


Aerosol absorption has an underappreciated role in historical precipitation change

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Precipitation change has proven notoriously hard to simulate consistently between global climate models. Aerosol induced shortwave absorption over the historical era is also poorly constrained in both observations and modelling. These factors are closely linked, since absorption induced heating of the atmospheric column inhibits precipitation formation. Here I show that the spread in simulated aerosol absorption in the most recent generation of climate models (CMIP6) can be a dominating cause of uncertainty in simulated precipitation change, globally and regionally. Consequently, until improvements are made in scientific understanding of the key absorbing aerosol types, projections of precipitation change under future anthropogenic emissions will have major, irreducible uncertainties. Black carbon, which has recently been found to have only a weak influence on global surface temperature, regains prominence as a contributor to regional precipitation change and its historical and future evolution.

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Anthropogenic influences have caused a net increase in global mean surface temperature by 1.1 °C over the historical era^{1,2}, along with a wide range of other aspects of climate change that include, notably, mean and extreme precipitation³. However, while the observed magnitude and regional pattern of global surface warming are well reproduced by the most recent generation of global climate models^{4,5}, historical precipitation change has proven more challenging to simulate^{6–8}, which in turn reduces confidence in projections of hydroclimate-related future hazards^{9,10}. It is well recognized that this uncertainty is partly due to the high complexity of the geophysical processes involved⁸, which include clouds¹¹, evaporation¹², and the atmospheric energy balance¹³, and partly because observations of precipitation are more uncertain, sparse, and of shorter duration than for surface temperature, which makes model validation more challenging⁸.

Another, less appreciated, cause of model diversity in simulated precipitation change is the sensitivity to changes in atmospheric aerosols^{14,15}, which is still a major source of uncertainty in global climate models¹⁶. This influence has two main components¹⁷. One is the reduction in average precipitation that follows from the net cooling influence of aerosols on global mean surface temperature (sometimes termed “slow precipitation change”). The other mechanism, which is much more scientifically uncertain, is the rapid adjustment of the atmospheric column to the presence of aerosol-induced atmospheric heating^{15,18}. This process inhibits precipitation formation, as the release of latent heat due to condensation has to compete with the warming rate absorbing aerosols. Cloud formation is also affected¹⁸, due both to warming-induced changes in lapse rate and to droplet evaporation if an absorbing aerosol is present within a cloud.

Previous studies have established a robust, linear relationship between atmospheric absorption and precipitation inhibition, in a wide range of recent climate models, both on global mean^{14,19} and for regional changes in aerosol emissions^{20,21}. This relationship is well understood in terms of the influence of aerosols on the local energy balance^{15,22,23}.

The amount of aerosol-induced shortwave energy absorption in the present atmosphere, and, consequently, in simulations of historical climate change in Earth System Models, is however highly uncertain^{24–26}. The primary reason for this is that aerosol-induced absorption is, as yet, virtually unconstrained by observations²⁴. Most current photometric satellite sensors do not have the capability to measure absorption. It can be retrieved through an inversion of measurements from sun-sky photometers at Aerosol Robotic Network (AERONET) stations^{27,28}, albeit with notable uncertainties, sparse geographical coverage, and limitations on capabilities in low aerosol loading conditions^{29,30}. Model estimates, on the other hand, suffer from temporal and spatial uncertainties in aerosol emission inventories, limited knowledge of aerosol optical properties, transport, wet removal, ageing, atmospheric chemistry, aerosol-cloud interactions and deposition rates²⁴. Moreover, even though there have been marked improvements over the 5th and 6th phases of the Coupled Model Intercomparison Project (CMIP5, CMIP6), the treatment of aerosols in many global climate models is still simplified, partly for reasons of computational efficiency, partly because physical processes such as internal aerosol mixing and ageing are not always implemented²⁵.

It is therefore prudent to ask what the influence of poorly constrained aerosol absorption is on scientific knowledge of historical precipitation change. The main absorbing aerosol species is black carbon (BC), a byproduct of incomplete combustion, that has long been studied as a contributor to global warming³¹. While this influence was assessed in the IPCC 6th Assessment Report to be only ~0.1 °C over the historical era³², the potential influence of

BC-induced absorption on precipitation inhibition has been much less studied. BC was recently found to constitute around 60% of the total aerosol absorption in current models²⁵. The remainder comes from the absorbing component of organic carbon (brown carbon, or BrC; 11%), and from dust (31%). BC, BrC and dust atmospheric loadings have all changed over the historical era, either from anthropogenic emissions or as feedbacks to global surface temperature and land use changes. The inter-model uncertainties on this set of processes are however very high, leading to a potentially quite marked propagated uncertainty on modelled precipitation.

