Matters arising

Uncertain climate effects of anthropogenic reactive nitrogen

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The net climate effect of anthropogenic reactive nitrogen (Nr) is the sum of several terms that vary in sign and are associated with substantial uncertainties. Gong et al.[1] reported a net negative direct radiative forcing (RF) of Nr in the year 2019 relative to the year 1850. We argue that their estimates and associated uncertainties of individual Nr climate effects, most notably aerosol, ozone and methane RF, do not reflect the current state of the art. We show that ref. 1 presents overly narrow uncertainty ranges and that their estimates of individual Nr climate effects are outliers compared with our multi-model ensemble, carrying important implications for future projections.

Emissions of Nr lead to the formation of ammonium nitrate aerosols ($NH_4^+NO_3^-$; hereafter denoted nitrate), but their atmospheric abundance is highly uncertain. The Intergovernmental Panel on Climate Change Sixth Assessment Report (AR6) states that "there is high confidence that the NH_4^+ and NO_3^- burdens have increased from the pre-industrial period to the present day, although the magnitude of the increase is uncertain especially for NO_3^-"[2]. The present-day global nitrate burden differs by up to a factor 13 across models in two separate studies[3,4]. This spread holds for fine-mode nitrate aerosols, which drive RF[4]. The complexity of aerosol processes make it challenging to represent nitrate in models. Model diversity in this task has remained almost unchanged between the two latest generations of models[2].

Sulfate (SO_4^{2-}) aerosols, including ammonium sulfate ($(NH_4^+)_2SO_4^{2-}$), are also influenced by Nr emissions, mainly through nitrogen oxide (NO_x) emissions, which alter the oxidation pathways of SO_2 to sulfate by changing the abundances of hydroxyl radicals (OH), ozone (O_3) and hydrogen peroxide (H_2O_2)[5]. Although the latest generation of aerosol-chemistry models are improved, the diversity in modelled sulfate burdens remains considerable[3] and reproducing observations is still challenging[2,3,6]. Estimates of aerosol RF due to Nr must recognize the large uncertainty reflected in the multi-model intercomparisons.

We have carried out simulations with a set-up similar to ref. 1, using five independent latest-generation models (see method description in Supplementary Information), namely, one chemistry-transport model (OsloCTM3 (ref. 7)) and four chemistry–climate models (CESM2 (ref. 8), GISS ModelE[9], GFDL-AM4.1 (ref. 10) and LMDZ-INCA[11]). The change over the industrial era of nitrate and sulfate aerosol abundances owing to Nr emissions varies greatly across the models, both horizontally (Extended Data Fig. 1a,b) and vertically (Extended Data Fig. 2a,b). Consequently, our estimated direct aerosol RF, which is the RF term with the largest magnitude in ref. 1, differs widely by model, even in sign (Fig. 1a and Extended Data Fig. 3a). Our multi-model results show that GEOS-Chem aerosol RF is at the low end (that is, strong cooling). Moreover, none of the other models fall within the GEOS-Chem uncertainty range, which appears to include only emissions uncertainty and not model diversity. The nitrate RF is negative in all models, and the sulfate RF can either add to or counteract the nitrate cooling, depending on the model. The different sulfate RF responses in the models are, at least partly, caused by different responses in the SO_2 to sulfate oxidants OH and H_2O_2 (not shown).

The RF of ozone due to anthropogenic NO_x emissions varies widely across models, ranging from 0.07 W m^{-2} to 0.27 W m^{-2} (for 1850 to 2014) in the study used in AR6 (refs. 2,12). Here we find a similarly large range in tropospheric ozone caused by anthropogenic Nr emissions (Extended Data Figs. 1c and 2c), and a resulting ozone RF range of 0.17–0.35 W m^{-2} across the five models (Fig. 1b and Extended Data Fig. 3b). These results are a factor 3–7 higher than the GEOS-Chem ozone RF and far outside their reported uncertainty (0.03–0.07 W m^{-2}). Although the GEOS-Chem range includes a ±30% uncertainty to account for nonlinear atmospheric chemical reactions, it is applied to their very small ozone RF. The GEOS-Chem results fail to account for the well-known model diversity.

As with ozone, the methane RF due to NO_x emissions varies considerably across models, partly as a result of differing CH_4 lifetimes and feedbacks[12]. The common approach of quantifying CH_4 RF due to NO_x emissions is to base it on atmospheric chemistry model calculations of CH_4 lifetime variations due to OH (see Supplementary Information for details). However, ref. 1 did not use the GEOS-Chem model for this purpose but rather a CH_4 box model, which does not properly account for the complex and nonlinear atmospheric chemistry, including effects arising from the inhomogeneous atmospheric distribution of chemical compounds. The well-known effects of CH_4 being a precursor of tropospheric ozone[13] and enhancing stratospheric water vapour[2] have also been ignored. Using our five models and a method in line with AR6 (ref. 2), we get a considerably stronger negative CH_4 RF term than that in ref. 1 (Fig. 1c), most of them outside their uncertainty range.

