Horizon 2020 Societal Challenge 5:
Climate action, environment,
resource efficiency and raw materials

CONSTRAIN: 'Constraining uncertainty of multi-decadal climate projections'

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Key messages:

- This KGSIR summarises recent advances in our understanding of Effective Radiative Forcing (ERF) and components of ERF.
- Global IRF is diagnosed for the first time from satellite observations using radiative kernels. This provides direct evidence of the impact of anthropogenic activity on the Earth's energy budget.
- There is robust evidence of a reversal in the negative trend of aerosol ERF.
- Total ERF has increased and strengthened the top-of-atmosphere radiative imbalance.

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Knowledge Gains: Summary and Implication Report on ERF

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Context

Effective radiative forcing (ERF) measures the change in net radiative flux at the top-of-atmosphere (TOA) following a perturbation to the Earth's energy balance by drivers such as greenhouse gases (GHGs), aerosols or changes in land-surface properties. These drivers alter the balance of radiative fluxes in the climate system and impose an instantaneous radiative forcing (IRF) at the TOA that subsequently initiates rapid adjustments in tropospheric and stratospheric temperature, water vapour, surface albedo and clouds, which further alter the initial TOA radiative imbalance. ERF is defined as the sum of both IRF and the total radiative effect of rapid adjustments associated with a climate driver (Forster et al. 2021).

Quantifying ERF is an important component of climate science, principally because changes in the Earth's energy balance result in changes in surface temperature. Calculating ERF therefore allows us to estimate the amount of surface warming or cooling associated with a forcing mechanism and compare the strength of different drivers. It also allows us to attribute historical trends in surface temperature to a particular

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forcing agent, project future changes in climate and generate policy-relevant metrics such as Global Warming Potentials (GWPs), which are vital in climate mitigation strategies.

The recent Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6; Forster et al. 2021) estimated total anthropogenic ERF to be 2.71 (1.96 to 3.48) W m^{-2} for the year 2019 relative to 1750. This value is largely due to increases in the atmospheric concentration of GHGs over the historical era, in particular carbon dioxide (CO_2). The combined 2019-1750 ERF of well-mixed GHGs is estimated to be 3.32 (3.03 to 3.61) W m^{-2}, which is partially offset by a total aerosol ERF (including both aerosol-radiation and aerosol-cloud interactions) of -1.06 (-1.71 to 0.41) W m^{-2}. Uncertainty in the exact magnitude of aerosol ERF is substantial however, caused largely by the strong spatial and temporal variation in aerosol emissions and concentration, and an incomplete understanding of the processes involved in atmospheric aerosol interactions.

The CONSTRAIN project has been particularly focussed on understanding the evolution of near-term temperature trends. This requires an up-to-date understanding of recent radiative forcing trends and their causes. Through this work, CONSTRAIN studies have supplied important contributions to the IPCC Working Group I AR6 Chapter 7 (Forster et al. 2021), in particular related to the evaluation of ERF and the sign and magnitude of rapid adjustments associated with different climate drivers (Smith et al. 2018, Smith et al. 2020). CONSTRAIN work for AR6 also confirmed that global aerosol ERF had been reducing in magnitude from around 2000. This assessment was largely based on the work of Smith et al. (2021), which applied historical constraints to Coupled Model Intercomparison Project phase 6 (CMIP6) models. A key piece of CONSTRAIN analysis since then has confirmed that the reversal of the aerosol ERF trend was robust. As detailed further below, Quaas et al. (2022) used multiple lines of evidence to robustly conclude that aerosol ERF has become less negative globally, leading to an acceleration of the anthropogenic forcing of climate change.

Summary of Knowledge Gains

Observational evidence of strengthening instantaneous radiative forcing

Observing the Earth's TOA IRF is difficult because satellites measure TOA net radiative fluxes, which are comprised of both the IRF component of a climate driver(s) and the climate system's subsequent radiative response. Estimates of IRF are therefore mainly derived from models, which allow for the initial radiative perturbation of a variety of climate drivers to be diagnosed across a range of timescales. However, physically observing IRF remains an important endeavour to provide direct evidence of anthropogenic influence on climate.

