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CONSTRAINING UNCERTAINTY OF MULTI-DECADAL CLIMATE PROJECTIONS

KNOWLEDGE GAINS: SUMMARY AND IMPLICATION REPORT 1

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IMPROVED CHARACTERIZATION AND UNDERSTANDING OF THE ERF CONCEPT

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KEY MESSAGES

- This KGSIR summarizes recent advances in our understanding of Effective Radiative Forcing (ERF), and methods to quantify ERF.
- ERF is better constrained by using key observations of changes to the climate system in recent advances.
- Uncertainties in ERF due to changes in CO_2 and other climate forcers remain substantial.
- Knowledge gains have been achieved on comparing various climate drivers relative to CO_2 changes.
- Next steps are to quantify causes of the diversity in ERF due to CO_2 in climate models, and improve understanding of aerosol-cloud interactions and thereby their ERF.

CONTEXT

Effective radiative forcing (ERF) is a perturbation to the Earth's energy budget by a climate driver, such as a change in atmospheric concentrations of greenhouse gases or aerosols. ERF is quantified at the top of the atmosphere and is essential to climate science since a change in the Earth's energy budget also leads to a surface temperature change.

ERF has been defined to include a) the initial radiative perturbation to the climate system (such as a reduction in outgoing radiation to space after an increase in greenhouse gases), and b) changes in the atmosphere occurring before global mean surface temperature changes (such as aerosol-cloud interactions and changes to atmospheric temperature). This allows a better representation of surface temperature change between climate drivers (Boucher et al., 2013; Myhre et al., 2013). The atmospheric changes occurring on a short time scale, after the initial radiative perturbation by the climate driver, are known as rapid adjustments (Quaas and Myhre, 2020).

Uncertainties in anthropogenically induced ERF are substantial where atmospheric aerosols are the main driver. The causes of the uncertainties are also different for atmospheric aerosols and greenhouse gases.

For aerosols, a strong regional and temporal variation in concentration combined with lack of a complete process understanding are major causes of uncertainty. Greenhouse gases are to a large extent well-mixed in the atmosphere and the physical understanding of their initial radiative perturbation to the energy budget is mostly well known. Nevertheless, simulations of greenhouse gases in global climate models are associated with uncertainties in ERF because of approximations in radiative transfer scheme, and rapid atmospheric adjustments from the initial perturbation.

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UNCERTAINTIES IN TOTAL EFFECTIVE RADIATIVE FORCING

Figure 1 shows the probability distribution function (PDF) of ERF based on estimates of the Earth's radiative response combined with historical observations of changes in global mean temperature and the Earth's total heat uptake (Andrews and Forster, 2020).

The uncertainty ranges based on the PDF are compared to the IPCC Fifth Assessment Report (AR5) (Myhre et al., 2013) and the Fifth Coupled Model Intercomparison Project (CMIP5) simulations (Taylor et al., 2012). In addition to the total ERF from all anthropogenic climate drivers, the PDF of ERF from atmospheric aerosols are also shown. The time periods in the three estimates are approximately the same (from pre-industrial to around 2010).

In Figure 1 the estimate for total ERF is +2.3 [+1.7 to +3.0] W m^{-2} (5-95% confidence interval) which is a reduction in the uncertainty range of 40% compared to the estimate from IPCC AR5. Figure 1 also shows a similar best estimate and uncertainty range for total aerosols ERF estimated in Andrews and Forster (2020) and IPCC AR5. The results shown in Figure 1 suggest that many global climate models from CMIP5 may include a cooling effect from anthropogenic aerosols that is too strong.

EFFECTIVE RADIATIVE FORCING DUE TO CO_2 CHANGES

Uncertainties in the radiative forcing of CO_2 changes in Global Climate Models (GCMs) have been a long-standing problem (Cess et al., 1993; Collins et al., 2006; Soden et al., 2018). Between the most accurate radiative transfer schemes available (line-by-line), the differences in forcing due to CO_2 changes are small (Soden et al., 2018) and it is a similar case for the uncertainties associated with the spectroscopic data (Mlynczak et al., 2016). However, in GCMs the radiative transfer schemes need to be simplified because of computer time requirements, which causes differences due to uncertainties in the applied parameterizations.

