hurtt, G. C., Arneth, A., Brovkin, V., Calvin, K. V., Jones, A. D., Jones, C. D., Lawrence, P. J., de Noblet-Ducoudré, N., Pongratz, J., Seneviratne, S. I., and Shevliakova, E.: The Land Use Model Intercomparison Project (LUMIP) contribution to CMIP6: rationale and experimental design, Geoscientific Model Development, 9, 2973–2998, https://doi.org/10.5194/gmd-9-2973-2016, 2016.

Le Quéré, C., Rödenbeck, C., Buitenhuis, E. T., Conway, T. J., Langenfelds, R., Gomez, A., Labuschagne, C., Ramonet, M., Nakazawa, T., Metzl, N., Gillett, N., and Heimann, M.: Saturation of the Southern Ocean CO_2 Sink Due to Recent Climate Change, Science, 316, 1735–1738, https://doi.org/10.1126/science.1136188, 2007.

Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J. P., Engelbrecht, F., Fischer, E., Fyfe, J. C., Jones, C., Maycock, A., Mutemi, J., Ndiaye, O., Panickal, S., and Zhou, T.: Future Global Climate: Scenario-Based Projections and Near-Term Information, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 553–672, https://doi.org/10.1017/9781009157896.006, 2021.

Li, X., Zhang, L., Wang, G., Cao, H., Zhang, H., Jia, B., Zhou, Z., Liu, L., and Zhang, L.: Anthropogenic forcing decreases the probability of the 2020 Yangtze River extreme flood and future risk, Atmospheric Research, 311, 107662, https://doi.org/10.1016/j.atmosres.2024.107662, 2024a.

Li, Y., Xia, Y., Xie, F., and Yan, Y.: Influence of stratosphere-troposphere exchange on long-term trends of surface ozone in CMIP6, Atmospheric Research, 297, 107086, https://doi.org/10.1016/j.atmosres.2023.107086, 2024b.

Liddicoat, S. K., Wiltshire, A. J., Jones, C. D., Arora, V. K., Brovkin, V., Cadule, P., Hajima, T., Lawrence, D. M., Pongratz, J., Schwinger, J., Séférian, R., Tjiputra, J. F., and Ziehn, T.: Compatible Fossil Fuel CO2 Emissions in the CMIP6 Earth System Models' Historical and Shared Socioeconomic Pathway Experiments of the Twenty-First Century, Journal of Climate, 34, 2853–2875,