Recent work by Kramer et al. (2021) offers significant progress to this effort by diagnosing global IRF directly from satellite observations across the 2003-2018 period. Using radiative flux anomalies from NASA's Clouds and Earth's Radiant Energy System (CERES) Energy Balance and Filled (EBAF) product (Loeb et al. 2018, Loeb et al. 2020), Kramer et al. (2021) use radiative kernels (Soden et al. 2008) to isolate the IRF component of the TOA energy imbalance from radiative feedbacks and adjustments. Results show a significant, positive linear trend in observed global-mean IRF of 0.033 ± 0.007 W m^{-2} $year^{-1}$, predominantly driven by an increase in longwave IRF (0.027 ± 0.007 W m^{-2} $year^{-1}$) due to rising GHG concentrations. A smaller but significant increase in shortwave IRF (0.006 ± 0.003 W m^{-2} $year^{-1}$) also contributes, due in part

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to policy-driven reductions in anthropogenic aerosol emissions from several main source regions. In total, Kramer et al. (2021) demonstrate that observed IRF has increased and strengthened the TOA radiative imbalance by 0.53 ±0.11 W m^{-2} across 2003 to 2018, providing direct evidence of anthropogenic effect on the Earth's energy budget.

Updated indicators of global climate change

Climate policy and decision-making must be underpinned by robust and up-to-date information on the state of the climate system. The publication of IPCC reports forms an important source of knowledge to a range of actors working to address the challenges of climate change by providing key data and analysis to inform adaptation and mitigation strategies. However, a lack of annually updated, reliable climate information for the public can lead to an information gap between scientists and decision makers. A lack of recent inventories for short-lived climate pollutants (SLCPs) also remains a problem. Forster et al. (2023) instigated an annual update process to bring the global community together to provide an update of key indicators of global climate change including: emissions of GHGs and SLCPs, ERF and human-induced warming. This study found that ERF is currently increasing at an unprecedented rate of 0.6 Wm^{-2} per decade (see Figure 1). Two thirds of this trend can be attributed to GHGs and one third to recovery in the negative ERF of aerosols. Recently submitted work (Hodnebrog et al. 2023) confirms this with the CERES satellite data record and dedicated model experiments.

Reversal in the trend of aerosol effective radiative forcing

Anthropogenic aerosols exert a net negative ERF on the Earth's energy balance through their direct interaction with shortwave radiation (reflecting it back to space) and their indirect effect on cloud microphysics. IPCC AR6 used multiple lines of evidence to estimate this forcing to be -1.1 W m^{-2} across the 2019 – 1750 period, with a 5% to 95% confidence interval of -1.7 to -0.4 W m^{-2} (Forster et al. 2021). Despite large uncertainty on the precise magnitude, the cooling effect of aerosols works to offset a sizeable amount of warming associated with the positive ERF of GHGs. However, unlike GHGs which have comparatively longer lifetimes, aerosols reside in the atmosphere for much shorter periods of time (from days to weeks in the troposphere), meaning that aerosol ERF responds quickly to changes in the rate of emissions into the atmosphere. This makes the magnitude of aerosol ERF more susceptible to fluctuations over shorter periods of time.

Recent policy seeks to reduce aerosol emissions in several regions of the world to improve air quality and environmental health. Whilst there are clear benefits to these reductions, a decrease in aerosol emissions means a less negative global aerosol ERF and a reduction in its ability to counteract the positive ERF of GHGs. Observing and modelling the climate effects of aerosol emissions is therefore important for both ongoing local air quality assessment and the quantification of global climate change.

Quaas et al. (2022) conduct a comprehensive review of the evolution of aerosol ERF since 2000 using multiple datasets to show that aerosol emissions and atmospheric concentrations have declined across many regions of the world. Bottom-up inventories (i.e., datasets of emission quantities by source) show declines in anthropogenic aerosol and aerosol precursor emissions across many regions of the world along with declining trends in observed atmospheric aerosol burden. Satellite measurements of cloud droplet number concentration also show declining trends, particularly over oceanic regions of the Northern

Hemisphere mid-latitudes that are downwind of regions that display declining aerosol emissions. Key regions that exhibit aerosol decreases (over North America, Europe and East Asia) dominate over other regions that continue to display increasing aerosol trends (Figure 2), resulting in a robust signal of overall declining anthropogenic aerosol influence on climate since 2000. Quaas et al. (2022) estimate that this results in a reduction in the negative aerosol ERF by 0.1 to 0.3 W m^{-2}, which consequently leads to a strengthening of the positive anthropogenic forcing.

