https://doi.org/10.5194/egusphere-2026-398
Preprint. Discussion started: 29 January 2026

The Cloud Feedback Model Intercomparison Project (CFMIP) contribution to CMIP7

Paulo Ceppi[1], Alejandro Bodas-Salcedo[2], Mark D. Zelinka[3], Timothy Andrews[2,4], Florent Brient[5,6], Robin Chadwick[2,7], Jonathan M. Gregory[8], Yen-Ting Hwang[9], Sarah M. Kang[10], Jennifer E. Kay[11,12], Thorsten Mauritsen[13,14], Tomoo Ogura[15], George Tselioudis[16], Masahiro Watanabe[17], Mark J. Webb[2], and Allison A. Wing[18]

[1]Department of Physics, Imperial College London, London, UK
[2]Met Office Hadley Centre, Exeter, UK
[3]Lawrence Livermore National Laboratory, Livermore, CA, USA
[4]School of Earth and Environment, University of Leeds, Leeds, United Kingdom
[5]LMD/IPSL, Sorbonne Université, Paris, France
[6]Institut Universitaire de France (IUF), Paris, France
[7]Global Systems Institute, Department of Mathematics and Statistics, University of Exeter, Exeter, UK
[8]National Centre for Atmospheric Science, University of Reading, Reading, UK
[9]Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan
[10]Max Planck Institute for Meteorology, Hamburg, Germany
[11]Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, Colorado, USA
[12]Cooperative Institute for Research in Environmental Science, University of Colorado Boulder, Boulder, Colorado, USA
[13]Department of Meteorology, Stockholm University, Stockholm, Sweden
[14]Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden
[15]Earth System Division, National Institute for Environmental Studies, Tsukuba, Japan
[16]Goddard Institute for Space Studies, NASA, New York, NY, USA
[17]Atmosphere and Ocean Research Institute, University of Tokyo, Kashiwa, Japan
[18]Department of Earth, Ocean and Atmospheric Science, Florida State University, Tallahassee, FL, USA

Correspondence: Paulo Ceppi (p.ceppi@imperial.ac.uk)

Abstract. Cloud processes constitute one of the key uncertainties for climate change projections. The fourth iteration of the Cloud Feedback Model Intercomparison Project, CFMIP4, contributes to the Coupled Model Intercomparison Project phase 7 (CMIP7), by providing a set of global climate model experiments aiming to enhance our understanding of clouds, circulation and climate sensitivity, thereby informing improved projections of future climate change. CFMIP4 targets four knowledge gaps: (1) Physical mechanisms of cloud feedback and adjustment; (2) Dependence of cloud feedback and adjustment on climate base state and on the nature of the forcing; (3) Coupled mechanisms of the sea-surface temperature "pattern effect"; and (4) Coupling of clouds with circulation and precipitation. CFMIP4 contributes four CMIP7 Assessment Fast Track experiments that are central to the quantification of climate feedback and sensitivity in past, present and future climates, essential for process understanding and model evaluation. Furthermore, CFMIP4 supports the joint analysis of models and observations through a data request that includes process and satellite simulator output.

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1 Introduction

Clouds play a fundamental role for climate variability and change by modulating the Earth's radiation budget, as well as by coupling with atmospheric circulation and precipitation. These processes are however subject to substantial and long-standing uncertainty in global climate models (GCMs), and they are difficult to constrain observationally. The purpose of the Cloud Feedback Model Intercomparison Project (CFMIP) is to inform improved projections of future climate change, by understanding and evaluating clouds, circulation and climate sensitivity. The present paper aims to motivate and describe the science questions and experimental protocol of the fourth iteration of CFMIP, hereafter CFMIP4, which will contribute to phase seven of the Coupled Model Intercomparison Project (CMIP7; Dunne et al., 2025).

A long-standing focus of CFMIP activities has been on understanding and quantifying cloud feedback and adjustment, the two main processes through which clouds affect the climate sensitivity. Cloud feedback and adjustment represent respectively the slow, SST-mediated and the fast, non-SST-mediated components of the cloud-radiative response to forcing. Cloud feedback in particular has dominated inter-model spread in climate sensitivity across generations of GCMs (Charney et al., 1979; Cess et al., 1990; Zelinka et al., 2020), and also constitutes a key uncertainty in process-based assessments of the climate sensitivity (Sherwood et al., 2020; Forster et al., 2021). Radiative feedback is commonly estimated by least-squares regression of top-of-atmosphere radiative anomalies onto global-mean surface temperature, under the assumption that the Earth's global radiative response, R, is approximately linear with respect to surface temperature anomaly ΔT: $R \approx \lambda \Delta T$, with the climate feedback parameter λ assumed near-constant (Gregory et al., 2004).

Over the last decade, the CFMIP community has played a leading role in demonstrating that cloud feedback is in fact non-constant, and in particular that it differs substantially between observed historical climate and future projected climate change (e.g., Zhou et al., 2016; Gregory and Andrews, 2016; Andrews et al., 2018, 2022). Analysis of experiments involving different forcing agents and forcing time evolutions has revealed that λ varies with time, forcing agent, forcing magnitude, and the climate base state (e.g., Hansen et al., 2005; Marvel et al., 2016; Ceppi and Gregory, 2019; Bloch-Johnson et al., 2021; Salvi et al., 2022; Günther et al., 2022; Zhou et al., 2023; Salvi et al., 2023; Ringer et al., 2023; Mutton et al., 2024), with cloud feedback often dominating the variations in λ.