https://doi.org/10.1175/JCLI-D-19-0991.1, 2021.
Liu, W., Hegglin, M. I., Checa-Garcia, R., Li, S., Gillett, N. P., Lyu, K., Zhang, X., and Swart, N. C.: Stratospheric ozone depletion and tropospheric ozone increases drive Southern Ocean interior warming, Nat. Clim. Chang., 12, 365–372, https://doi.org/10.1038/s41558-022-01320-w, 2022.
Luo, X., Ge, J., Cao, Y., Liu, Y., Yang, L., Wang, S., and Guo, W.: Local and Nonlocal Biophysical Effects of Historical Land Use and Land Cover Changes in CMIP6 Models and the Intermodel Uncertainty, Earth's Future, 12, e2023EF004220, https://doi.org/10.1029/2023EF004220, 2024.
Marvel, K., Schmidt, G. A., Shindell, D., Bonfils, C., LeGrande, A. N., Nazarenko, L., and Tsigaridis, K.: Do responses to different anthropogenic forcings add linearly in climate models?, Environ. Res. Lett., 10, 104010, https://doi.org/10.1088/1748-9326/10/10/104010, 2015.
Matthews, H. D. and Wynes, S.: Current global efforts are insufficient to limit warming to 1.5°C, Science, 376, 1404–1409, https://doi.org/10.1126/science.abo3378, 2022.
Menary, M. B., Robson, J., Allan, R. P., Booth, B. B. B., Cassou, C., Gastineau, G., Gregory, J., Hodson, D., Jones, C., Mignot, J., Ringer, M., Sutton, R., Wilcox, L., and Zhang, R.: Aerosol-Forced AMOC Changes in CMIP6 Historical Simulations, Geophysical Research Letters, 47, e2020GL088166, https://doi.org/10.1029/2020GL088166, 2020.
Mitchell, D. M.: Attributing the forced components of observed stratospheric temperature variability to external drivers, Quarterly Journal of the Royal Meteorological Society, 142, 1041–1047, https://doi.org/10.1002/qj.2707, 2016.
Morgenstern, O.: The Southern Annular Mode in 6th Coupled Model Intercomparison Project Models, Journal of Geophysical Research: Atmospheres, 126, e2020JD034161, https://doi.org/10.1029/2020JD034161, 2021.
Naveau, P., Hannart, A., and Ribes, A.: Statistical Methods for Extreme Event Attribution in Climate Science, Annual Review of Statistics and Its Application, 7, 89–110, https://doi.org/10.1146/annurev-statistics-031219-041314, 2020.
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, Geosci. Model Dev., 9, 3461–3482, https://doi.org/10.5194/gmd-9-3461-2016, 2016.
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.
Rantanen, M. and Laaksonen, A.: The jump in global temperatures in September 2023 is extremely unlikely due to internal climate variability alone, npj Clim Atmos Sci, 7, 1–4, https://doi.org/10.1038/s41612-024-00582-9, 2024.
Ribes, A., Qasmi, S., and Gillett, N. P.: Making climate projections conditional on historical observations, Sci. Adv., 7, eabc0671, https://doi.org/10.1126/sciadv.abc0671, 2021.
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., ul Hasson, S., 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, Geosci. Model Dev., 18, 1307–1332, https://doi.org/10.5194/gmd-18-1307-2025, 2025.
Rothenberg, D., Mahowald, N., Lindsay, K., Doney, S. C., Moore, J. K., and Thornton, P.: Volcano impacts on

climate and biogeochemistry in a coupled carbon–climate model, Earth System Dynamics, 3, 121–136, https://doi.org/10.5194/esd-3-121-2012, 2012.

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, 2024.

Santer, B. D., Bonfils, C., Painter, J. F., Zelinka, M. D., Mears, C., Solomon, S., Schmidt, G. A., Fyfe, J. C., Cole, J. N. S., Nazarenko, L., Taylor, K. E., and Wentz, F. J.: Volcanic contribution to decadal changes in tropospheric temperature, Nature Geosci, 7, 185–189, https://doi.org/10.1038/ngeo2098, 2014.

Santer, B. D., Po-Chedley, S., Zhao, L., Zou, C.-Z., Fu, Q., Solomon, S., Thompson, D. W. J., Mears, C., and Taylor, K. E.: Exceptional stratospheric contribution to human fingerprints on atmospheric temperature, Proceedings of the National Academy of Sciences, 120, e2300758120, https://doi.org/10.1073/pnas.2300758120, 2023.

Schaller, N., Otto, F., Van Oldenborgh, G. J., Massey, N., Sparrow, S., and Allen, M.: THE HEAVY PRECIPITATION EVENT OF MAY-JUNE 2013 IN THE UPPER DANUBE AND ELBE BASINS, Bulletin of the American Meteorological Society, 95, S69–S72, 2014.

Shiogama, H., Stone, D. A., Nagashima, T., Nozawa, T., and Emori, S.: On the linear additivity of climate forcing-response relationships at global and continental scales, International Journal of Climatology, 33, 2542–2550, https://doi.org/10.1002/joc.3607, 2013.

Shiogama, H., Tatebe, H., Hayashi, M., Abe, M., Arai, M., Koyama, H., Imada, Y., Kosaka, Y., Ogura, T., and Watanabe, M.: MIROC6 Large Ensemble (MIROC6-LE): experimental design and initial analyses, Earth Syst. Dynam., 14, 1107–1124, https://doi.org/10.5194/esd-14-1107-2023, 2023.