Aerosol-cloud interactions

Work using natural analogies to probe the fidelity of the representation of aerosol-cloud interactions has focussed on the large fissure eruption near Holuhraun in Iceland that occurred in 2014. A novel Machine Learning (ML) approach was developed (Chen et al. 2022), that used the long cloud retrieval record available from the Moderate Resolution Imaging Spectrometer (MODIS) satellite instruments to predict cloud droplet number concentrations (N_d), cloud top effective radius (r_{eff}), cloud liquid water path (LWP), and cloud fraction (CF). This approach enabled prediction of what the cloud fields would have looked like in the absence of the eruption. Comparing the ML-MODIS observations with those that were observed by MODIS in the 2014 period that was influenced by the eruption, Chen et al. (2022) were able to tease out the impact of sulfate aerosols upon clouds. As expected, N_d increased, and r_{eff} decreased with little (if any) influence on LWP. The most interesting finding was that the cloud fraction increased significantly (Figure 3).

Further work with multiple-climate models (following Jordan et al. 2023; Figure 4) assesses the fidelity of climate models in reproducing the changes in cloud fields that are observed. While there is significant variability across the models, the multi-model mean change in the monthly mean r_{eff} appears accurate, but the observed change in the cloud fraction appears under-estimated. This suggests that aerosol-cloud interactions may play a greater role in offsetting radiative forcing (and hence the global warming) from GHGs than previously thought.

Efficacy

ERF is used widely to compare the strength of different climate drivers. However, this is reliant on the assumption that different climate drivers will inflict the same magnitude of surface temperature change given the same magnitude of ERF. ERF is an ideal metric to compare drivers if this assumption is correct, however it is important to evaluate this notion and understand how and why an equivalent ERF from different forcing mechanisms could result in a different surface temperature response. We can determine the so-called efficacy of different drivers by calculating the global-mean surface temperature response per unit ERF relative to that from CO_2.

It is also important to evaluate climate driver efficacy across a range of experiment types. Previous CONSTRAIN work (Richardson et al. 2019) conducted analysis of 11 climate models participating in the Precipitation Driver and Response Model Intercomparison Project (PDRMIP; Myhre et al. 2017) to calculate efficacy for abrupt forcing perturbations, whereby the full forcing mechanism is enacted instantaneously. However, such abrupt forcing experiments do not characterise transient changes in ERF, the climate feedback parameter and surface temperature response. Recent work by Myhre et al. (2023, due to be submitted soon) analyses transient forcing experiments, whereby the forcing mechanism is applied across a period of time (e.g., over the industrial era from 1850-to present). Figure 5 compares the geometric mean efficacies from the CMIP6 experiments analysed by Myhre et al. (2023) against the PDRMIP experiments of Richardson et al. (2019). Two main findings are evident from this comparison: 1) that the mean efficacy of different climate drivers is close to unity, even in experiments including aerosol forcings, and 2) that efficacies in the transient experiments are similar to the abrupt experiments. Furthermore, experiments with large forcing magnitudes (i.e., quadrupling of CO_2) exhibit an efficacy greater than one, whilst experiments conducted with few models (i.e., land-use change and black carbon specified at lower altitudes in the atmosphere; BCSLT) have an efficacy notably lower than one. In the case of the latter two experiments, a weak forcing magnitude and surface temperature response can result in a stronger signal-noise ratio. In accord with previous findings, Myhre et al. (2023) also demonstrate large model range in aerosol-related efficacy highlighting the need for further research to constrain its magnitude.

