Efficacy of climate forcings in transient CMIP6 simulations

Gunnar Myhre[1]*, Rachael E. Byrom[1], Timothy Andrews[2],
Piers M. Forster[3] and Christopher J. Smith[3,4]

[1]CICERO Center for International Climate Research, Oslo, Norway, [2]Met Office Hadley Centre, Exeter,
United Kingdom, [3]Priestley Centre, University of Leeds, Leeds, United Kingdom, [4]Energy, Climate and
Environment Program, International Institute for Applied Systems Analysis, Laxenburg, Austria

For effective radiative forcing (ERF) to be an ideal metric for comparing the
strength of different climate drivers (such as CO_2 and aerosols), the ratio of
radiative forcing to global-mean temperature change must be the same for
each driver. Typically, this ratio is divided by the same ratio for CO_2 and termed
efficacy. Previously it has been shown that efficacy is close to unity in abrupt
perturbation experiments for a range of climate drivers, but efficacy with respect
to CO_2 has not been investigated in transient realistic simulations. Here, we
analyse transient simulations from CMIP6 experiments and show comparable
results between transient and abrupt perturbation experiments. We demonstrate
that aerosol efficacy is not significantly different from unity, however inter-model
differences in aerosol experiments are notably large.

KEYWORDS

effective radiative forcing, imbalance, climate response, climate models, CMIP6

1 Introduction

Effective radiative forcing (ERF) has become the preferred metric to quantify the top
of atmosphere (TOA) perturbation to the Earth's energy budget by a given climate driver
(Boucher et al., 2013; Myhre et al., 2013; Forster et al., 2021). This is because ERF, by
definition, includes tropospheric rapid adjustments to the initial perturbation (Hansen
et al., 2005; Sherwood et al., 2015) which leads to a more similar equilibrium temperature
change for different climate drivers for a given forcing magnitude (Shine et al., 2003;
Hansen et al., 2005; Richardson et al., 2019).

The utility of ERF as a metric to compare the relative strength of different climate
drivers in inducing surface temperature change is also dependent on the behavior of the
climate feedback parameter (α; W m^{-2} K^{-1}), which represents the radiative response of
the climate system to temperature change induced by a forcing (Forster et al., 2021).
Namely, this dependency relies on whether α varies with forcing mechanism (Hansen
et al., 2005) and time [e.g., Andrews et al. (2015), Rugenstein et al. (2016), Richardson
et al. (2019)]. Quantifying the efficacy of different climate drivers (i.e., the global-mean
surface temperature response per unit ERF relative to CO_2) is therefore important for
understanding the contribution of various climate drivers throughout the industrial era
(Shindell, 2014; Richardson et al., 2019) and for the projection of future temperature trends
and climate metrics (Myhre et al., 2013; Forster et al., 2021). The relationship between ERF
and temperature change can be described as (Gregory and Andrews, 2016) in Equation (1):

$$dN = dF - \alpha dT \tag{1}$$

where dT is the global-mean surface temperature change resulting from an ERF (dF) from
a climate driver and dN is the TOA energy imbalance. Efficacy (Equation 2) is defined as

Hansen et al. (2005) when the climate system is in equilibrium
($dN = 0$):

$$E = \frac{dT_i/dF_i}{dT_{CO_2}/dF_{CO_2}} \qquad (2)$$

where dT is the global-mean surface temperature change resulting
from an ERF (F) from climate driver i (such as non-CO_2
greenhouse gases and aerosols) relative to that for CO_2. An efficacy
of one demonstrates that ERF is ideal for comparing surface
temperature changes from different climate drivers, since the
magnitude of warming in response to CO_2 forcing is equal to that
from i.

For a climate system not in equilibrium the efficacy becomes as
in Equation (3):

$$E = \frac{dT_i/(dF_i - dN_i)}{dT_{CO_2}/(dF_{CO_2} - dN_{CO_2})} \qquad (3)$$

Since the climate feedback parameter, $\alpha = \frac{dF - dN}{dT}$, efficacy can
also be described in terms of the radiative response induced by a
forcing, whereby in Equation (4):

$$E = \frac{\alpha_{CO_2}}{\alpha_i} \qquad (4)$$

Here an efficacy close to unity illustrates that radiative feedback
processes are similar for climate driver i relative to CO_2.