Simpson, I. R., Rosenbloom, N., Danabasoglu, G., Deser, C., Yeager, S. G., McCluskey, C. S., Yamaguchi, R., Lamarque, J.-F., Tilmes, S., Mills, M. J., and Rodgers, K. B.: The CESM2 Single-Forcing Large Ensemble and Comparison to CESM1: Implications for Experimental Design, Journal of Climate, 36, 5687–5711, https://doi.org/10.1175/JCLI-D-22-0666.1, 2023.

Sippel, S., Mitchell, D., Black, M. T., Dittus, A. J., Harrington, L., Schaller, N., and Otto, F. E. L.: Combining large model ensembles with extreme value statistics to improve attribution statements of rare events, Weather and Climate Extremes, 9, 25–35, https://doi.org/10.1016/j.wace.2015.06.004, 2015.

Smith, D. M., Gillett, N. P., Simpson, I. R., Athanasiadis, P. J., Baehr, J., Bethke, I., Bilge, T. A., Bonnet, R., Boucher, O., Findell, K. L., Gastineau, G., Gualdi, S., Hermanson, L., Leung, L. R., Mignot, J., Müller, W. A., Osprey, S., Otterå, O. H., Persad, G. G., Scaife, A. A., Schmidt, G. A., Shiogama, H., Sutton, R. T., Swingedouw, D., Yang, S., Zhou, T., and Ziehn, T.: Attribution of multi-annual to decadal changes in the climate system: The Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP), Front. Clim., 4, 955414, https://doi.org/10.3389/fclim.2022.955414, 2022.

Stott, P. A. and Kettleborough, J. A.: Origins and estimates of uncertainty in predictions of twenty-first century temperature rise, Nature, 416, 723–726, https://doi.org/10.1038/416723a, 2002.

Stott, P. A., Stone, D. A., and Allen, M. R.: Human contribution to the European heatwave of 2003, Nature, 432, 610–614, https://doi.org/10.1038/nature03089, 2004.

Swart, N. C., Cole, J. N. S., Kharin, V. V., Lazare, M., Scinocca, J. F., Gillett, N. P., Anstey, J., Arora, V., Christian, J. R., Hanna, S., Jiao, Y., Lee, W. G., Majaess, F., Saenko, O. A., Seiler, C., Seinen, C., Shao, A., Sigmond, M., Solheim, L., Von Salzen, K., Yang, D., and Winter, B.: The Canadian Earth System Model version 5 (CanESM5.0.3), Geoscientific Model Development, 12, 4823–4873,

https://doi.org/10.5194/gmd-12-4823-2019, 2019.
Szopa, S., Naik, V., Adhikary, B., Artaxo, P., Berntsen, T., Collins, W. D., Fuzzi, S., Gallardo, L., Kiendler-Scharr, A., Klimont, Z., Liao, H., Unger, N., and Zanis, P.: Short-Lived Climate Forcers, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 817–922, https://doi.org/10.1017/9781009157896.008, 2021.
UNFCCC: Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on its third session, held in Glasgow from 31 October to13 November 2021, 2022.
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.