In the following, simulations from a range of recent single model and multi-model intercomparison studies are used to quantify the current model diversity in aerosol absorption, and how it has changed over the historical era. A relation is then established that can be used to propagate this diversity to a contribution to global and regional uncertainty in modelled precipitation, via rapid adjustments. The main conclusion is that aerosol absorption may make up a dominating source of current inter-model differences, and that this uncertainty is irreducible until improvements are made to treatments of absorbing aerosols in global models, and tighter observational constraints become available. Currently, aerosol-induced shortwave absorption constitutes a limiting factor for the capability of the climate modelling community to project and communicate near-term climate hazards related to precipitation change.

Results

Aerosol absorption uncertainty in CMIP6. The starting point for this analysis is the inter-model spread in aerosol-induced shortwave absorption in CMIP6, over the historical era. Aerosol absorption is commonly quantified in two ways. One is through absorbing aerosol optical depth (AAOD), a quantity that is retrievable (albeit not directly measurable) from observations³⁰. Broadly, AAOD is the integrated extinction of shortwave energy by aerosols through the atmospheric column attributable to absorbing aerosols, and a component of the more commonly used total Aerosol Optical Depth (AOD). AAOD is retrievable from observations and is therefore often used for model validation, even though its magnitude is not presently well constrained²⁴. The second method for quantifying absorption is as the difference between top-of-atmosphere and surface radiative forcing, in Wm^{-2} . This can be done exclusively in shortwave radiation, in long wave, or as their net. While this second measure is more directly relatable to the physical effects of aerosols on the climate, and thus more useful for quantifying precipitation change, it is only available from climate models. The following analysis uses both quantities, and also documents and exploits their close relation.

Figure 1 shows the historical evolution and inter-model diversity in aerosol-induced absorption in CMIP6, in terms of AAOD at 550 nm. Already in the 1850–1900 period, the simulated absolute global, annual mean AAOD varies between 0.002 and 0.006. This is related to differences in amount and treatment of natural aerosols in the models (mainly dust and biomass burning), and to differences in aerosol optical properties and distribution.

Subtracting the 1850–1900 value from each model leaves the change over the historical era, which can be attributed to anthropogenic emissions, land use change, or feedbacks from surface temperature change to the extent that they are captured in CMIP6 models. In the following, this is termed “anthropogenic AAOD”. While all models exhibit a clear increase up to 2014 (the last year of the CMIP6 historical simulations), related primarily to aerosol emission inventories common to all the models^{33,34}, simulated anthropogenic AAOD in 2014 varies from 0.001 to