Radiative feedbacks act to amplify or dampen climate
sensitivity to a forcing and are demonstrated to play an important
role in driving different temperature responses for different forcers
(Shindell, 2014; Marvel et al., 2016; Smith and Forster, 2021;
Salvi et al., 2022). Largely, a forcing occurring in regions with a
weaker radiative response results in stronger warming per unit
increase in ERF and an efficacy greater than unity. Zhou et al.
(2023) calculate the efficacy of 10 different abrupt forcing agents
to demonstrate its dependency on a combination of feedback
state-dependence (e.g., Ceppi and Gregory (2019)) and "pattern-
effect" (Haugstad et al., 2017), whereby different forcings initiate
different radiative feedbacks via the pattern of change in sea-
surface temperature (SST). They find enhanced warming over
tropical regions leads to increased low clouds globally, a weaker
lapse rate and more negative TOA radiative fluxes, resulting in
a pattern-effect induced efficacy deviating from unity. Further,
Zhou et al. (2023) find that a negative change in global surface
temperature (e.g., from non-BC aerosol forcing) results in stronger
radiative dampening and a reduced efficacy relative to abrupt
$2xCO_2$ forcing. Comparing aerosols and greenhouse gases (GHGs),
Salvi et al. (2022) also consider how historical forcings affect SST
and stability and modulate radiative response, concluding that
net radiative feedback is stronger for aerosols, consistent with
their different latitudinal forcing distribution compared to GHGs;
proposing that differences in α arise from different tropospheric
stability responses and the subsequent impact on cloud and lapse-
rate feedbacks. To further investigate how the spatial pattern of
forcing affects climate feedback and sensitivity, Zhang et al. (2023)
perform sensitivity simulations by applying solar forcing over
the entire globe, Northern Hemisphere mid-latitudes, Southern

Ocean, and tropics. They show that varied forcing patterns lead to
large differences in feedback mechanisms. In particular, the lapse
rate feedback and cloud feedback show large regional dependence
which is mainly caused by differences in coupling between the
surface and troposphere. Overall, their study found that the global
mean surface temperature change is doubled when the forcing is
imposed over the Southern Ocean compared to when the forcing is
applied in the tropics.

Several studies report efficacies that deviate from unity (Hansen
et al., 2005; Shindell, 2014; Shindell et al., 2015; Marvel et al.,
2016; Modak et al., 2018), largely depending on the model and
method used to derive forcing estimates. Richardson et al. (2019)
conduct a multi-model analysis of 11 global climate models
(GCMs) participating in the Precipitation Driver and Response
Model Intercomparison Project [PDRMIP; Myhre et al. (2017)]
to diagnose efficacy for abrupt forcing perturbations. With ERF
calculated using fixed sea-surface temperatures and sea-ice (fsst)
they report a solar forcing (2% increase in insolation) efficacy of
less than one across all models (0.77-0-95) with multi-model mean
efficacy of slightly less than one for 3x methane (CH_4; 0.87), 5x
sulfate (SO_4; 0.94) and 10x black carbon (BC; 0.87), with large
intermodel spread. They note that multi-model mean efficacy is
marginally closer to unity when ERF is adjusted for land-surface
temperature change and that efficacy varies substantially for SO_4
and BC model ensembles in particular, causing uncertainty in
whether it significantly deviates from unity.

Such abrupt forcing experiments more inherently embody the
equilibrium temperature response however, and do not characterize
transient changes in ERF, α and dT. The novelty in this study is
that we analyse CMIP6 transient fully-coupled GCM simulations
with ERF diagnosed from corresponding fsst simulations to
compare efficacy calculated across the historical period against that
diagnosed from abrupt $4xCO_2$.

2 Materials and methods

We use results from the CMIP6 DECK simulations (Eyring
et al., 2016) and the two CMIP6 MIPs: DAMIP (Gillett et al.,
2016) and RFMIP (Pincus et al., 2016). Specifically, we use the
DECK fully coupled transient simulations forced by a 1% increase
in CO_2 until quadrupling (1pctCO2) and by all climate drivers
over the industrial era from 1850 to 2014 (historical) along with
the DAMIP fully coupled transient simulation of historical change
in CO_2 (hist-CO2), historical change in all well-mixed greenhouse
gases (hist-GHG) and historical change in all aerosols (hist-aer). In
addition, we include the fully coupled DECK simulation of abrupt
quadrupling of CO_2 (abrupt-4xCO2) which is distinct from the
aforementioned transient simulations under investigation in this
study. This abrupt-4xCO2 is similar to the setup of all experiments
in the PDRMIP study (Richardson et al., 2019).