Vicedo-Cabrera, A. M., Scovronick, N., Sera, F., Royé, D., Schneider, R., Tobias, A., Astrom, C., Guo, Y., Honda, Y., Hondula, D. M., Abrutzky, R., Tong, S., Coelho, M. de S. Z. S., Saldiva, P. H. N., Lavigne, E., Correa, P. M., Ortega, N. V., Kan, H., Osorio, S., Kyselý, J., Urban, A., Orru, H., Indermitte, E., Jaakkola, J. J. K., Ryti, N., Pascal, M., Schneider, A., Katsouyanni, K., Samoli, E., Mayvaneh, F., Entezari, A., Goodman, P., Zeka, A., Michelozzi, P., de'Donato, F., Hashizume, M., Alahmad, B., Diaz, M. H., Valencia, C. D. L. C., Overcenco, A., Houthuijs, D., Ameling, C., Rao, S., Di Ruscio, F., Carrasco-Escobar, G., Seposo, X., Silva, S., Madureira, J., Holobaca, I. H., Fratianni, S., Acquaotta, F., Kim, H., Lee, W., Iniguez, C., Forsberg, B., Ragettli, M. S., Guo, Y. L. L., Chen, B. Y., Li, S., Armstrong, B., Aleman, A., Zanobetti, A., Schwartz, J., Dang, T. N., Dung, D. V., Gillett, N., Haines, A., Mengel, M., Huber, V., and Gasparrini, A.: The burden of heat-related mortality attributable to recent human-induced climate change, Nat. Clim. Chang., 11, 492–500, https://doi.org/10.1038/s41558-021-01058-x, 2021.
Wang, Z., Lin, L., Xu, Y., Che, H., Zhang, X., Zhang, H., Dong, W., Wang, C., Gui, K., and Xie, B.: Incorrect Asian aerosols affecting the attribution and projection of regional climate change in CMIP6 models, npj Clim Atmos Sci, 4, 1–8, https://doi.org/10.1038/s41612-020-00159-2, 2021.
Watson-Parris, D., Christensen, M. W., Laurenson, A., Clewley, D., Gryspeerdt, E., and Stier, P.: Shipping regulations lead to large reduction in cloud perturbations, Proceedings of the National Academy of Sciences, 119, e2206885119, https://doi.org/10.1073/pnas.2206885119, 2022.
Watson-Parris, D., Wilcox, L. J., Stjern, C. W., Allen, R. J., Persad, G., Bollasina, M. A., Ekman, A. M. L., Iles, C. E., Joshi, M., Lund, M. T., McCoy, D., Westervelt, D., Williams, A., and Samset, B. H.: Weak surface temperature effects of recent reductions in shipping SO_2 emissions, with quantification confounded by internal variability, EGUsphere, 1–30, https://doi.org/10.5194/egusphere-2024-1946, 2024.
Zhang, M., Gao, Y., Ting, M., Yu, Y., and Wang, G.: Land-use induced changes in extreme temperature predominantly influenced by downward longwave radiation, Commun Earth Environ, 5, 1–11, https://doi.org/10.1038/s43247-024-01936-0, 2024a.
Zhang, W., Zhou, T., and Wu, P.: Anthropogenic amplification of precipitation variability over the past

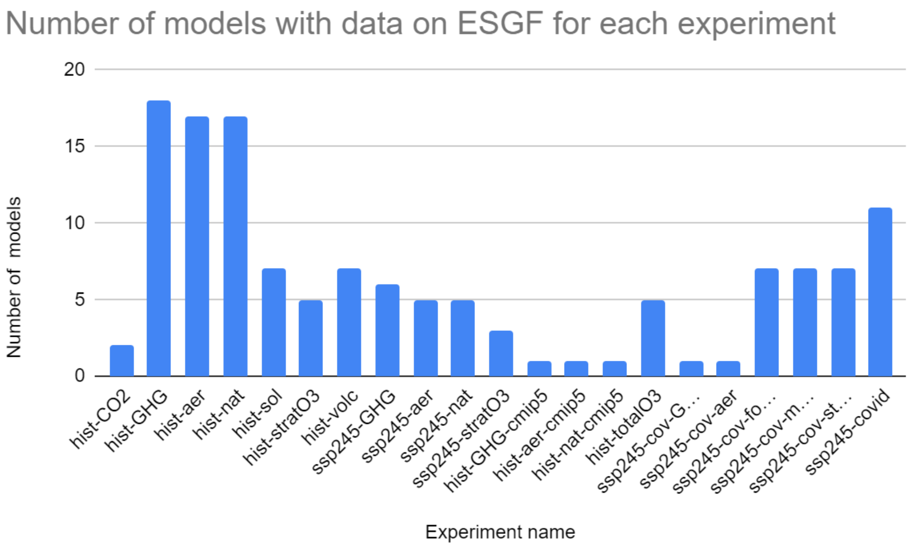
century, Science, 385, 427–432, https://doi.org/10.1126/science.adp0212, 2024b.
Zhang, Y., Hajat, S., Zhao, L., Chen, H., Cheng, L., Ren, M., Gu, K., Ji, J. S., Liang, W., and Huang, C.: The burden of heatwave-related preterm births and associated human capital losses in China, Nat Commun, 13, 7565, https://doi.org/10.1038/s41467-022-35008-8, 2022.
Zhuang, Y., Fu, R., Santer, B. D., Dickinson, R. E., and Hall, A.: Quantifying contributions of natural variability and anthropogenic forcings on increased fire weather risk over the western United States, Proceedings of the National Academy of Sciences, 118, e2111875118, https://doi.org/10.1073/pnas.2111875118, 2021.