The N_2O and CO_2 RF terms due to anthropogenic Nr have been calculated using the RRTMG radiative transfer scheme in GEOS-Chem in ref. 1. As these two compounds are well mixed in the atmosphere, and the RRTMG scheme is tailored for fast calculations in global models, we have instead chosen to base the RF calculations on the expressions in ref. 14, as in AR6 (ref. 15) (see Supplementary Information for details). Assuming the same N_2O and CO_2 concentration changes as

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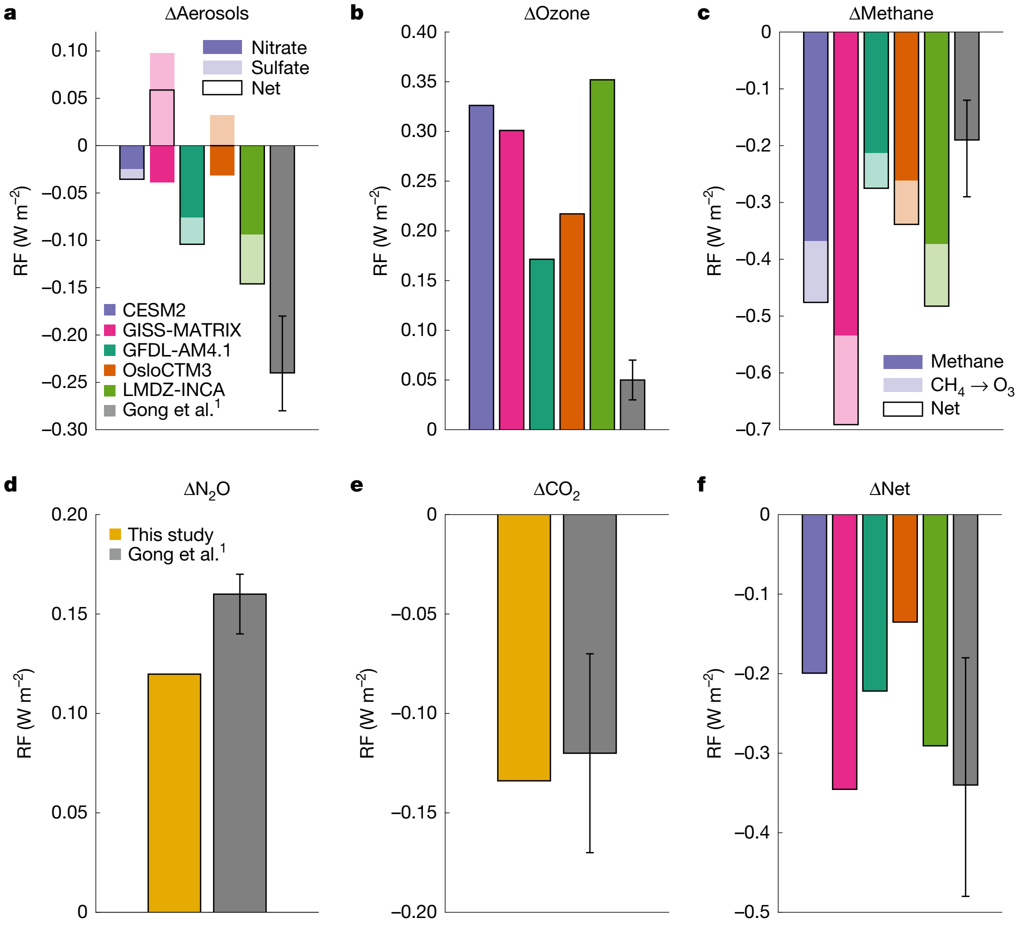

Fig. 1 | Global pre-industrial to present-day (1850 to 2019) RF due to anthropogenic Nr. Direct aerosol RF (**a**), ozone RF (**b**), methane RF (**c**), N_2O RF (**d**), CO_2 RF (**e**) and the net RF calculated as the sum of the individual terms (**f**). The grey bars and whiskers are from ref. 1 (see ref. 1 for definition of error bars), and the other coloured bars are from this study. N_2O RF and CO_2 RF in this study are calculated based on ref. 14 and are independent of the model data. RF due to ammonium is included in the nitrate and sulfate terms in **a**.

in ref. 1, our calculations give a smaller N_2O RF term that is outside their uncertainty range (Fig. 1d), but a more similar CO_2 RF term (Fig. 1e). If tropospheric adjustments would have been added to obtain effective RF (ERF), which is more state of the art, this would change the N_2O, CO_2 and CH_4 forcing by +7 ± 13%, +5 ± 5% and −14 ± 15%, respectively, according to AR6 (ref. 15).

Interestingly, the sum of the RF terms gives a net RF that is within the uncertainty range of ref. 1 for most models, but with nearly all model estimates being less negative than their net RF (Fig. 1f). Although most of the individual RF terms are very different, our upwards and downwards revisions largely compensate. Although the absolute RF terms can partly cancel, the absolute uncertainty keeps growing as we add the terms. The fact that our individual RF terms differ strongly from those of ref. 1 could have large consequences for the future predictions shown in their Fig. 5. We therefore argue that those results cannot be used without applying appropriate uncertainties. We also note that the choice of year for present-day Nr emissions (in this case 2019) could influence the RF results as emissions change rapidly.