Implications

Overall, CONSTAIN has provided much more timely radiative forcing analysis to the community that helps us to understand recent temperature trends. There is still work to be done. As we write this, we still don’t have a complete understanding of why 2023 has been such a hot year and to what extent different forcing mechanisms have specifically contributed to this, such as the recent pollution controls on shipping emissions. Nevertheless, we can apply the understanding forged from our research to help this endeavour (e.g., Hausfather and Forster 2023).

We have made use of available time series of satellite observations to diagnose global IRF to provide direct evidence of the impact of anthropogenic activity on the Earth’s energy budget. This has demonstrated that IRF trends can be detected from satellites and that near-real time monitoring could provide an important and useful source of information to climate change assessment. We have further documented robust evidence of a reversal in the negative trend of aerosol ERF and progress our understanding of aerosol-cloud interactions using machine learning techniques. We further find that total ERF has increased and strengthened the top-of-atmosphere radiative imbalance, from which we can expect to observe accelerated warming over the coming decades unless a rapid reduction in GHG emissions occurs, or if a volcanic eruption transpires to cause a negative radiative forcing that can offset warming.

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Johannes Quaas also co-leads CONSTRAIN Work Package 1. He is Professor for Theoretical Meteorology at Leipzig University. His research interest is in clouds and climate change, in particular aerosol-cloud interactions, analysis of satellite observations, and atmospheric modelling. Johannes was lead author for the IPCC AR6 Working Group I.

About this Knowledge Gains: Summary and Implication Report

CONSTRAIN’s Knowledge Gains: Summary and Implication Reports outline CONSTRAIN’s contributions to 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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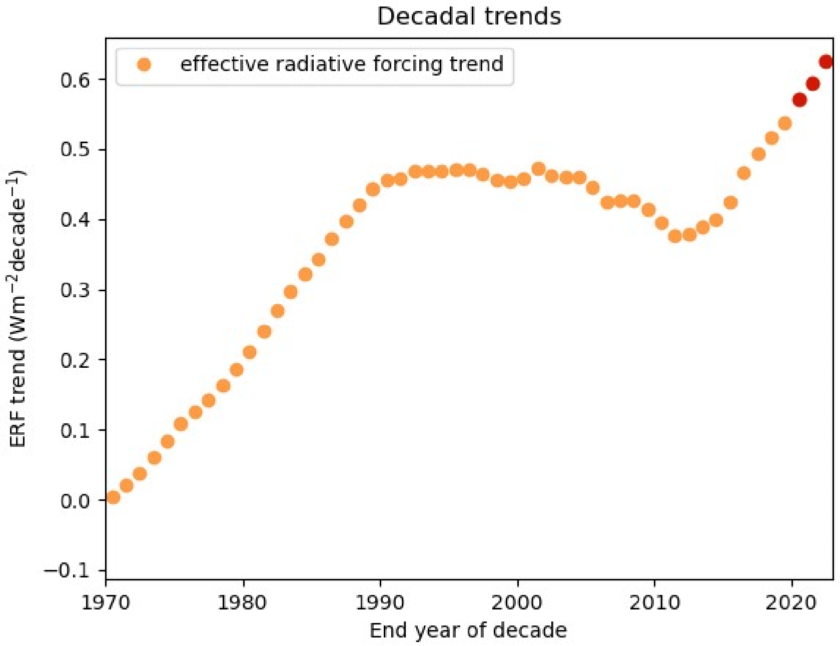

Figure 1: Decadal trends in anthropogenic effective radiative forcing (ERF). The red points mark the three additional years since the IPCC AR6 (Forster et al. 2021) time series, which ended in 2019. Adapted from Forster et al. (2023).