Much of this variation in cloud feedback is now understood to result from anomalous patterns of sea-surface temperature (SST), via their effect on lower-tropospheric stability and boundary-layer cloud – a phenomenon known as the "SST pattern effect" (Stevens et al., 2016; Rugenstein et al., 2023). This pattern effect accounts for cloud-radiative variability on timescales ranging from inter-annual to multi-decadal, involving both forced SST responses and unforced coupled climate variability. Beyond the SST pattern effect however, the climate base state also affects cloud feedback (and potentially also cloud adjustment), particularly through a dependence on temperature (e.g., Bloch-Johnson et al., 2015; Bjordal et al., 2020; Bloch-Johnson et al., 2021) – thus further contributing to changes in λ as the climate warms.

The climate impact of clouds occurs not only via the global radiation budget, but also through interactions with regional climate processes. The CFMIP community therefore has a long-standing interest in cloud–circulation coupling across a range of scales (Bony et al., 2015), from convective processes (Wing et al., 2018; Bony et al., 2020; Wing et al., 2024) to planetary-

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scale circulations such as the Hadley cells and the midlatitude jets (Tselioudis et al., 2016; Natchiar et al., 2024). Recent years have seen an increased focus on interactions between clouds and ocean processes, producing novel insights into how clouds can affect patterns of SST under both natural variability and forced climate change (Ying and Huang, 2016; Bellomo et al., 2016; Brown et al., 2016; Myers and Mechoso, 2020; Kim et al., 2022; Hsiao et al., 2022; Kang et al., 2023b; Breul et al., 2025).

These recent advances in the understanding of clouds and their coupling with circulation and climate sensitivity motivate a new set of science questions that underpin the CFMIP4 experimental protocol. Section 2 will introduce the CFMIP4 science questions, review the insights gained from the previous iteration of CFMIP experiments (i.e. CFMIP-3; Webb et al., 2017), and discuss new opportunities for progress. The experimental protocol and data request are described in sections 3 and 4 respectively.

2 CFMIP4 science questions and opportunities for progress

The CFMIP4 science questions are deliberately broad in scope, to encompass the range of current and future research directions within the CFMIP community. We however highlight specific knowledge gaps relevant to our science questions, where we hope the new CFMIP4 experiment protocol and data request will provide new opportunities for progress.

Q1: What are the physical mechanisms underlying *cloud feedbacks and adjustments* in nature, and how credibly do models represent these?

Considerable uncertainty remains on feedback mechanisms for individual cloud regimes. While the rise of high clouds with warming is reasonably well understood (Hartmann and Larson, 2002; Zelinka and Hartmann, 2010) and observed (Norris et al., 2016; Richardson et al., 2022; Chepfer et al., 2025), there are ongoing efforts to elucidate how high-cloud amount and optical depth respond to warming, and how this affects longwave and shortwave radiation (McKim et al., 2024; Raghuraman et al., 2024; Wilson Kemsley et al., 2025). As for low-cloud feedback, while observational evidence of a positive feedback is now strong (Myers et al., 2021; Cesana and Del Genio, 2021; Ceppi et al., 2024), the relative importance of various potential physical drivers remains unclear (Nuijens and Siebesma, 2019; Myers et al., 2023; Ogura et al., 2023; Vogel et al., 2022). The magnitude and microphysical mechanisms of phase-change feedbacks also require further investigation (Mülmenstädt et al., 2021; Wall et al., 2022; McCoy et al., 2023; Tan et al., 2025).

Recent trends in clouds and radiation are providing new opportunities to observationally assess the feedback and adjustments of clouds, and to validate the behaviour of GCMs, particularly through the use of satellite simulator output provided as part of CFMIP-3 (Bodas-Salcedo et al., 2011; Webb et al., 2017; Swales et al., 2018). Observations indicate a rapid increase in Earth's energy imbalance since the turn of the century, at a rate close to 0.5 W m^{-2} $decade^{-1}$ (Loeb et al., 2024; Kuhlbrodt et al., 2024; Mauritsen et al., 2025), with changes in marine low clouds and storm-track clouds making a large contribution to this trend (Goessling et al., 2025; Tselioudis et al., 2025; Ceppi et al., 2025; Zelinka et al., submitted). GCMs appear unable to replicate the magnitude of this energy imbalance increase, whether SSTs are interactive (Olonscheck and Rugenstein, 2024) or

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prescribed (Raghuraman et al., 2021; Hodnebrog et al., 2024); the reasons for this discrepancy are presently unclear. There is a pressing need to quantify the contributions of cloud feedback and adjustments to the observed trends, and the ability of GCMs to represent these. While much research so far has focused on the cloud response to weakening aerosol emissions (Quaas et al., 2022; Hodnebrog et al., 2024), we highlight the need for observational constraints on greenhouse gas adjustments, which may have made a comparably large contribution to the recent cloud-radiative trends (Ceppi et al., 2025; Zelinka et al., submitted).