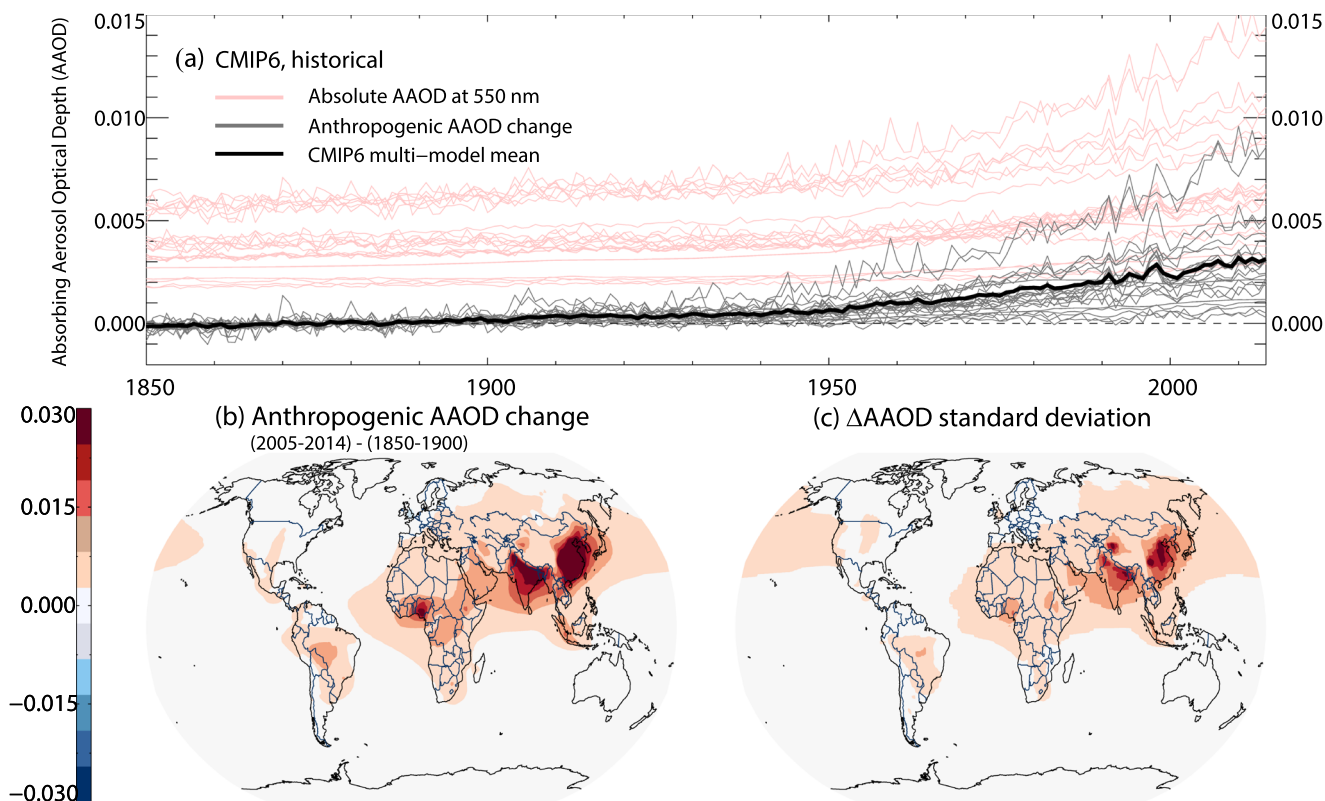


Fig. 1 CMIP6 model spread in simulated absorbing aerosol optical depth (AAOD). **a** Absolute (red) and anthropogenic (black) AAOD over the historical era. **b** Geographical pattern of the multi-model annual mean AAOD change. **c** Inter-model standard deviation of AAOD change over the historical era.

0.009. The multi-model mean anthropogenic AAOD is 0.003, with a standard deviation of 100% relative to the mean (0.003). For comparison, Sand et al. recently reported a multi-model mean total, present day AAOD at 550 nm of 0.0054 [0.0030, 0.0098] from the AeroCom Phase III exercise²⁵, which is consistent with the mean and spread of the CMIP6 results presented here.

Atmospheric aerosol loading is, however, highly spatially heterogeneous. Precipitation inhibition will initially occur where the absorbing aerosols are located (which generally differs from where they are emitted, depending on prevailing wind and precipitation patterns), but changes can also be induced remotely depending on teleconnections from the region of absorption^{35–37}. Figure 1 also shows the geographical distribution of AAOD change, for the period 2005–2014 relative to 1850–1900. The pattern is dominated by the current regions of high BC emissions, notably South and East Asia, and their downwind regions. The biomass-burning regions of Africa and South America are also visible. Finally, panel c shows the CMIP6 inter-model standard deviation, on the same scale. For key, highly populated regions in India and China, the standard deviation is comparable in magnitude to the absorption itself, underscoring the low level of scientific understanding that still exists for this climate-relevant quantity. Again, CMIP6 results are consistent with AeroCom Phase III (ref. 25, their Fig. 2).

Relating absorbing optical depth to precipitation inhibition.

The next step is to quantify the emergent relation between aerosol absorption and precipitation inhibition, using a linear expansion:

$$\Delta P = \frac{dP}{dAbs} \times \frac{dAbs}{dAAOD} \Delta AAOD \quad (1)$$

here Abs denotes atmospheric absorption (in Wm^{-2}), and P is

precipitation (in mm year^{-1}). The two terms of Eq. 1 have been separately investigated in, or can be quantified from, recent multi-model intercomparison projects (MIPs) and publications. These results are synthesized in Fig. 2.