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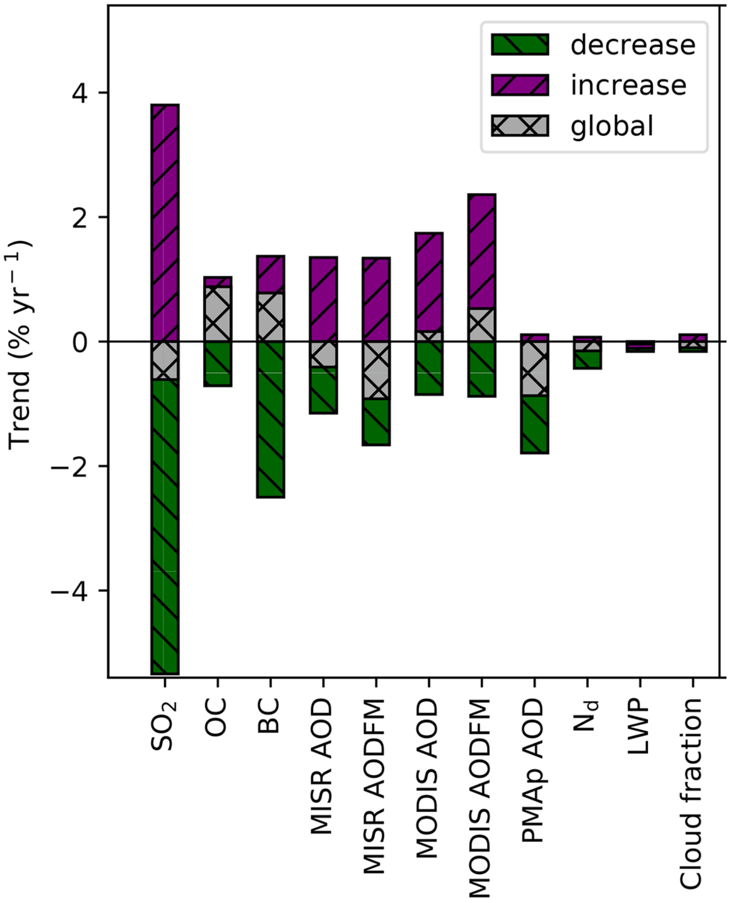

Figure 2: Mean values from 2000-2019 averaged across global regions (green/downward hatching) with substantial negative trends in clear-sky solar ERF (i.e., larger than 0.05 W m^{-2} yr^{-1} in absolute terms) and global regions (positive/upward hatching) with substantial positive trends. Grey bars (crosses) show the global mean between 60°N and 60°S. Regions with negative trends and positive trends cover 7.3% and 1.1% of the Earth's surface respectively.

From left to right these bars show trends in anthropogenic emissions of sulfur dioxide (SO_2), organic carbon (OC) and black carbon (BC) from the Community Emissions Data System (CEDS v_2021_04_21) and aerosol optical depth (AOD) and fine-mode AOD (AODFM) from the Multi-Angle Imaging Spectro-Radiometer (MISR) and the MODerate Resolution Imaging Spectroradiometer (MODIS) and the Polar Multi-sensor aerosol optical properties product (PMAp) from the Metop-A satellite. Cloud droplet concentration (N_d), liquid water path (LWP) and cloud fraction are taken from MODIS. Note that the PMAp timeseries only spans the period 2008-2017. Adapted from Quaas et al. (2022).