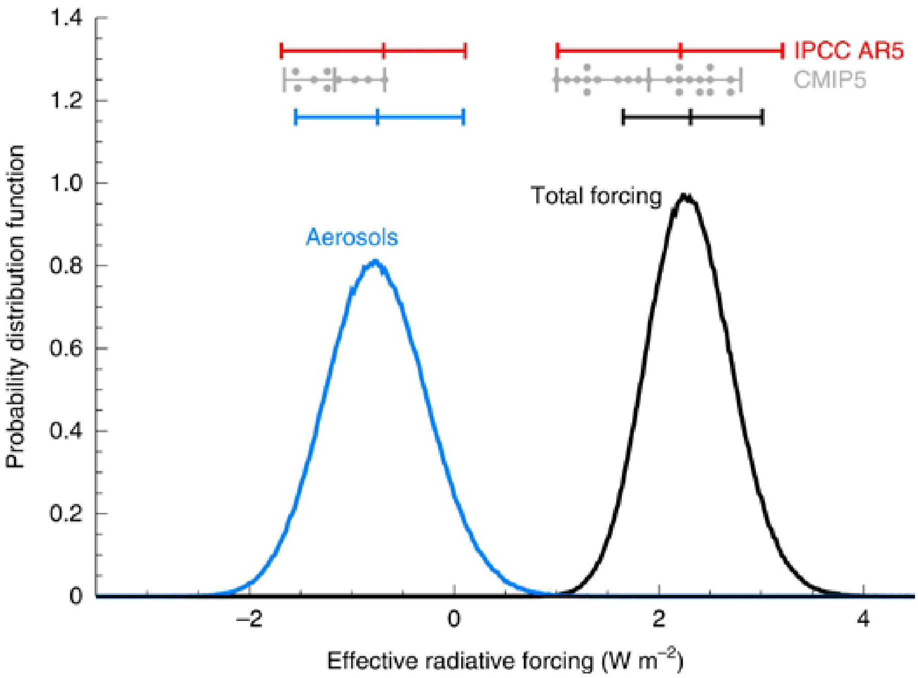

***FIGURE 1:** Historical ERF derived from an energy budget constraint. The black line shows historical ERF (1861–1880 to near-present) probability distribution function derived from historical energy budget constraints (Andrews and Forster, 2020). The blue line denotes the aerosol component. The 5-95% uncertainty range of historical ERF as assessed by IPCC AR5 is shown in red and the one inferred from the Fifth Coupled Model Intercomparison Project (CMIP5) climate model ERFs in grey. Grey dots represent individual CMIP5 models. Lines and bars represent the best estimate and 5–95% confidence interval.*

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Figure 2a shows multi-model simulations of ERF from the Precipitation Driver Response Model Intercomparison Project (PDRMIP) (Myhre et al., 2017) and the Radiative Forcing Model Intercomparison Project (RFMIP) (Pincus et al., 2016) for a doubling in atmospheric CO_2 concentrations. The RFMIP results are shown as half of quadrupling of the CO_2 concentrations simulations. The range in PDRMIP and in RFMIP is about 1 W m^{-2}, with standard deviations of 37 % and 25 %, respectively. Zelinka et al. (2020) found the standard deviation in doubling of atmospheric CO_2 concentration to be reduced by about 30% between GCMs in the newer generation models in the Sixth Coupled Model Intercomparison Project (CMIP6; here the RFMIP contribution to it) compared to CMIP5 (Soden et al., 2018).

The explanation for the differences in the range in the ERF due to CO_2 in PDRMIP (and CMIP5) compared to RFMIP is unresolved, but can be due to updates in radiation schemes in the climate models, differences in simulated atmospheric temperature profiles, differences in simulated water vapour which has a strong absorption overlap with CO_2, representation of clouds, or differences in simulated rapid adjustments. Stratospheric cooling due to CO_2 is a well-known feature, and has a large radiative effect for CO_2 changes.

Cloud changes are another important rapid adjustment in the atmosphere, and show large model diversity (Smith et al., 2018). Ongoing work in the CONSTRAIN project is investigating whether there is a particular cause for this diversity or whether it is a combination of several factors. Initial work indicates that temperature differences in the stratosphere may play an important role.

FIGURE 2: *Effective Radiative Forcing (W m^{-2}) due to a doubling of the CO_2 concentration (a). Green bars are results from PDRMIP and blue bars from RFMIP (taken as half of the quadrupling experiment). Efficacy of a range of climate drivers (b), defined as global, annual mean surface temperature change in response to the ERF in comparison to the surface temperature change in response to the same global-mean ERF due to CO_2 concentration change.*

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EFFICACY

To understand the role of non-CO_2 climate drivers in past and future evolutions of ERF, the methodology used to quantify ERF is important. Additionally, this has implications for policy decisions since climate metrics (such as global warming potentials - GWP) are applied to compare emissions of non-CO_2 gases relative to CO_2 emissions (Myhre et al., 2013). IPCC AR5 included rapid adjustments beyond stratospheric temperature adjustment to allow a better comparison between climate drivers (Boucher et al., 2013; Myhre et al., 2013). ERF is a useful quantity if the temperature change from a given ERF due to a climate driver (climate sensitivity parameter) is equal to the change in response to a CO_2 ERF of the same magnitude. Therefore, the method to derive the efficacy (ratio of the climate sensitivity parameter for a non-CO_2 climate driver to the climate sensitivity parameter for CO_2) is sought to be as close as possible to 1.0 for all climate drivers.