$\Delta Abs/\Delta AAOD$ was first investigated in Phase II of the AeroCom exercise²⁶. Here, aerosol models, primarily running with fixed meteorology, quantified the radiative impacts of all present-day anthropogenic aerosols relative to preindustrial conditions. Their multi-model median result, $\Delta Abs/\Delta AAOD = 479 \pm 165 \text{ Wm}^{-2}/(\text{unit AAOD})$, shows marked inter-model diversity, but still a clear correlation between the two quantities. CMIP6 has no directly comparable experiments. However, a comparable result can be extracted from the ScenarioMIP historical simulation, by quantifying the shortwave absorption (change in top-of-atmosphere shortwave flux minus the change in surface flux), and accounting for the simultaneous change in methane concentration. See Methods. The results are shown in Fig. 2a, overlain with AeroCom Phase II. Results from the two MIPs have correlation coefficients that are consistent within the estimated uncertainties.

The relation between precipitation inhibition due to rapid adjustments, and atmospheric absorption, was first quantified in Andrews et al.¹⁹, using idealized perturbations to single climate forcings (CO_2 , CH_4 , BC, SO_4 , insolation) in a single climate model. Similar experiments were later performed in a multi-model setting by PDRMIP^{14,17}. Their results are shown in Fig. 2b, with a ratio of $\Delta P/\Delta Abs = -9.7 \pm 0.1 \text{ mm year}^{-1}/\text{W m}^{-2}$. However, as the PDRMIP experiments were primarily global perturbations, a question remains about whether this global relation holds for all regions. No dataset yet exists that can fully answer this, but PDRMIP did include one regional experiment with absorbing aerosols, increasing BC over Asia, which yields results in line with the above relation²⁰. Also, this question was recently further

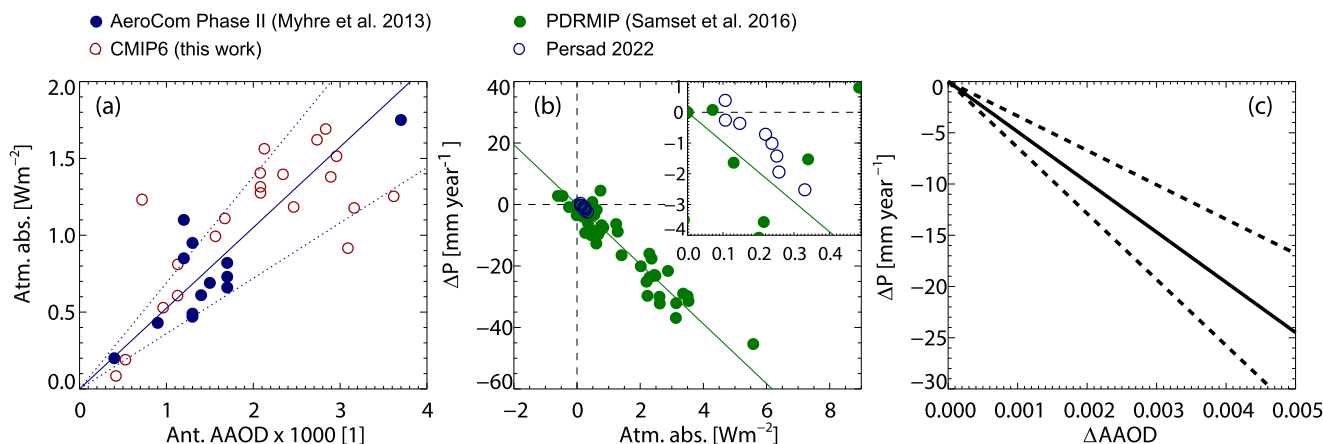


Fig. 2 Emergent relationship between AAOD and precipitation inhibition. **a** Relation between AAOD change and atmospheric absorption, derived from models participating in AeroCom Phase II and CMIP6. **b** Relation between atmospheric absorption and precipitation inhibition, from PDRMIP (global perturbations) and Persad 2022 (regional perturbations). **c** Derived relationship from combining (a) and (b) according to Eq. 1.

addressed in Persad²¹, who performed simulations using a single model, altering BC concentrations in a number of selected regions in all continents except Antarctica. Their results are overlain with PDRMIP in Fig. 2b. While the perturbations in the regional experiments are weaker in magnitude and will have a lower spread because they are performed in a single model, it is still worth noting that they follow a comparable correlation, within the multi-model uncertainty, as that quantified from PDRMIP.