ERFs are derived from the RFMIP fsst simulations as detailed
in Smith et al. (2020) and are calculated relative to the piClim-
control reference case following the method denoted as ERF_trop
in Smith et al. (2020), which corrects for land surface change in
fsst experiments and the portion of tropospheric temperature and
water vapor changes associated with it [also see further discussions
in Andrews et al. (2021)]. Tables 1, 2 summarize the models and

TABLE 1 List of models with institutions and resolution.

Model	Institution	Resolution
ACCESS-CM2	Commonwealth Scientific and Industrial Research Organization-Australian Research Council Center of Excellence for Climate System Science	192 × 144
CanESM2	Canadian Center for Climate Modeling and Analysis	128 × 64
CESM2	National Center for Atmospheric Research United States	288 × 192
CNRM-CM6-1	Center National de Recherches Meteorologiques-Center Europeen de Recherche et de Formation Avancee en Calcul Scientifique	256 × 128
CNRM-ESM2-1	Center National de Recherches Meteorologiques-Center Europeen de Recherche et de Formation Avancee en Calcul Scientifique	256 × 128
EC-Earth3-Veg	EC-Earth consortium	512 × 256
GFDL-CM4	National Oceanic and Atmospheric Administration-Geophysical Fluid Dynamics Laboratory	288 × 180
GFDL-ESM4	National Oceanic and Atmospheric Administration-Geophysical Fluid Dynamics Laboratory	288 × 180
GISS-E2-1-G	Goddard Institute for Space Studies	144 × 90
HadGEM3-GC31-LL	Met Office Hadley Center	192 × 144
IPSL-CM6A-LR	Institut Pierre Simon Laplace	144 × 143
MIROC6	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and RIKEN Center for Computational Science	256 × 128
MPI-ESM1-2-LR	Max Planck Institute for Meteorology	192 × 96
MRI-ESM2-0	Meteorological Research Institute	320 × 160
NorESM2-LM	NorESM Climate modeling Consortium	144 × 96
NorESM2-MM	NorESM Climate modeling Consortium	288 × 192
UKESM1-0-LL	Met Office Hadley Center	192 × 144

TABLE 2 List of CMIP6 experiments investigated in this study and a description.

Experiment	Description
historical	Industrial era (1850–2014) simulations with all anthropogenic and natural drivers included.
hist-CO2	Same as Historical, except only the CO_2 forcing included.
hist-GHG	Same as Historical, except only well-mixed greenhouse gases included.
hist-aer	Same as Historical, except only aerosols included.
abrupt-4 × CO2	Abrupt quadrupling of the CO_2 concentration.
1pctCO2	1% yr^{-1} CO_2 concentration increase until doubling (occurs after 70 years). The experiment has also been used for 1% yr^{-1} CO_2 concentration increase until quadrupling (occurs after 140 years) and denoted here as 1pctCO2-4x.

(Hansen et al., 2005), including the reference 1ptCO2 experiment. Here, the TOA imbalance is calculated as the difference between the given transient CMIP6 experiment listed in Table 2 and the CMIP6 piControl experiment. Note that a line-by-line model (Myhre et al., 2006; Etminan et al., 2016) has been used to establish the relation of doubling of CO_2 to quadrupling of CO_2 since only quadrupling is available from the RFMIP simulations (Smith et al., 2020).

3 Results

Figure 1 shows efficacy values for the six CMIP6 experiments, using 1ptCO2 as the reference case. The uncertainties bars represent the outcomes relative to the ten 5-year periods in the piControl simulations. In most models, the hist-GHG experiment has efficacies closest to unity. The hist-GHG experiment includes all major GHGs over the industrial era, with CO_2 being the dominant (Forster et al., 2021). The largest model range in efficacy is in the hist-aer experiment. However, the hist-aer experiment has the weakest ERF and thus the internal variability for the surface temperature response may cause part of the large range in efficacy and large uncertainty range for some of the models. The reasons for the large range in the efficacy in the hist-aer experiment could be manyfold, including that models have very different spatial distributions of aerosol, the type of aerosol i.e., absorbing vs. scattering, and their balance between aerosol-radiation interaction and aerosol-cloud interaction (Smith et al., 2020). On top of this the efficacy is dependent on the relation between Northern hemisphere vs. Southern Hemisphere forcing pattern (Zhang et al., 2023), possibly the land vs. ocean forcing (Shindell, 2014) and how the forcing pattern initiates the feedbacks (Haugstad et al., 2017). There is not a clear relation between the results for the historical and hist-aer experiments. All the models have an efficacy above one for the abrupt-4xCO2 experiment, except UKESM1. The efficacy for this experiment is weakly correlated with the effective climate sensitivity (EffCS; 0.35) with EffCS calculated in Zelinka et al. (2020).