Table 1 DAMIP v2.0 simulations.

Name	**Description of prescribed concentration simulations (forcing agents perturbed)**	**Interactive CO_2 equivalent simulation name (modifications)**	**Modifications for coupled chemistry models**	**Start year**	**End year**	**Minimum ensemble size**
historical and Medium scenario	Enlarging ensemble size of historical (1850-2021) and ScenarioMIP Medium scenario (scen7-mc, 2022-2035) to an ensemble size of at least 3. Forcings: WMGHGs, BC, OC, SO_2, SO_4, NO_x , NH_3, CO, NMVOC, nitrogen deposition, ozone, stratospheric aerosols, solar irradiance, land use)	esm-hist and esm-scen7-m (prescribe fossil CO_2 emissions instead of concentrations)		1850	2035	3
hist-nat	Natural-only historical simulations (solar irradiance, stratospheric aerosol)	esm-hist-nat		1850	2035	3
hist-GHG	Well-mixed greenhouse gas only historical simulations (WMGHGs)	esm-hist-GHG (prescribe fossil CO_2 emissions instead of CO_2 concentrations)	Prescribe emissions instead of concentrations of those WMGHGs simulated interactively	1850	2035	3
hist-aer	Anthropogenic aerosol-only historical simulations (BC, OC, SO_2, SO_4, NO_x , NH_3, CO, NMVOC)	esm-hist-aer		1850	2035	3
hist-O3	Ozone-only historical	esm-hist-O3	NA	1850	2035	3

	simulations (ozone concentration)					
hist-lu	Land-use change only historical simulation	esm-hist-lu		1850	2035	3
historical-CMIP6	Historical simulation with forcings from CMIP6 historical and SSP2-4.5 (WMGHGs, BC, OC, SO_2, SO_4, NO_x , NH_3, CO, NMVOC, nitrogen deposition, ozone, stratospheric aerosols, solar irradiance, land use)	NA	NA	1850	2035	3
hist-volc	Volcanic aerosol only historical simulation (stratospheric aerosols)	esm-hist-volc		1850	2035	3
Medium-GHG	Extension of at least one hist-GHG experiment to 2100 using the Medium scenario.	esm-Medium-ghg (prescribe fossil CO_2 emissions instead of CO_2 concentrations)	Prescribe emissions instead of concentrations of those WMGHGs simulated interactively	2036	2100	1
Medium-aer	Extension of at least one hist-aer experiment to 2100 using the Medium scenario.	esm-Medium-aer		2036	2100	1
Medium-O3	Extension of at least one hist-O3 experiment to 2100 using the Medium scenario.	esm-Medium-O3	NA	2036	2100	1

(a)



(b)