The relations in Fig. 2a, b, and their uncertainties, can be combined using Eq. 1 into the joint relation between AAOD and precipitation inhibition shown in Fig. 2c. Numerically, the relation is $\Delta P/\Delta \text{AAOD} = -4646 \pm 1600 \text{ mm year}^{-1}/(\text{unit AAOD})$, where the uncertainty (relative standard deviation (RSD) of 34%) is dominated by the model diversity in the relation between AAOD and atmospheric absorption (RSD of 31%; Fig. 2a). The reason that this assumption can be made, is that while the aerosol treatment of the models included in the various studies (AeroCom, PDRMIP and others) differ markedly, they are all of sufficient complexity to include the atmospheric heating rates resulting from the presence of a SW absorbing agent. Hence, differences in the aerosol assumptions will initially contribute to the spread in AAOD, as discussed above, and any further differences in response will be captured by the uncertainties of the two relations.

Diagnosed precipitation inhibition. Having quantified the uncertainty in AAOD in CMIP6, globally and regionally, and found a relation between AAOD and precipitation inhibition that can be assumed to be valid for the historically major anthropogenic aerosol emission regions, we can estimate the influence of anthropogenic aerosol absorption on historical precipitation change. Figure 3a shows the diagnosed precipitation inhibition from rapid adjustments for 28 CMIP6 models (or ensemble members; see Supplementary Methods). The multi-model, global, annual mean precipitation inhibition in 2014 is -15 mm year^{-1} , with an inter-model spread (5–95%) of $-2 - -40 \text{ mm year}^{-1}$.

Assuming global validity of Eq. 1 (while noting that this assumption will require further work to fully substantiate) allows calculation of the regional distribution of precipitation inhibition. Figure 3b shows the regions of maximum influence, where the annual mean influence of absorption reaches $-200 \text{ mm year}^{-1}$, or up to 25% of the regional total (Fig. 3c). Similar to the result for AAOD, the inter-model spread is very high, with a standard deviation numerically similar to the inhibition itself (Fig. 3d).

Aerosol absorption influence on historical precipitation change. Finally, the absorption-induced precipitation inhibition and its uncertainty in CMIP6 can be put in the context of historical precipitation change. Figure 4 shows results from the Detection and Attribution Model Intercomparison Project (DAMIP)³⁸, for surface temperature (4a), and for precipitation (4b). As has been shown in a number of studies^{3,4,39}, the observed net change in global mean surface temperature attributable to GHG-induced warming and aerosol-induced cooling, closely tracks both observations and the CMIP6 mean simulated historical evolution.

For global annual mean precipitation, the corresponding net change is weak ($\sim 5 \text{ mm year}^{-1}$), and there is near balance between GHG and aerosol influences, reflecting the stronger hydrological sensitivity of the global climate to aerosol changes ($3.7\%/^{\circ}\text{C}$) relative to greenhouse gases ($1.7\%/^{\circ}\text{C}$); a difference that is mainly attributable to differences in absorption^{15,40}. See Methods. While the global means used here do not reflect underlying geographical shifts in precipitation, this near-balance does indicate a high sensitivity of the total precipitation change to both aerosols and greenhouse gases as they are presently treated in global climate models.

For comparison, the CMIP6 inter-model spread in precipitation inhibition due to uncertainty in aerosol absorption, calculated from the analysis above, is around 35 mm year^{-1} (5–95% range, Fig. 4b). Note that this uncertainty is markedly larger than the inter-model spread in historical precipitation change simulated by CMIP6 models ($\pm 5 \text{ mm year}^{-1}$), and around four times higher than the absolute change over the historical era simulated by both ScenarioMIP and DAMIP. This apparent contradiction indicates that there are compensating processes, and likely some degree of tuning, in precipitation responses in current models, and further indicates a potentially high sensitivity of precipitation to future changes in aerosol absorption.

Discussion

The above analysis documents how precipitation inhibition from aerosol-induced absorption can be a key factor in simulating both global and regional hydroclimate. Together with the weak constraints that can currently be placed on global AAOD, and its historical evolution, this implies that aerosol-induced absorption is a key—and possibly dominating—uncertainty factor in our understanding of historical precipitation change. This is particularly