Q2: How and why do cloud feedbacks and adjustments depend on *climate base state* and on the *nature of the climate forcing*?

Analyses of CFMIP-3 experiments forced with different levels of SST (± 4 K) and CO_2 (halving, doubling, quadrupling from pre-industrial) have revealed a remarkable inter-model spread in cloud feedback state-dependence, with most GCMs simulating a more amplifying feedback as the climate warms (Bloch-Johnson et al., 2021; Ringer et al., 2023). This is a first-order control on climate sensitivity in some GCMs; for example, CESM2 simulates a near-doubling of the climate sensitivity between the *abrupt-2xCO2* and *abrupt-4xCO2* experiments (Bloch-Johnson et al., 2021; Poletti et al., 2024). Understanding to what extent this feedback state-dependence is due to changing SST patterns, feedback temperature dependence, or other processes, is an avenue for future research.

It has long been recognised that forcing agents can differ in their "efficacy", i.e. the amount of temperature change per unit radiative forcing, as a result of differences in climate feedback (Hansen et al., 2005). Hence, temporal changes in the relative importance of various forcing agents mean that climate feedback may differ between the historical period and future climate change (Marvel et al., 2016). Several studies have identified a role for the patterns of SST response, and thus cloud feedback, in explaining forcing efficacy differences (Haugstad et al., 2017; Ceppi and Gregory, 2019; Salvi et al., 2022; Günther et al., 2022; Zhou et al., 2023; Zhang et al., 2023). The results are however highly model dependent (Richardson et al., 2019; Myhre et al., 2024), and it remains therefore uncertain to what extent changes in the relative strength of diverse forcing agents may contribute to time variation in historical climate feedback (Zhou et al., 2016; Andrews et al., 2022).

Q3: What coupled processes underlie the *SST pattern effect*, and how does this affect cloud feedback?

Understanding the mechanisms of SST pattern formation has been identified as one of four fundamental science questions guiding the activities of CMIP7 (Dunne et al., 2025). There is compelling evidence that aspects of the observed SST warming pattern in recent decades, for example the east–west contrast across the tropical Pacific Ocean, lie outside of the range of coupled GCM simulations (Wills et al., 2022; Simpson et al., 2025). This has important implications for the time evolution of climate feedback via the pattern effect, as revealed by CFMIP-3 experiment *amip-piForcing* (Andrews et al., 2022; Salvi et al., 2023). It is presently unclear whether this model bias indicates issues with the GCM representation of natural variability, the forced response, or both.

Of particular relevance to CFMIP is the potential role of subtropical marine stratocumulus clouds, whose feedback GCMs tend to under-represent (Myers et al., 2021; Ceppi et al., 2024). Recent modelling evidence suggests that a stronger (and thus more realistic) stratocumulus cloud feedback results in a stronger coupling between Southern Ocean and tropical Pacific SST

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anomalies (Kim et al., 2022). Thus, GCMs with Southern Ocean SSTs nudged towards the observed decadal cooling trend during 1979 to 2013 produce a more realistic tropical Pacific warming pattern, with suppressed East Pacific warming, to the extent that they simulate a realistically strong stratocumulus cloud feedback (Kang et al., 2023a, b). Coupled mean-state biases in SSTs, clouds and circulation around the Intertropical Convergence Zone (ITCZ) region may also play an important role for the SST warming pattern through their impact on the trade winds (Dong et al., submitted; Espinosa et al., submitted).

Q4: What are the mechanisms underlying *cloud–circulation coupling* and *regional precipitation change*, and how credibly do models represent these?

Under global warming, climate models simulate shifts in features of the atmospheric circulation such as the jet streams, the subtropical dry zones, and tropical rainfall – all of which will have substantial impacts on regional climate through their coupling with the radiative budget components and the hydrological cycle. Shifts in these circulation features are however highly uncertain among climate models (Harvey et al., 2020; Curtis et al., 2020; Grise and Davis, 2020; Wang et al., 2020). Cloud–circulation coupling contributes to this uncertainty, with cloud-radiative heating affecting atmospheric temperature gradients through local diabatic effects as well as via coupling with SSTs (Rädel et al., 2016; Byrne and Zanna, 2020; Voigt et al., 2021).

CFMIP-3 atmosphere-only experiments *piSST*, *a4SST*, and their variants with perturbed sea-ice and CO_2 concentration (Webb et al., 2017; Chadwick et al., 2017) allow for a decomposition of the coupled $4\times CO_2$ climate response into contributions from SST, sea-ice, and direct responses to CO_2, providing insight into sources of inter-model uncertainty. Analysis of these simulations has revealed that rapid adjustments, uniform SST changes and SST warming patterns all contribute substantially to model uncertainty in tropical circulation and precipitation, with the balance between mechanisms varying by region (Chadwick et al., 2017; Mutton et al., 2025). This highlights the need for tighter constraints on the coupled response of clouds and circulation to rapid adjustments and SST-mediated warming.