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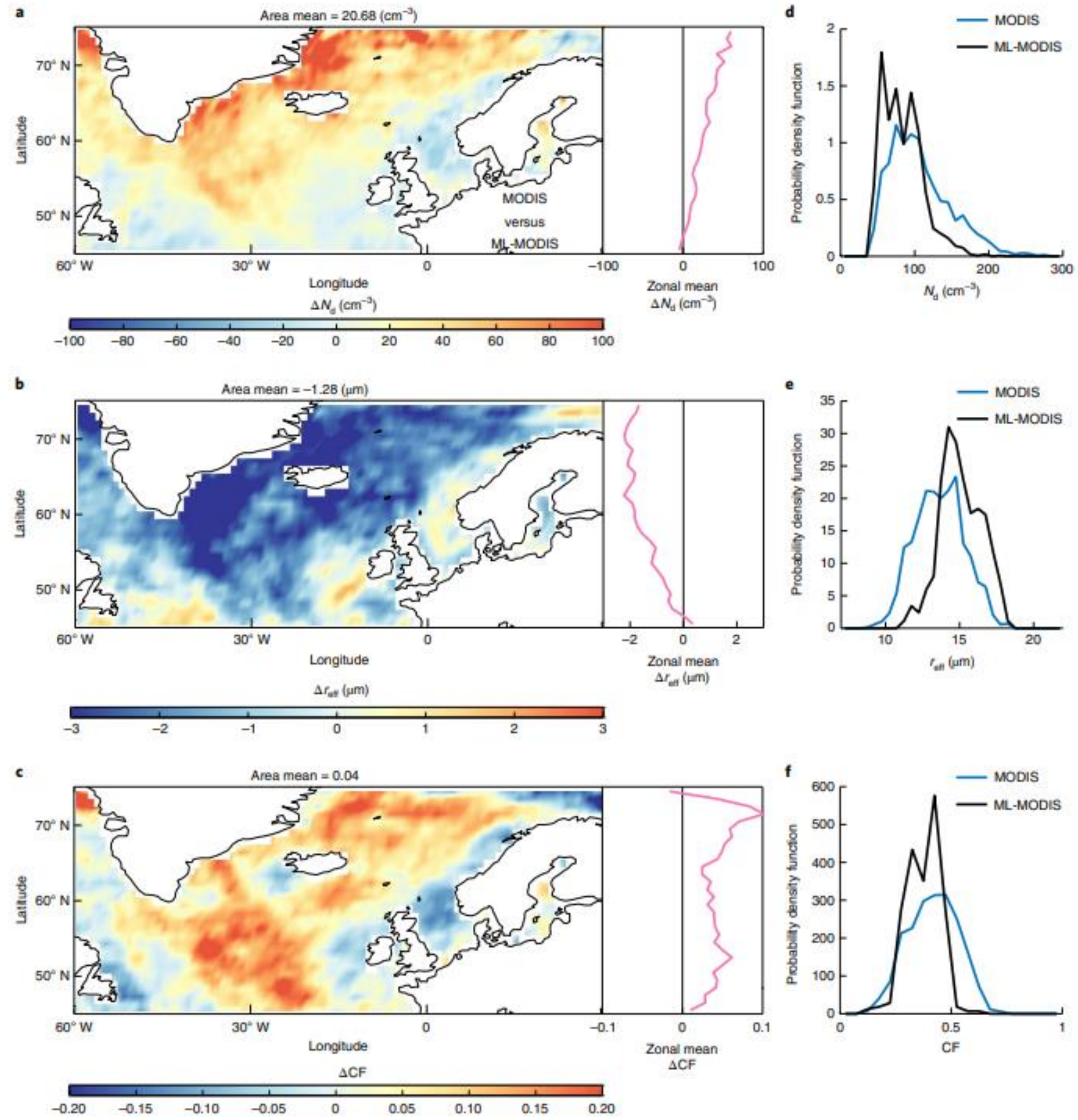

Figure 3. Spatial distribution of the changes induced by the volcanic eruption for the month of October 2014 evident in MODIS cloud retrievals for a) N_d, b) r_{eff}, c) CF for October 2014. From Chen et al. (2014).