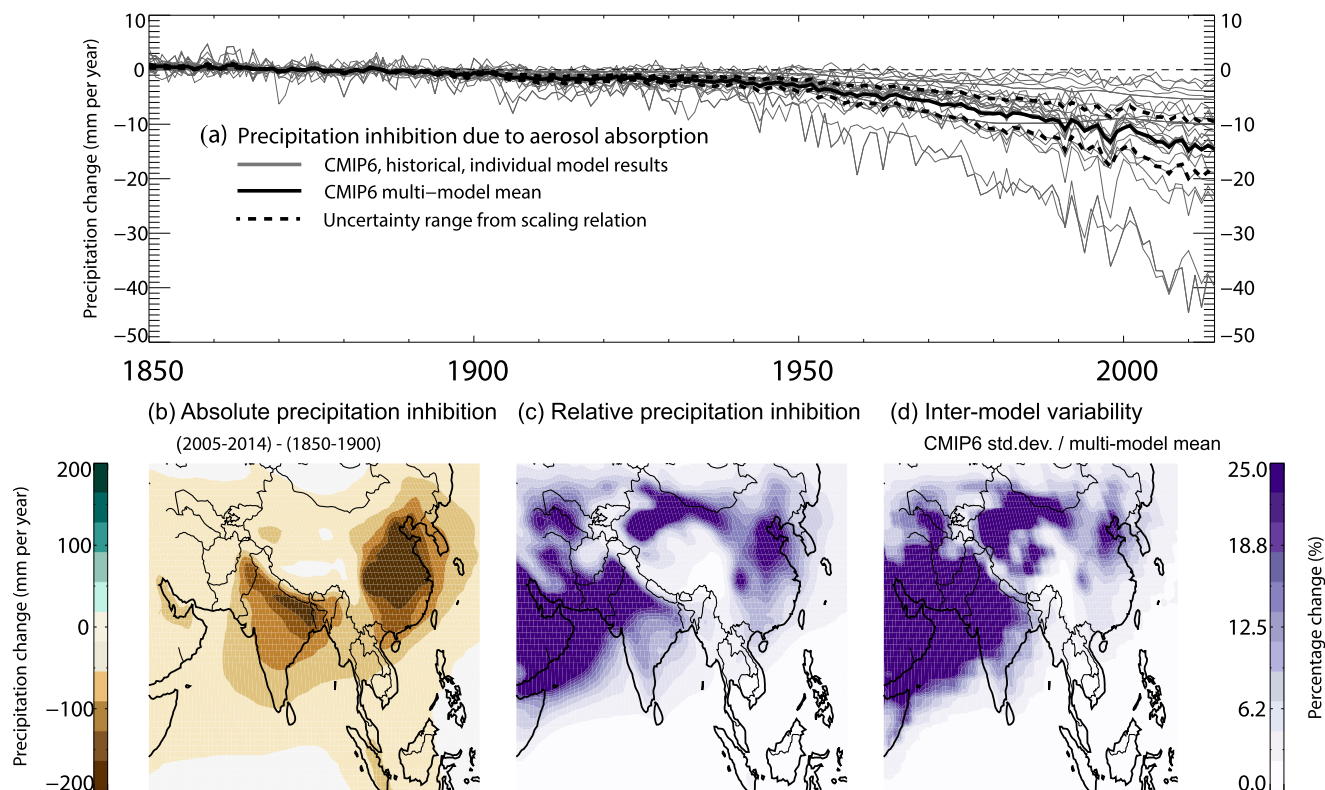


Fig. 3 Diagnosed precipitation inhibition due to aerosol-induced absorption. **a** Global, annual mean precipitation reduction in CMIP6 models. The uncertainty from the scaling relation (Eq. 1) is shown as dashed lines. **b** CMIP6 mean precipitation inhibition over South and East Asia. **c** As **b**, but relative to the simulated climatological mean precipitation. **d** Inter-model variability in precipitation inhibition, relative to the climatological mean.

important given the ongoing and expected future rapid changes in aerosol emissions in several regions, including the current hotspots in South and East Asia.

Among aerosol species, the key absorbing anthropogenic emission type is BC. While the IPCC recently assessed the global mean temperature impact of present-day BC emissions to be relatively weak (~ 0.1 °C), the results described here indicate that BC may have a much more important role in anthropogenic precipitation change. Should BC emissions be markedly reduced over the coming decades, as happens e.g. in Shared Socio-economic Pathways assuming stringent air quality (SSP1)^{41,42}, this may unmask currently inhibited mean and extreme precipitation in populated regions, including India, China and North America, as has been indicated in recent model-based literature^{43–47}. Future changes in BrC and dust emissions are also of importance, notably as they affect different regions to BC, and also as potential feedback from GHG-induced surface temperature change and industrial activities.