3 CFMIP4 experimental protocol

Table 1 summarises the CFMIP4 protocol and the science questions addressed by each experiment. A summary schematic of the experiments is provided in Fig. 1. In our experiment names, we follow the convention that "4k" has a lower-case k in CMIP7 (Dunne et al., 2025), whereas it was upper-case K in CMIP6. Compared to the previous iteration, CFMIP-3, the main changes include:

- A contribution to the new CMIP7 Assessment Fast Track (AFT; Dunne et al., 2025), through the following experiments: *amip-piForcing* for historical feedback and pattern effect; *amip-p4k* for cloud feedback; *abrupt-2xCO2* and *abrupt-0p5xCO2* for forcing and feedback state-dependence.

- Three new experiments, described in greater detail in the subsections below: *amip-p4k-rad* and *amip-p4k-turb* (cloud feedback processes); *piClim-deltaSST* (CO_2-forced pattern effect).

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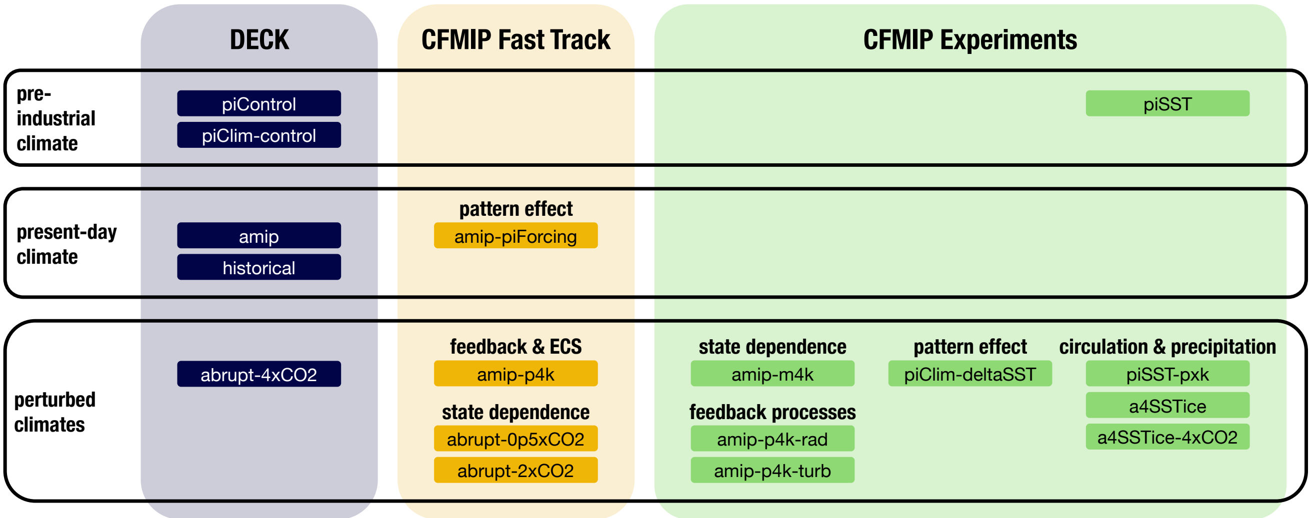

Figure 1. Schematic of the CFMIP4 and related CMIP7 DECK experiments. Experiments are grouped horizontally according to pre-industrial, present-day, or perturbed climates; experiments are also grouped according to the key science questions they address (see Table 1 for additional details).

- An additional *amip-piForcing* variant forced with HadISST1 SST and sea-ice concentration (SIC; Rayner et al., 2003), and extending to December 2025.
- An overall more compact set of experiments: we have discontinued the aquaplanet experiments, *amip-4xCO2*, *amip-future4K*, the abrupt solar forcing experiments, and the *lwoff* experiments with longwave cloud-radiative effects switched off (Webb et al., 2017). The *piSST* and *a4SST* set of experiments has also been reduced from eight to four, to focus on the processes identified as most important in previous analyses.

Note that the former *amip-4xCO2* experiment has been superseded by Radiative Forcing Model Intercomparison Project (RFMIP; Kramer et al., 2025) experiments *piClim-4xCO2* and *piClim-4xCO2-rad*. By comparison with *piClim-control*, both experiments quantify the effective radiative forcing of CO_2, respectively with and without plant physiological responses. *piClim-4xCO2-rad* is therefore the closest analogue to *amip-4xCO2*, which did not include the plant physiological effect.

Contrary to CFMIP-3, the CFMIP4 protocol does not distinguish between mandatory Tier 1 experiments and optional higher tiers. Our hope is that the reduced set of experiments will encourage full participation in our protocol by modelling groups.

3.1 Coupled abrupt CO_2 forcing experiments

Assessments of climate feedback and equilibrium climate sensitivity (ECS) are typically based on the *abrupt-4xCO2* experiment (e.g., Andrews et al., 2012; Zelinka et al., 2020), part of the Diagnostics, Evaluation and Characterization of Klima (DECK) group of core CMIP7 experiments (Dunne et al., 2025). To support research on cloud processes, we ask modelling

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Table 1. Summary of CFMIP4 and related CMIP7 DECK experiments. For abrupt CO_2 forcing experiments, we request a minimum of 300 years of simulation, but encourage modelling groups to extend the simulations to 1000 years or longer if possible.