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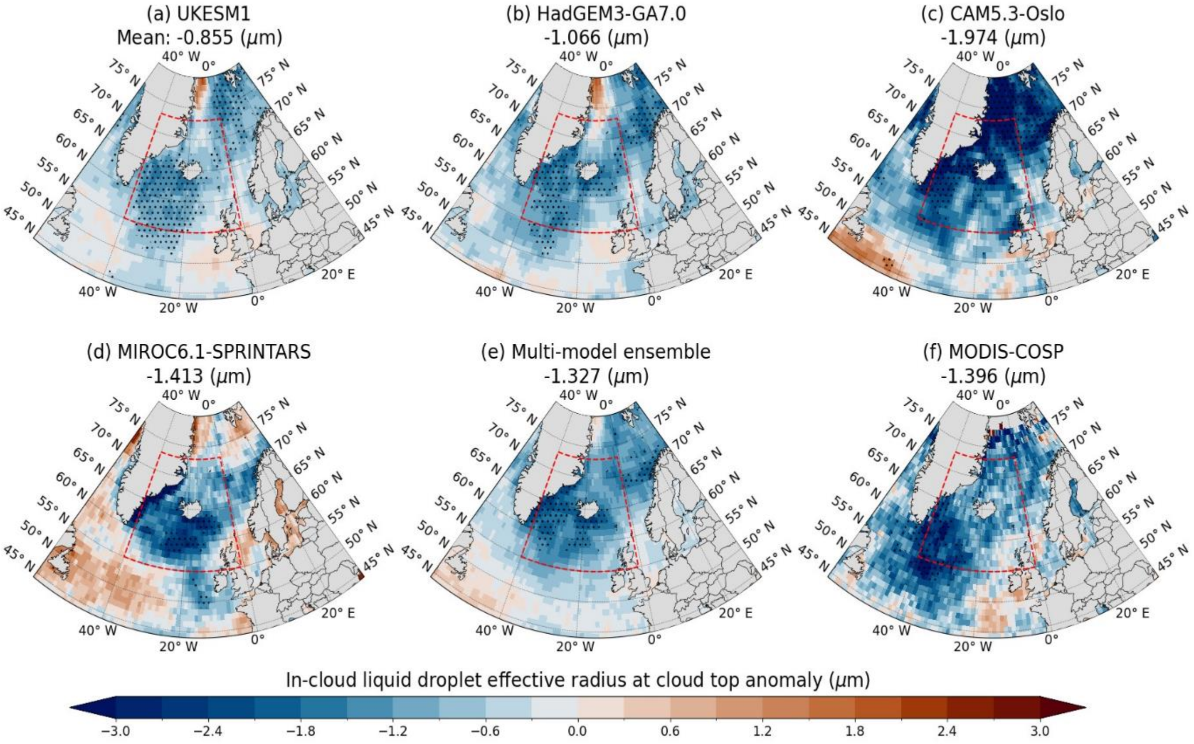
(a) UKESM1
Mean: -0.855 (μm)

(b) HadGEM3-GA7.0
-1.066 (μm)

(c) CAM5.3-Oslo
-1.974 (μm)

(d) MIROC6.1-SPRINTARS
-1.413 (μm)

(e) Multi-model ensemble
-1.327 (μm)

(f) MODIS-COSP
-1.396 (μm)

Figure 4: The change in r_{eff} diagnosed from the different global models diagnosed as the difference between 2014 and the 2002-2020 climatology (following Jordan et al. 2023). The mean value of the change in r_{eff} over the grid-box shown in red is provided for each model, the model ensemble and the MODIS (MODIS-COSP) product.

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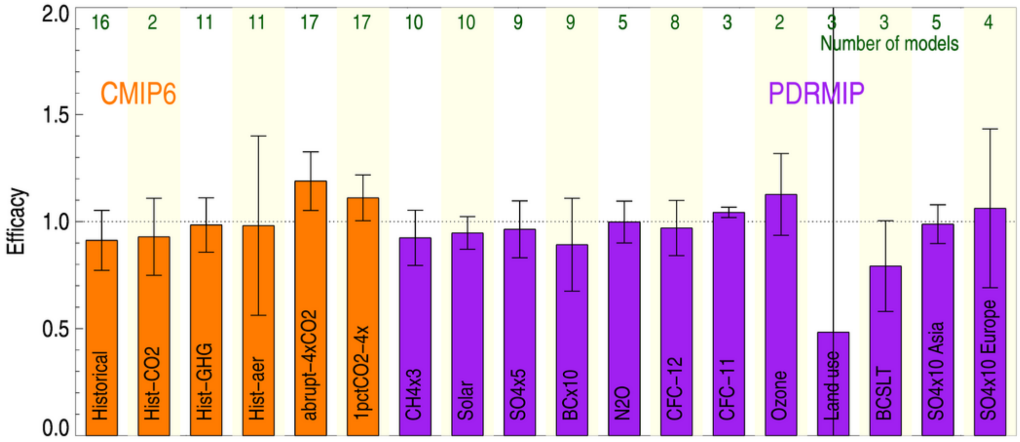

Figure 5: Comparison of efficacies in CMIP6 and PDRMIP (Richardson et al. 2019) experiments. Bars show the geometric mean efficacies with uncertainties given as one standard deviation. The number of model simulations available for each experiment are shown in green along the top of the figure. From Myhre et al. (2023).

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