Reasons for the diversity in simulated aerosol absorption in CMIP6 models include uncertainties in emission inventories, differences in the complexity of the modelled aerosol-climate interactions, and various poorly constrained quantities and processes such as optical properties, transport, growth, ageing and wet removal of particles, aerosol-cloud interactions, and more. It is, however, worth noting that the precipitation inhibition discussed above is independent of the details of aerosol emission and transport, as it occurs primarily through the influence of short-wave heating aloft on precipitation formation. This process is well represented in all modern Earth System Models, so it is reasonable to expect that the uncertainty in aerosol absorption translates directly into precipitation uncertainty. Regional rapid responses

to absorbing aerosols are likely to be highly heterogeneous and seasonally dependent, notably near complex dynamical phenomena such as monsoons. It is unlikely, however, that this heterogeneity will act to reduce the inter-model diversity in aerosol-precipitation modelling.

Robust projections of global and regional precipitation change, in response to the wide range of possible future greenhouse gas and aerosol emissions and the associated global warming, remains both a challenge for the scientific community and an important topic at the science-policy interface. The results shown here indicate a need for heightened focus on constraining the emissions and atmospheric distributions of atmospheric aerosols, notably black carbon, organic carbon and dust. While this has long been recognized as a tough challenge, rapid progress is possible with joint effort from the observational and modelling communities²⁴. Notably, there is a need for systematic aircraft measurements, improved capabilities for both ground and satellite-based retrieval systems, and for inclusion and uptake of any improved constraints in global climate models. The latter requires further development and validation of aerosol processes in Earth System Models, and also reduced biases in the modelled regional and seasonal cloud and precipitation climatologies. In addition, further analyses and sensitivity experiments are required in order to understand the influence of aerosol-induced absorption on current CMIP6 based projections of mean and extreme precipitation under future emissions and global warming—and their strong impacts on nature and society.

Methods

Model simulations used. For a full list of models and experiments, see the Supplementary Methods.