Supplementary Figure S1 illustrates the same as Figure 1, except that the TOA imbalance has not been excluded in the calculations of efficacies. In Supplementary Figure S1 unlike in Figure 1, the efficacy is beyond unity for all models in the abrupt-4xCO2 experiment. Of the seven CMIP6 experiments analyzed in this study, the abrupt-4xCO2 and 1pctCO2-4x experiments

CMIP6 experiments included in this study, respectively. All CMIP6 data used are monthly means.

To calculate efficacy following Equation 3 we use the CMIP6 1pctCO2 experiment until doubling of CO_2 (which occurs at year 70) as the reference CO_2 ERF and surface temperature response for the six other experiments (Table 2), whereby the surface temperature response is calculated as the difference between last 5 years of each fully-coupled experiment and the pre-industrial simulation (piControl). Note, that the 5 years are centered around year 70 in the reference 1pctCO2. To derive an estimate of internal variability, the last 5 years of each experiment are also differenced from 10 different piControl 5-year periods taken from across the simulation length. As given in Equation 3, the TOA imbalance is subtracted from the ERF in each experiment to calculate efficacy

FIGURE 1

Efficacy for six CMIP6 experiments and seventeen CMIP6 models. The reference is the CMIP6 experiment 1ptCO2 at 2xCO2. Uncertainty bars shown as reference to ten PiControl time intervals.

FIGURE 2

(A) TOA imbalance in seven CMIP6 experiments, **(B)** the remaining imbalance given in percent for individual CMIP6 models, **(C)** the remaining imbalance given in percent for CMIP6 multi-model mean.

have the largest TOA imbalance (Figure 2A). However, these experiments have at least twice as strong an ERF than in the other experiments. Figure 2B shows that the models have responded to about 80% of the initial ERF and thus 20% is remaining to full equilibrium (in abrupt-4xCO2). In millennial-length simulations of CO_2 perturbation, the models are close to equilibrating and EffCS is 17% higher than the analysis of the 150 years simulations (Rugenstein et al., 2020). Figures 2B, C shows that the abrupt-4xCO2 experiment is closer to equilibrium than the other CMIP6 experiments. Among the six other CMIP6 experiments, which are transient simulations, there is a marked similarity in the remaining fraction of imbalance. However, it is apparent that the 1ptCO2 experiment at 4xCO2 (year 140) exhibits a relatively smaller imbalance compared to 1ptCO2 at 2xCO2, and likewise with hist-aer contrasted against the historical experiment. The latter effect may be because the rate of increase in negative aerosol forcing has been weaker or has even exhibited a reversal of sign over the last one to two decades of the CMIP6 historical experiments (Smith et al., 2021; Quaas et al., 2022) whilst there has been a continued increase in the GHG forcing (Forster et al., 2021).