Experiment	Description	Years	Science questions & applications
abrupt-4xCO2[a]	Abrupt quadrupling of CO_2 concentration relative to *piControl*	300+ (1000)	Q1 Climate feedback & sensitivity Q2 Forcing & feedback state-dependence; palaeoclimate feedback Q3 CO_2-forced pattern effects Q4 CO_2-forced circulation & precipitation changes
	Additional 9+ ensemble members for years 1–10, initialised in 10-year intervals	90+	
abrupt-2xCO2[b]	Abrupt doubling of CO_2 concentration relative to *piControl*	300+ (1000)	
abrupt-0p5xCO2[b]	Abrupt halving of CO_2 concentration relative to *piControl*	300+ (1000)	
amip[a]	Atmosphere-only with observed SST/SIC prescribed and historical forcing	43	Q1 Observed forcing and feedback Q3 Observed pattern effects Q4 Observed circulation & precipitation changes
amip-piForcing[b,c,d]	As *amip*, but with constant pre-industrial forcing and from January 1870 to December 2022	153	
	Additional *amip-piForcing* variant with HadISST1 SST and SIC, January 1870 to December 2025	156	
amip-p4k[b]	*amip* with uniform 4-K SST increase	43	Q1 Climate feedback Q2 Feedback state-dependence Q4 Circulation & precipitation changes
amip-m4k	*amip* with uniform 4-K SST decrease	43	
amip-p4k-rad	*amip* with surface radiative emission perturbed according to a 4-K increase in surface skin temperature	43	Q1 Cloud feedback processes
amip-p4k-turb	*amip* with surface turbulent energy fluxes perturbed according to a 4-K increase in surface skin temperature	43	
piClim-deltaSST[d]	*piClim-control* with added monthly time-varying SST anomalies from years 1–20 of a representative set of seven CMIP6 *abrupt-4xCO2* simulations	20×7	Q2 CO_2-forced pattern effects
piSST	Atmosphere-only with monthly time-varying SST and SIC prescribed from 30 years of each model's own *piControl* simulation	30	Q4 Decomposition of CO_2-driven circulation & precipitation changes into: CO_2 adjustment; response to uniform SST increase; response to SST pattern and sea-ice change
piSST-pxK	*piSST* with uniform x-K SST increase taken from each model's own global, climatological annual-mean ice-free SST change between *abrupt-4xCO2* and *piControl*	30	
a4SSTice	Atmosphere-only with monthly time-varying SST and SIC prescribed from years 111–140 of each model's own *abrupt-4xCO2*, and pre-industrial CO_2 concentration	30	
a4SSTice-4xCO2	*a4SSTice* with quadrupled CO_2 concentration	30	

[a]DECK; [b]Assessment Fast Track; [c]Minimum three realisations; [d]SST forcing variants to be denoted by different forcing indices

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groups to output the CFMIP variables requested as part of our “Baseline” opportunity (section 4) for this and all other DECK experiments.

The *abrupt-4xCO2* experiment is complemented by CO_2 doubling and halving experiments, *abrupt-2xCO2* and *abrupt-0p5xCO2*, both of which are part of the AFT (Dunne et al., 2025). Comparing among these experiments will quantify the degree to which climate feedback, ECS and the pattern effect are sensitive to climate state and forcing magnitude. This will be supported by RFMIP experiments *piClim-4xCO2*, *piClim-2xCO2* and *piClim-0p5xCO2*, addressing the state-dependence of effective radiative forcing, including cloud adjustments (Kramer et al., 2025). The *abrupt-0p5CO2* experiment can also support the assessment of feedback processes in colder palaeoclimates, for example the Last Glacial Maximum (Cooper et al., 2024).

As a novel aspect of CFMIP4 and CMIP7, all abrupt CO_2 forcing experiments should be run for a minimum of 300 years, and ideally 1000 years or longer (Dunne et al., 2025). This will facilitate an assessment of the longer timescales of the coupled climate response (Geoffroy et al., 2013; Andrews et al., 2015; Proistosescu and Huybers, 2017; Rugenstein et al., 2019), including the time evolution of climate feedback and the pattern effect, and thus the true value of the ECS (Rugenstein et al., 2020; Bloch-Johnson et al., 2021).

Another addition to CFMIP4 is the request of an extra nine *abrupt-4xCO2* ensemble members (and more if possible) for the first 10 years of the experiment, to support the assessment of the fast timescale of the SST response pattern (e.g., Rugenstein et al., 2016; Ceppi et al., 2018; Heede et al., 2020; Olonscheck and Kang, submitted). The choice of 10 years aims to keep the computational burden of the request limited, while also allowing for an accurate characterisation of the early SST response to CO_2 forcing. The ensemble members should be initialised in 10-year intervals from the parent *piControl* simulation, to ensure variability in ocean conditions is adequately sampled.

3.2 Atmosphere-only experiments

3.2.1 *amip*

The DECK experiment *amip* simulates historical climate conditions (including atmospheric composition and insolation) with prescribed observed SST and SIC from January 1979 to December 2021. To support process studies of cloud-radiative trends and feedback, and comparison with observations, for *amip* and its variants with uniform 4-K SST increase or decrease we request outputs from both our “Baseline” and “Extension for process-level studies” opportunities (section 4). The “Extension” outputs should be supplied for at least one ensemble member.