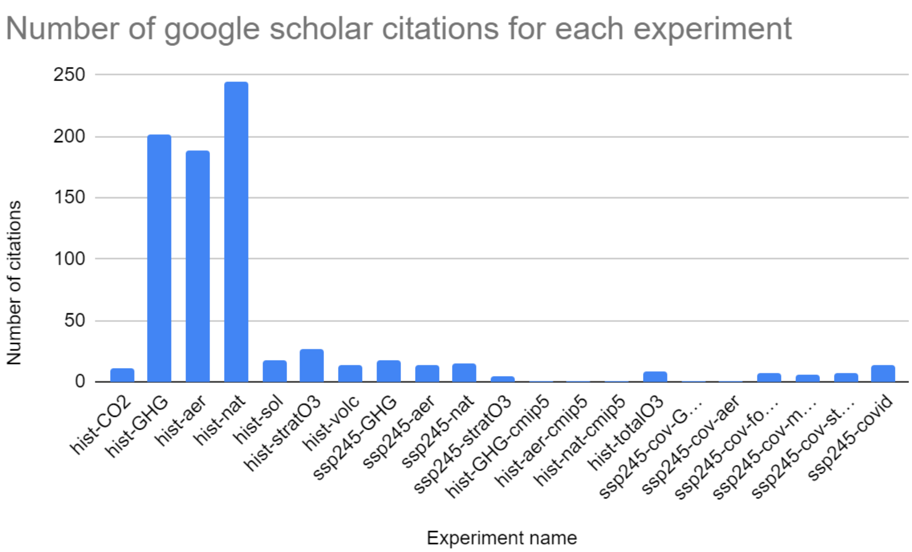


Figure 1. Bar graphs showing (a) the number of models with data published on ESGF for each DAMIP v1.0 experiment, and (b) the number of Google Scholar citations for each DAMIP v1.0 experiment (based on a search for ‘CMIP6’ and each experiment name), as of July 31st 2024.