In PDRMIP the required simulations to quantify efficacy, i.e. simulations to diagnose both ERF and surface temperature change, are available. Figure 2b is obtained thanks to significant contributions from the CONSTRAIN project and shows results for the efficacy for a range of climate drivers as well as some regional experiments (Richardson et al., 2019). Results show an efficacy close to unity, but slightly below for all but one forcing scenario. Richardson et al. (2019) show that the efficacy is even closer to one when the radiative effect of the small land surface temperature change has been corrected in the fixed sea-surface simulation to calculate ERF. The recommended method for calculating ERF in Richardson et al. (2019) has been compared to other approaches.

Overall, knowledge gains from the CONSTRAIN project provide a method to calculate ERF from climate model simulations keeping sea-surface temperature constant. This can be applied to a large range of climate drivers and is thus important for understanding climate change.

ERF OF AEROSOLS

Figure 1 shows the large uncertainty in ERF of anthropogenic aerosols. Aerosols scatter and absorb solar radiation (aerosol-radiation interactions, or direct aerosol effect) and can influence cloud microphysics (aerosol-cloud interactions, or indirect aerosol effect). Bellouin et al. (2020) recently concluded that the radiative effect of anthropogenic aerosols in clear sky is relatively well constrained among several studies including multi-model analysis. Based on this finding Bellouin et al. (2020) estimated a reduction in the uncertainty of the radiative forcing of the direct aerosol effect compared to earlier estimates.

Anthropogenic aerosols increase the number concentration of cloud droplets giving a cooling effect. Compared to other indirect aerosol effects, this effect is relatively well constrained (Ghan et al., 2016; Malavelle et al., 2017)

Recent observation-based studies show that changes to cloud liquid water by anthropogenic aerosols are likely to be small and negative (Malavelle et al., 2017; Toll et al., 2017; Toll et al., 2019). The adjustment of cloud fraction is less well understood (Quaas and Myhre, 2020). The understating of rapid adjustment to aerosol-radiation interactions due to black carbon has been substantially improved, giving a general strong reduction in ERF compared to its direct aerosol effect (Smith et al., 2018).

Overall, there has been progress in the scientific knowledge of the anthropogenic aerosol influences on climate, but only a small reduction in the uncertainty in aerosol ERF (see Figure 1 and further discussion in Bellouin et al. (2020)).

IMPLICATIONS

- A method providing efficacy for a broad range of climate forcers yields values close to unity, which allows improved understanding of the role of non-CO_2 climate drivers on past and future climate change.
- Global Warming Potentials (GWP) or other climate metrics are used in policy decisions on reductions of non-CO_2 gases relative to CO_2 emissions. These are applied in the United Nations Framework Convention on Climate Change and are thus relevant to the Paris agreement. GWPs depend on both ERF and the lifetime of the non-CO_2 greenhouse gases. Improved quantification of ERF, and improved comparability of climate effects of different drivers, implies improved climate metrics.

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Johannes Quaas also co-leads CONSTRAIN Work Package 1. He is Professor for Theoretical Meteorology at the University of Leipzig. His research interest is in clouds and climate change, in particular aerosol-cloud interactions, analysis of satellite observations, and atmospheric modelling. Johannes is lead author for the IPCC 6th Assessment Report Working Group I.

ABOUT THIS KNOWLEDGE GAINS: SUMMARY AND IMPLICATION REPORT

CONSTRAIN’s Knowledge Gains: Summary and Implication Reports outline CONSTRAIN’s contributions to the peer reviewed literature (knowledge gains), and summarise the implications for both the scientific community and broader society. This report and other CONSTRAIN publications are available at http://constrain-eu.org.

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ABOUT CONSTRAIN

The 2015 Paris Agreement sets out a global action plan to avoid dangerous climate change by limiting global warming to well below 2°C, whilst pursuing efforts to limit warming to 1.5°C. However, predicting how the climate will change over the next 20-50 years, as well as defining the emissions pathways that will set and keep the world on track, requires a better understanding of how several human and natural factors will affect the climate in coming decades. These include how atmospheric aerosols affect the Earth’s radiation budget, and the roles of clouds and oceans in driving climate change.

The EU-funded CONSTRAIN project, a consortium of 14 European partners, is developing a better understanding of these variables, feeding them into climate models to reduce uncertainties, and creating improved climate projections for the next 20-50 years on regional as well as global scales.

In doing so, CONSTRAIN will take full advantage of existing knowledge from the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) as well as other Horizon 2020 and European Research Council projects.

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