3.2.2 *amip-piForcing*

The AFT experiment *amip-piForcing* follows the same protocol as *amip*, but with forcing agents set to pre-industrial values. This facilitates the diagnosis of the SST-mediated radiative response, climate feedback and the pattern effect (Gregory and Andrews, 2016; Zhou et al., 2016; Andrews et al., 2022). Comparison of *amip* and *amip-piForcing* during their period of overlap also provides an estimate of the historical effective radiative forcing, complementary to the RFMIP experiment *piClim-histall* (Kramer et al., 2025).

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The CMIP7 protocol for *amip-piForcing* employs the Atmospheric Model Intercomparison Project (AMIP) II SST and SIC dataset, ending December 2022 (Hurrell et al., 2008; Durack et al., 2025; Dunne et al., 2025). This means that the period since 2023, which saw large anomalies in SST, global-mean surface temperature and the global energy budget (Kuhlbrodt et al., 2024; Schmidt, 2024; Goessling et al., 2025), is not covered. We therefore request that participating modelling centres run an additional *amip-piForcing* variant with HadISST1 SST and SIC (Rayner et al., 2003), extending up to December 2025 (see the Data Availability section). The choice of HadISST1 is motivated by the fact that it is a regularly updated, operational dataset, and that it has been used in previous studies to force atmosphere-only GCMs (Lewis and Mauritsen, 2021; Andrews et al., 2022; Modak and Mauritsen, 2023; Fan et al., 2025), despite known shortcomings in e.g. the representation of Southern Ocean SST trends (Schmidt et al., 2023).

Comparing between the AMIP II and the HadISST1 variants of *amip-piForcing* will provide a measure of the sensitivity of the radiative response to the choice of SST and SIC boundary conditions. (Note however that the HadISST1 and AMIP II datasets are not completely independent: AMIP II uses HadISST1 SST and SIC before 1981, with some post-processing to match the 1971–2000 climatology of the Optimum Interpolation v2 dataset (Reynolds et al., 2002) used from November 1981 onwards.) Previous studies have highlighted a substantial dependence of the radiative response on the SST dataset for certain historical periods, although most studies were based on single GCMs (Lewis and Mauritsen, 2021; Modak and Mauritsen, 2023; Fan et al., 2025).

Although the AFT request is for a single *amip-piForcing* realisation, we encourage modelling groups to perform a minimum of three realisations with perturbed initial conditions (and for each of the two sets of SST/SIC boundary conditions), as this will permit a more accurate characterisation of the time-varying historical climate feedback. Simulation output should be archived using different forcing indices corresponding to different boundary conditions; we request *f1* for AMIP II and *f2* for HadISST1. We therefore request a total of six *amip-piForcing* variants: *r1i1p1f1* to *r3i1p1f1* for AMIP II SST and SIC, and *r1i1p1f2* to *r3i1p1f2* for HadISST1. We will process the HadISST1 SST and SIC monthly-mean boundary conditions to ensure adequate sampling of the seasonal cycle according to the method of Taylor et al. (2000), and the datasets will be made available through the input4MIPs repository (Durack et al., 2018).

3.2.3 *amip-p4k*, *amip-m4k*

Experiments *amip-p4k* and *amip-m4k* follow the *amip* protocol, except that SSTs are uniformly increased or decreased by 4 K over ice-free regions; SIC and SSTs under sea-ice remain unchanged, with SSTs at the freezing point. *amip-p4k* was adopted into the AFT for the diagnosis of climate feedback. As an atmosphere-only experiment, it is relatively low-cost and therefore similar protocols can be applied to high-resolution models, e.g. the *highresSST-p4kuni* experiment of HighResMIP (Roberts et al., 2025).

Moreover, comparing between *amip-p4k* and *amip-m4k* responses provides an estimate of feedback state-dependence with SST patterns held fixed, thus isolating the role of global temperature changes for climate feedback (Bjordal et al., 2020; Ringer et al., 2023). This is complementary to estimates based on coupled abrupt CO_2 forcing experiments, which additionally include effects from changing SST patterns.

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3.2.4 *amip-p4k-rad*, *amip-p4k-turb*

The two experiments *amip-p4k-rad* and *amip-p4k-turb*, new to CFMIP4, aim to provide a better understanding of low-cloud feedback mechanisms. The idea behind the experiments is that uniform SST warming modifies the atmosphere via two causal pathways: first by increasing upwelling longwave radiation from the sea surface, and second by changing turbulent transport at the air-sea interface, particularly latent and sensible heat fluxes. The experiments isolate the impact of each of these two pathways on low-cloud feedback, motivated by previously hypothesized mechanisms involving changes in surface turbulent fluxes (e.g., Rieck et al., 2012).

Following Ogura et al. (2023), *amip-p4k-rad* is run exactly as *amip* but a 4-K anomaly is added (over ocean regions only) to the SST used in the radiation code for the calculation of surface upwelling longwave radiation. For *amip-p4k-turb*, the protocol again follows *amip* but a 4-K anomaly is added to the SST seen by the model's surface turbulent exchange scheme only. We recommend perturbing sensible and latent heat fluxes only, and keeping any other turbulent fluxes (e.g. of momentum or aerosols) unperturbed. Test simulations indicate that perturbing momentum or aerosol fluxes has very little impact on low-cloud properties (T. Ogura, pers. comm.).