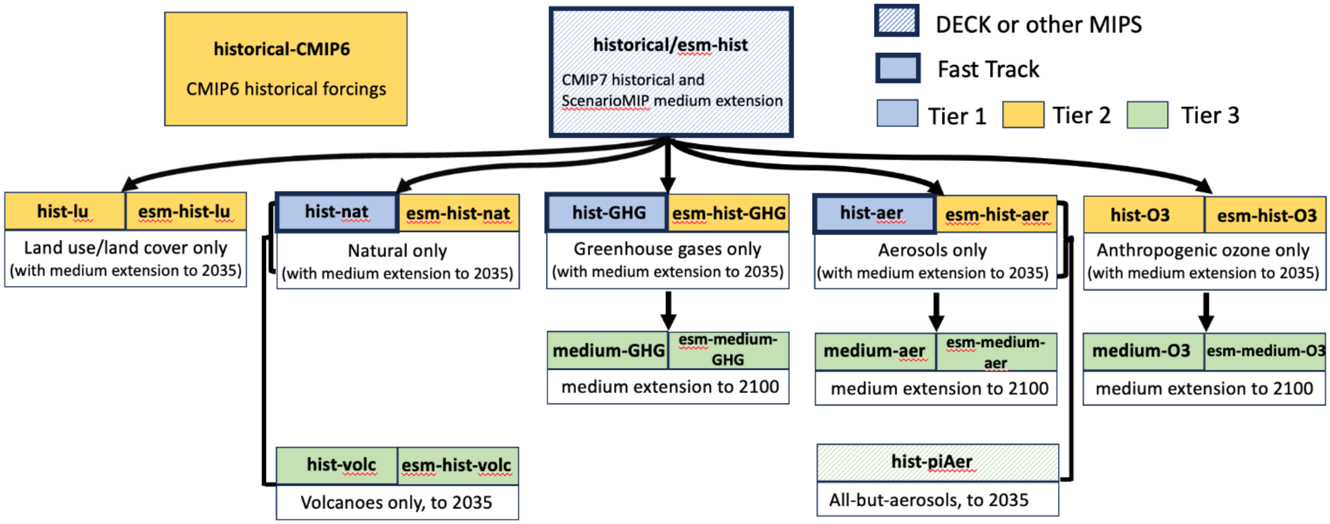


Figure 2. Schematic of the experiments proposed under DAMIP v2.0 for CMIP7. Blue boxes are Tier 1 experiments, yellow boxes are Tier 2 experiments, green boxes are Tier 3 experiments, and white boxes contain descriptive text. All historical simulations except historical-CMIP6 run from 1850 to 2035 using the Medium scenario forcings from 2022, while historical-CMIP6 runs from 1850 to 2035 using the SSP2-4.5 scenario from 2015. The *historical* or *esm-hist* simulation shown in the top row uses CMIP7 historical forcings which can be decomposed into the sets of forcings used in each of the simulations in the second row. Three of these simulations are extended using the Medium scenario from 2036 to 2100 as shown in the third row. The fourth row depicts two additional experiments that are complementary to those in the second row. Hatched boxes show simulations which are in other MIPs, but which are of particular relevance to DAMIP.

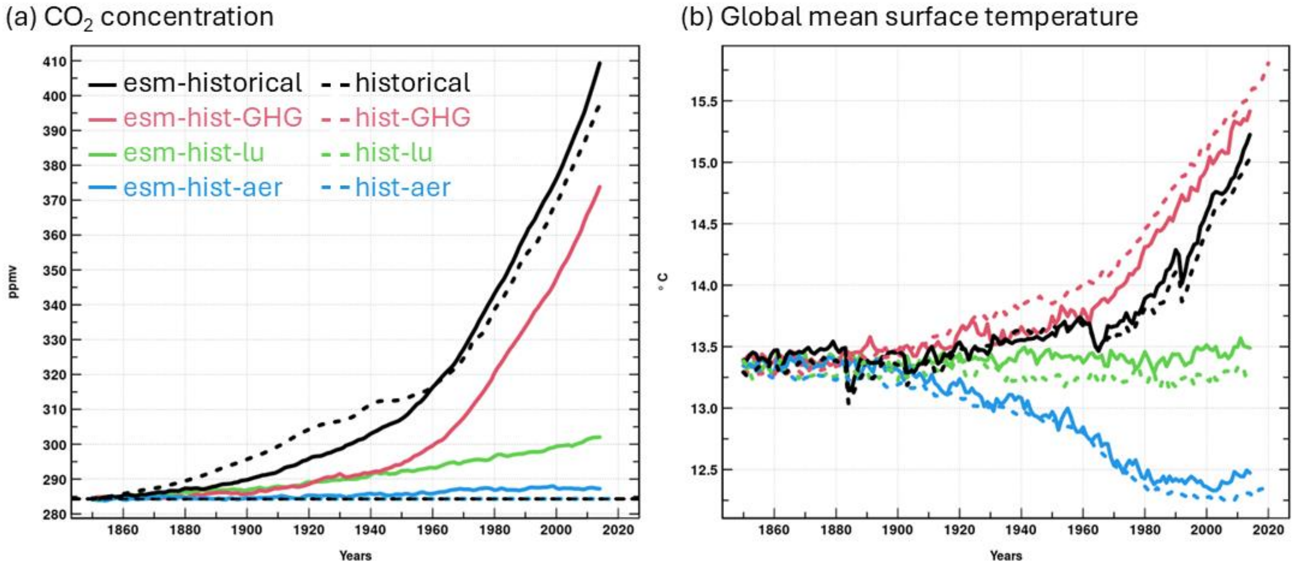


Figure 3. Global mean surface CO_2 concentration (a) and global mean near-surface air temperature (b) in interactive CO_2 experiments performed with CanESM5.0 (Swart et al., 2019). Solid lines show results from interactive CO_2 simulations (esm-hist (black), esm-hist-GHG (red), esm-hist-lu (green), and esm-hist-aer (blue)), and dashed lines show results from corresponding prescribed CO_2 simulations (historical (black), hist-GHG (red), hist-lu (green), and hist-aer (blue)). Results shown are ensemble means of at least five ensemble members. Note that the CO_2 concentration prescribed in hist-GHG is the same as that in historical, and is fixed at the preindustrial level in hist-lu and hist-aer.