Figure 3 shows the geographical distribution of efficacy calculated as the geographical distribution of dT_i/dF_i divided by the global mean α_{CO_2}. Note that the imbalance is not taken into account in the figure. Across all experiments, a clear Arctic amplification is evident (Previdi et al., 2021; Rantanen et al., 2022) and efficacies below 1 are common over ocean. The abrupt-4xCO2 has the highest efficacies (as shown in Figure 1, Supplementary Figure S1) with values around unity over ocean with much higher values over Antarctica than in the other CMIP6 experiments shown here. An interesting feature of the hist-aer experiment is the notably higher efficacies over land in the Northern hemisphere. Moreover, distinct strongly negative local efficacies over the southern hemisphere ocean are evident in the hist-aer experiment relative to the other experiments. The historical and hist-GHG experiments exhibit substantial similarity
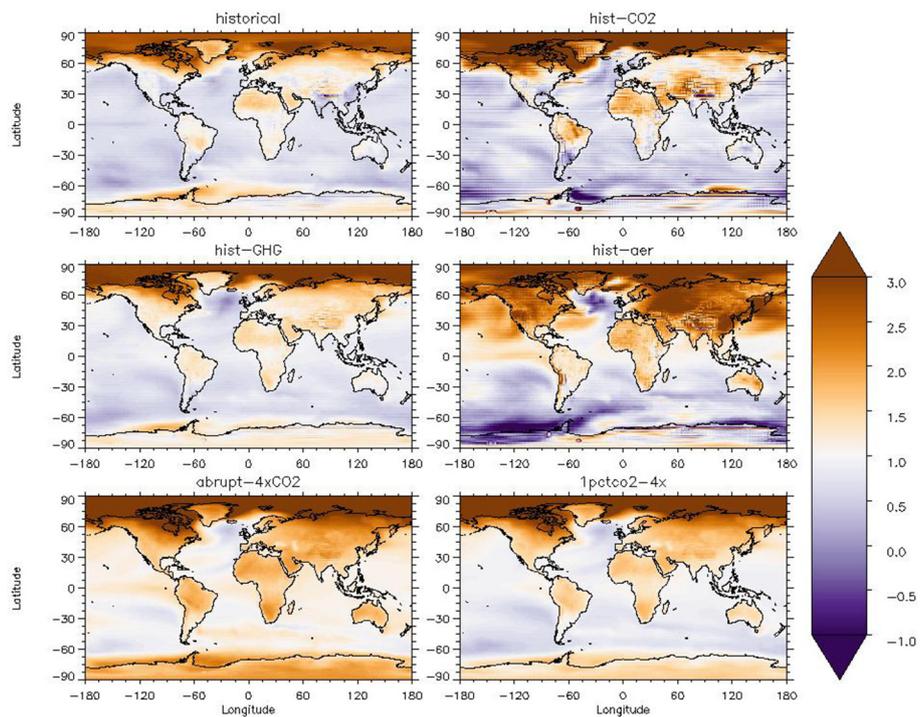
FIGURE 3
Geographical distribution of efficacy for six CMIP6 experiments. Multi-model mean results are shown.
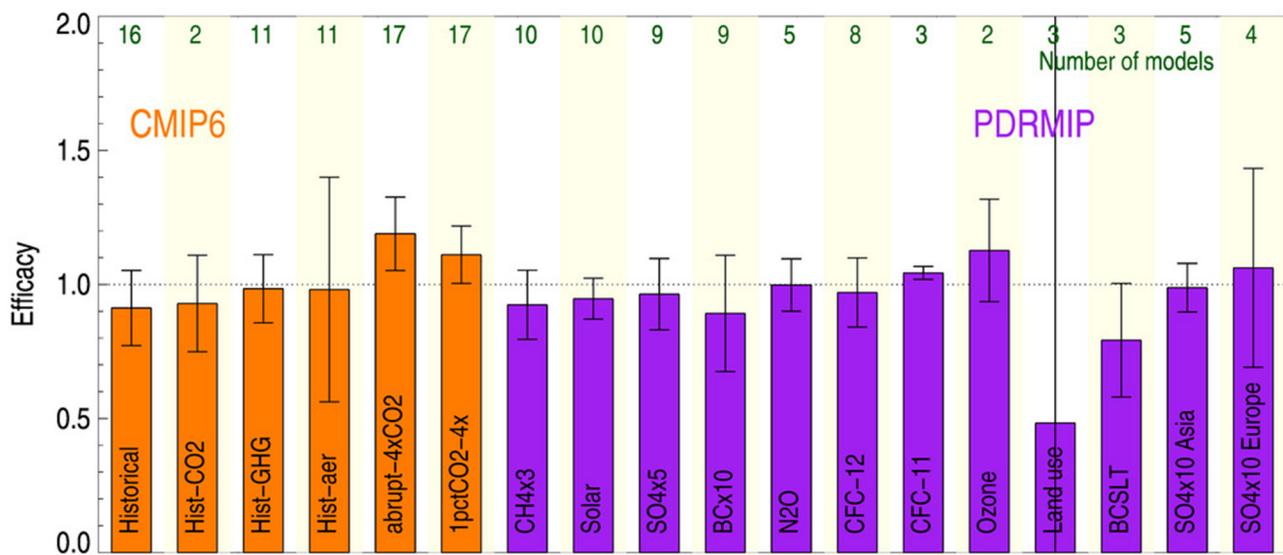
FIGURE 4
Efficacies in CMIP6 and PDRMIP experiments. The bars show the geometric means and uncertainties shown as one standard deviation. The number of model simulations available for each experiment is shown in green.

in most regions. However, deviations arise in areas with elevated anthropogenic aerosol abundance, such as China, India and eastern part of US, where the Historical experiment has efficacies below unity.