3.3 *piClim-deltaSST*

In previous CFMIP protocols, experiment *amip-future4K* (or *amipFuture* in CMIP5) served to assess the global climate response to patterned warming, with the warming pattern taken from the model-mean response in CMIP3 *1pctCO2* simulations (Webb et al., 2017). Being calculated from a model mean, the *amip-future4K* warming pattern was muted and underestimated the amplitude of SST anomaly patterns found in individual models. Furthermore, the use of the *1pctCO2* experiment meant the pattern combined fast and slow timescales of the climate response to CO_2 forcing (Good et al., 2011; Andrews et al., 2015; Proistosescu and Huybers, 2017; Ceppi et al., 2018). Because of these issues, *amip-future4K* proved to be of limited use to interpret the CO_2-forced pattern effect in individual climate models.

In CFMIP4, we replace *amip-future4K* by the new experiment *piClim-deltaSST*. Instead of a single model-mean SST pattern, *piClim-deltaSST* uses SST anomalies from individual CMIP6 GCMs forced with abrupt CO_2 quadrupling (calculated relative to the corresponding *piControl* monthly climatology, taken from the contemporaneous period). The chosen GCMs are CanESM5, CESM2, CNRM-ESM2-1, GFDL-CM4, HadGEM3-GC31-LL, MIROC6, and NorESM2-LM. They are selected for their diverse representation of the pattern effect, as measured by the cloud-radiative effect (CRE) feedback simulated in *piClim-deltaSST* test simulations with the HadAM3 atmosphere-only model (J. M. Gregory, pers. comm.), and furthermore these GCMs come from different modelling groups. We use the first 20 years of these GCMs' integrations to calculate a set of monthly time-varying SST anomaly fields, $\Delta\mathrm{SST}_i(x,t)$, where x is location, t is time (in months), and subscript i refers to one of the seven GCMs listed above.

Modelling centres are requested to perform this experiment following the *piClim-control* protocol, but with the following modifications:

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- The monthly time-varying SST anomaly fields $\Delta\mathrm{SST}_i(x,t)$ should be added to the *piClim-control* SST monthly climatology. SIC is kept to the *piClim-control* climatology. SSTs should be kept to freezing (-1.8°C) wherever SIC is greater than zero, or wherever the $\Delta\mathrm{SST}_i(x,t)$ anomaly takes SST to below freezing.
- The simulations should be run for 20 years, i.e. the time range of the ΔSST datasets.
- The simulations with different SST anomaly fields should be saved under different forcing indices, in alphabetical order of the GCMs used to derive the SST anomaly fields. The recommended forcing indices are provided as part of the filenames of the input datasets (see Data Availability section).

3.4 *piSST* and *a4SSTice* time-slice experiments

This set of four atmosphere-only experiments provides a decomposition of the *abrupt-4xCO2* climate response into three main components: direct CO_2 effect; response to uniform SST increase; and response to SST pattern and sea-ice change. The science focus of these experiments is the coupled response of clouds, circulation and precipitation to CO_2 forcing in GCMs. To adequately resolve regional features of circulation and precipitation (and their variability), the experiments here use monthly time-varying SST and SIC fields. This is a key difference from the setup of the *piClim* experiments.

The four experiments are set up as follows:

- ***piSST*** uses monthly time-varying SST, SIC and atmospheric constituents from 30 years of each model's own *piControl* run. The 30 years should be chosen to be parallel to years 111–140 of the *abrupt-4xCO2* run.
- ***piSST-pxK*** is set up like *piSST*, but SSTs are uniformly increased by x K in ice-free regions, where x is the global, climatological annual-mean ice-free SST change between years 111–140 of *abrupt-4xCO2* and *piControl*.
- ***a4SSTice*** uses monthly time-varying SST and SIC from years 111–140 of each model's own *abrupt-4xCO2* run, but keeping atmospheric constituents to pre-industrial levels.
- ***a4SSTice-4xCO2*** is set up like *a4SSTice*, but CO_2 concentration is quadrupled.

Differences between experiment pairs can be interpreted as follows:

- ***a4SSTice-4xCO2* minus *piSST*** can be compared with the climate response simulated in years 111–140 of *abrupt-4xCO2* relative to *piControl*, to confirm that the atmosphere-only framework can adequately replicate coupled GCM responses. A previous analysis suggests that this is generally the case (Chadwick et al., 2017).
- ***piSST-pxK* minus *piSST*** provides the response to uniform SST increase.
- ***a4SSTice* minus *piSST-pxK*** provides the response to the (zero-mean) pattern of SST change and the change in SIC.
- ***a4SSTice-4xCO2* minus *a4SSTice*** provides the direct CO_2 effect, including the plant physiological response.