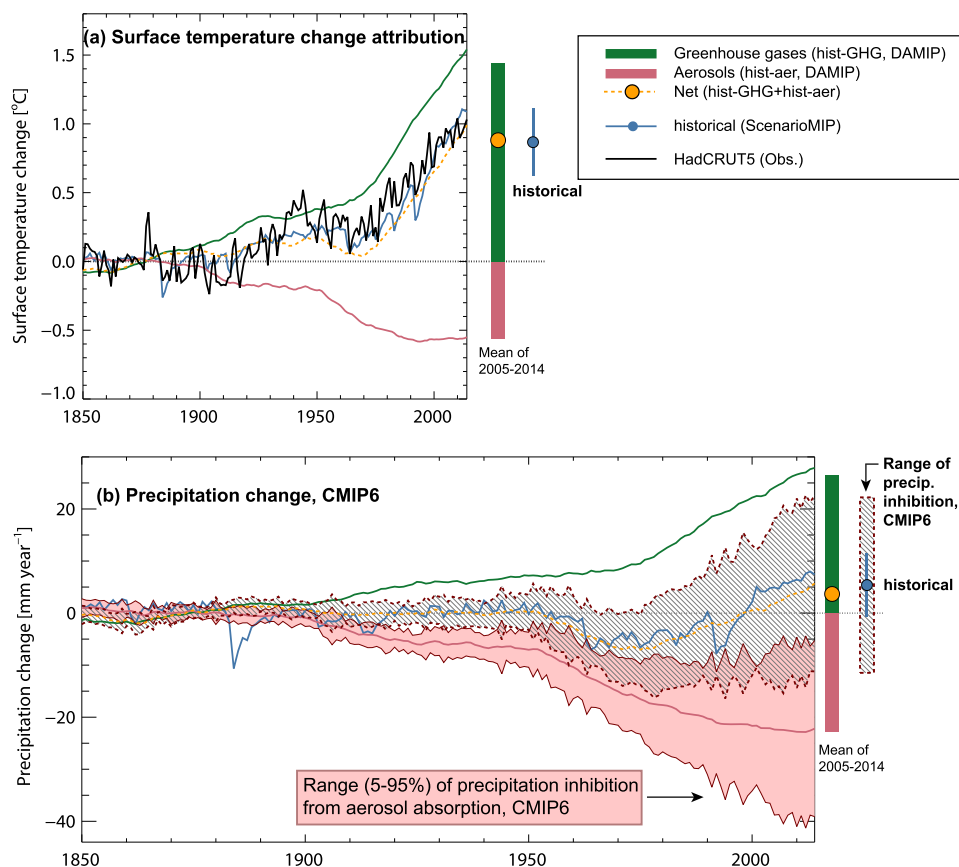


Fig. 4 Aerosol-induced absorption makes up a dominating source of uncertainty in simulated historical precipitation change. **a** The contributions of well-mixed greenhouse gases (green) and aerosols (red) to historical surface temperature change, from DAMIP simulations, compared to CMIP6 historical simulations (blue) and HadCRUT5 surface temperature observations (black). The yellow dashed line shows the net contribution from greenhouse gases and aerosols. Bars and dots show the mean over 2005–2014. **b** As **a**, but for precipitation. The red band shows the 5–95% range of precipitation inhibition diagnosed from the CMIP6 multi-model spread in anthropogenic absorbing aerosol optical depth. The grey shaded band shows the same range, shifted to lie around the precipitation change from CMIP6 historical all-forcing simulations.

ScenarioMIP⁴⁸: Simulated climate evolution over the historical era (1850–2014) is from ScenarioMIP, part of the CMIP6 exercise. Participating global climate models used the same emissions of greenhouse gases and aerosols, other forcings such as land use, as well as natural forcings such as insolation and volcanoes. The present analysis uses monthly mean output of near-surface (2 m) temperature, precipitation, shortwave radiative fluxes at top-of-atmosphere and surface level, and column-integrated absorbing aerosol optical depth.

DAMIP³⁸: Detection and Attribution MIP (DAMIP) performed model experiments where only anthropogenic well-mixed greenhouse gas (hist-GHG) or aerosol (hist-aer) emissions were allowed to vary over the period 1850–2020, leaving all other emissions and natural forcings at 1850 levels. For the period 2015–2020, the emissions followed the SSP2-4.5 pathway. The present analysis uses monthly mean output of near-surface (2 m) temperature and precipitation.

Additional values used for Fig. 3 were extracted directly from the cited literature.

Diagnosing shortwave absorption in CMIP6. The following procedure was used to estimate the shortwave (SW) atmospheric absorption ascribable to anthropogenic aerosols in CMIP6 historical simulations (Fig. 2a). For each model, the change in net SW flux (F_{SW}) was calculated over the historical era (1995–2014 relative to 1850–1900) at top-of-atmosphere (TOA) and surface (SURF). The total change in shortwave absorption (Abs_{SW}) is then

$$Abs_{SW}^{Total} = \Delta F_{SW}^{TOA} - \Delta F_{SW}^{SURF} \quad (2)$$

here, all radiation fields are all-sky (i.e. combining cloudy and cloud-free conditions). However, aerosols are not the only atmospheric component with shortwave absorption to change over the historical era. Notably, changes in methane concentration will influence the results of Eq. 2. Recently, Collins et al.⁴⁹ estimated a methane-induced SW absorption increase of 0.68 W m^{-2} over a period comparable to the one used here for CMIP6. We subtracted this to arrive at an estimate for the

aerosol-induced absorption:

$$Abs_{SW}^{Aero} = Abs_{SW}^{Total} - Abs_{SW}^{CH4} \quad (3)$$

This is clearly a simplified estimate, and consequently, it has not been included in the final quantification following Eq. 1. However, if the CMIP6 are included in the regression in addition to AeroCom Phase II, the correlation coefficient remains the same within the stated errors.

For an overview of historical anthropogenic SW aerosol absorption quantified from CMIP6 models, see Supplementary Table 1.

Hydrological sensitivity. The hydrological sensitivity in DAMIP, or precipitation change per degree Celsius of global mean surface temperature change, is calculated based on the multi-model mean total change in 2001–2020 relative to 1850–1900. This quantity is what is elsewhere termed the “apparent hydrological sensitivity” and is different to the “slow hydrological sensitivity” which is the response to surface temperature change in the absence of rapid adjustments⁵⁰.

Data availability

All simulations used for the present manuscript are publicly available through open data access portals. CMIP6 results are available through the Earth System Grid Federation (ESGF). PDRMIP simulations are available from the Norwegian storage service NIRD (<https://cicero.oslo.no/en/PDRMIP/PDRMIP-data-access>). AeroCom simulations are available through aerocom.met.no.

Code availability

All analyses were performed using the software packages IDL (version 8.3) and cdo (version 1.9.8). No custom code was used. Plotting scripts for all figures are available upon request to the corresponding author.

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Author contributions

B.H.S. conceived the study, performed the analysis, and wrote the paper.

Competing interests

The author declares no competing interests.

Additional information

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