Figure 4 shows the geometric mean efficacies from the CMIP6 experiments and compares them to the idealized experiments within PDRMIP. The PDRMIP results are same as in Richardson et al. (2019), but with the land surface temperature correction incorporated as in Andrews et al. (2021). Overall, the mean efficacies are close to unity, including for the experiments involving aerosols. The finding here is that efficacies in transient experiments are similar to abrupt experiments. Efficacies above unity occur

in experiments with large forcings such as in the quadrupling of CO_2 (transient and abrupt). The largest exception for the unity of efficacy is found for experiments with few models involved such as land use change (land use) and BC specified at lower altitudes in the atmosphere (BCSLT). In both of these experiments the surface temperature response is weak causing the internal variability to play a larger role than in many of the other experiments. In the land use experiment the direct change in the surface fluxes of sensible and latent heat can further cause difference in surface temperature response for a given ERF compared to the other experiments in this study.

4   Discussions and conclusions

A main finding from this study is that there is no indication that efficacies for aerosols are very different from unity, as shown in both in the CMIP6 and PDRMIP simulations. However, model differences in the aerosol experiments are much larger than for the other experiments. The advantage of the PDRMIP SO4x5 experiment is that a large perturbation is performed, resulting in a robust surface temperature response and thus signal to noise is large. In the other aerosol experiments a low surface temperature response may have contributed to large model deviations in the efficacy.

The spatial pattern of the ERF of anthropogenic aerosol changes for 11 models are shown in Supplementary Figure S2 to investigate further the large range in the efficacy of hist-aer. The magnitude and spatial pattern vary between the models with all models having the strongest negative forcing over South-East Asia. The higher efficacy over land in the Northern hemisphere shown in Figure 3 is not a feature that is causing the hist-aer efficacy to have a large model diversity as shown in Figure 1. The land fraction aerosol ERF is actually slightly anticorrelated (-0.25 Pearson correlation coefficient) to the efficacy for the models in the hist-aer experiment. All models have a stronger aerosol ERF in the tropics relative to the global mean (ratio range from 1.07 to 1.30) and this ratio is moderately anticorrelated (-0.58) to the model range in hist-aer efficacy, meaning models with high tropical aerosol ERF generally have low efficacy. The correlation of the efficacy to the fraction of polar aerosol ERF to global mean and fraction of Northern hemisphere to global mean are both low (-0.30 and 0.24, respectively). To draw firm conclusions of temperature response from aerosol perturbations we show that a large model ensemble is required since the model variations are large. We find no systematic cause of this large model diversity in efficacy for aerosol perturbation in terms of aerosol type (sulfate or BC), transient or abrupt or regional aerosol forcing.

Our surface temperature responses have been taken for the 5 last years of transient simulations. Expanding this to 10 years generally changes the efficacy modestly, but somewhat more for the hist-aer experiment (from 0.98 to 1.09 for the geometric mean) than the other experiments. The standard deviation among the models for the hist-aer experiment changes slightly from 0.42 to 0.46 using 10 years instead of 5 years for the surface temperature response. Overall, the selection of number of years at the end of the simulations seem to weakly influence the efficacy results.

ERF was introduced to make it a good indicator of surface temperature change from various climate drivers (Boucher et al., 2013; Myhre et al., 2013; Sherwood et al., 2015; Forster et al., 2021), in practice that is to have the efficacy of unity for all climate drivers. In the past several studies have shown that efficacy is unity in abrupt multi-model studies (Richardson et al., 2019) and in a comprehensive single-model study (Hansen et al., 2005). Here, we demonstrate that ERF is a good climate metric as multi-model simulations have efficacy close to unity in several realistic transient simulations. Our results show large model spread for aerosols, but unlike other studies no systematic differences from GHG experiments (Shindell, 2014; Salvi et al., 2022).

Data availability statement

CMIP6 model data used in this study are freely available from the CMIP6 repository on the Earth System Grid Federation nodes (https://esgf-node.llnl.gov/search/cmip6/, World Climate Research Programme, 2020). The PDRMIP data are available through the World Data Center for Climate (WDCC) https://www.dkrz.de/up/systems/wdcc with https://doi.org/10.26050/WDCC/PDRMIP_2012-2021.

Author contributions

GM: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft, Writing—review & editing. RB: Methodology, Writing—original draft, Writing—review & editing. TA: Methodology, Validation, Writing—original draft, Writing—review & editing. PF: Methodology, Validation, Writing—original draft, Writing—review & editing. CS: Methodology, Validation, Writing—original draft, Writing—review & editing.

Funding

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2024.1397358/full#supplementary-material

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