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4 CFMIP4 data request

The CMIP7 data request is structured into groups of scientific objectives referred to as “Opportunities”, two of which are related to CFMIP. Together, the data requested in these two opportunities includes all fields requested in CFMIP-3, augmented by several new fields. The first is the *Clouds, circulation and climate sensitivity: baseline* opportunity, which is intended to capture the base set of variables essential for performing analyses to answer the key CFMIP questions listed in Section 2. The data requested include the Baseline Climate Variables (Juckes et al., 2025), monthly 2D and 3D fields, daily 2D fields, and fixed fields. These data are requested from the 10 DECK experiments in addition to the suite of CFMIP experiments listed in Table 1.

Supplementing this is a second opportunity, *Clouds, circulation and climate sensitivity: extension for process-level studies*, which is intended to capture variables crucial for advanced diagnosis and evaluation of cloud, radiation, and precipitation processes in the present-day and warmed climate. In addition to requesting the same variables as the baseline opportunity, this opportunity requests daily 3D fields; sub-hourly fields at specified “cfSites” locations; additional output from the CFMIP Observation Simulator Package (COSP; Bodas-Salcedo et al., 2011; Swales et al., 2018); and monthly climatologies of hourly-resolved top-of-atmosphere (TOA) fluxes. Five new cfSites locations have been added to the request since CFMIP-3, corresponding to locations of field campaigns and surface-based observational facilities (Webb, 2025). Several new COSP outputs are requested, including phase-separated cloud fraction histograms produced by the MODIS simulator, which are useful for diagnosing cloud phase feedbacks (Wall et al 2025). Some of these COSP variables are only produced by COSP version 2 (Swales et al., 2018), but either COSP version can be used to contribute to CFMIP. To keep the data volume reasonable, this second opportunity is applicable only to a subset of five experiments (*amip*, *amip-p4K*, *amip-m4K*, *amip-p4K-rad*, and *amip-p4K-turb*) rather than for the full suite of experiments in Table 1.

Producing data from these two opportunities across a large collection of climate models will allow major progress across the topics of interest to the CFMIP community by facilitating advanced diagnosis and understanding of cloud processes, feedbacks, adjustments, and biases. Additional information about the CFMIP Data Request and how it fits into the broader CMIP7 Data Request can be found in Dingley et al. (submitted). The Data Request database is currently hosted on the Airtable cloud platform (https://bit.ly/CMIP-DR-Opportunities, Opportunity IDs 78–79).

5 Conclusions

The growing climate change signal means that understanding cloud processes and their impact on Earth’s energy imbalance is a critical challenge for the research community. CFMIP plays a central role in this endeavour, by supporting CMIP7 and its Assessment Fast Track with a set of experiments aimed at understanding cloud-radiative processes under past, present and future climate. The CFMIP protocol is also key to understanding the mechanisms of the “SST pattern effect”, one of four fundamental science questions underpinning CMIP7 activities (Dunne et al., 2025).

The scope of CFMIP extends beyond pure cloud processes: the CFMIP4 science questions and experimental protocol support improved understanding of climate feedback processes, coupled climate variability and change, atmosphere and ocean

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circulation, and precipitation. The CFMIP science community actively collaborates on these topics, particularly through its annual meeting. We invite interested members of the climate research community to engage with CFMIP through membership of the mailing list (https://groups.google.com/g/cfmip_all/) and attendance at the CFMIP annual meeting.

Beyond the protocol outlined here, CFMIP also supports informal experiments and model intercomparison projects (MIPs) related to the aims of CFMIP. This includes for example the Radiative-Convective Equilibrium Model Intercomparison Project (RCEMIP; Wing et al., 2018, 2024), the Extratropical–Tropical Interaction Model Intercomparison Project (ETIN-MIP; Kang et al., 2019), or the Green's Function Model Intercomparison Project (GFMIP; Bloch-Johnson et al., 2024). An up-to-date list of supported informal experiments is available at https://www.cfmip.org/experiments/informal-experiments, and the CFMIP committee welcomes additional informal experiment proposals.

Data availability. The required input data for experiments *amip-piForcing* and *piClim-deltaSST* will be made available prior to publication via the input4MIPs repository (Durack et al., 2018; https://esgf-node.ornl.gov/search/input4MIPs).

Author contributions. PC, ABS, MJW and MDZ jointly designed the protocol, with input from co-authors. PC led the writing of the paper. MDZ led the writing of section 4. All co-authors commented on and edited the draft.

Competing interests. None of the authors has any competing interests.

Acknowledgements. PC was supported by UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding Guarantee (grant EP/Y036123/1). PC was additionally supported through UK Natural Environmental Research Council (NERC) grants NE/V012045/1 and NE/T006250/1. MJW, ABS and TA were supported by the Met Office Hadley Centre Climate Programme funded by DSIT. The effort of MDZ was supported by the US Department of Energy (DOE) Regional and Global Model Analysis program area and was performed under the auspices of the DOE by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. FB acknowledges the financial support of grant MOBYDYC ANR-22-CE01-0005. AAW is supported by US National Science Foundation (NSF) Grant AGS-2140419. YTH was supported by the National Science and Technology Council, R.O.C. (112-2111-M-002-016-MY4). We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output. We also thank the Earth System Grid Federation (ESGF) for archiving the model output and providing access, and we thank the multiple funding agencies who support CMIP and ESGF.

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