Our results emphasize what is clear from previous literature—that a range of models are needed to quantify the climate effects of anthropogenic Nr, including uncertainty. Future research is clearly needed on this important topic, both to better define and narrow the uncertainties on the climate effects given here and (as discussed in ref. 1) to quantify climate effects for processes for which estimates do not yet exist (for example, aerosol–cloud interactions due to Nr emissions). Crucially, a natural way forward to reduce uncertainties involves continuous improvement of key processes in the models based on thorough evaluations against a range of observations.

Data availability

The GEOS-Chem output from Gong et al.[1] are available on Zenodo at https://doi.org/10.5281/zenodo.11202819 (ref. 16). The simulation output from the five models used in this work are available on archive.sigma2.no at https://doi.org/10.11582/2024.00179.

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Author contributions Ø.H., C.J., D.A.H. and F.P. carried out model simulations. M.B. provided NH_3 emission data. G.M. had the original idea. Ø.H made the figures and wrote the paper with input from all authors.

Competing interests The research project that has funded most of this work has received funding (approximately 25% of the total budget) from industry partners who have an interest in green or blue ammonia.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41586-025-09337-9.
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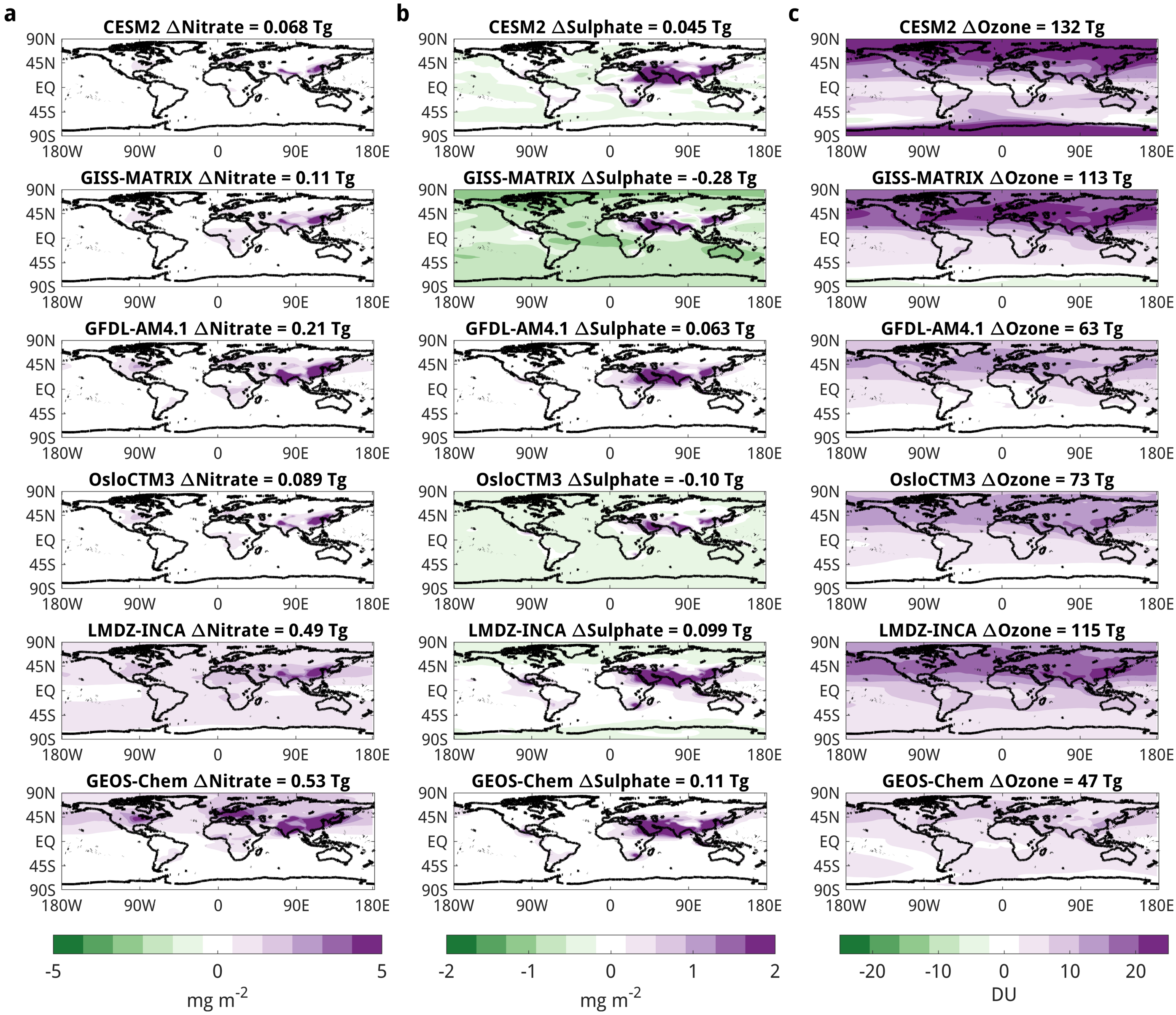
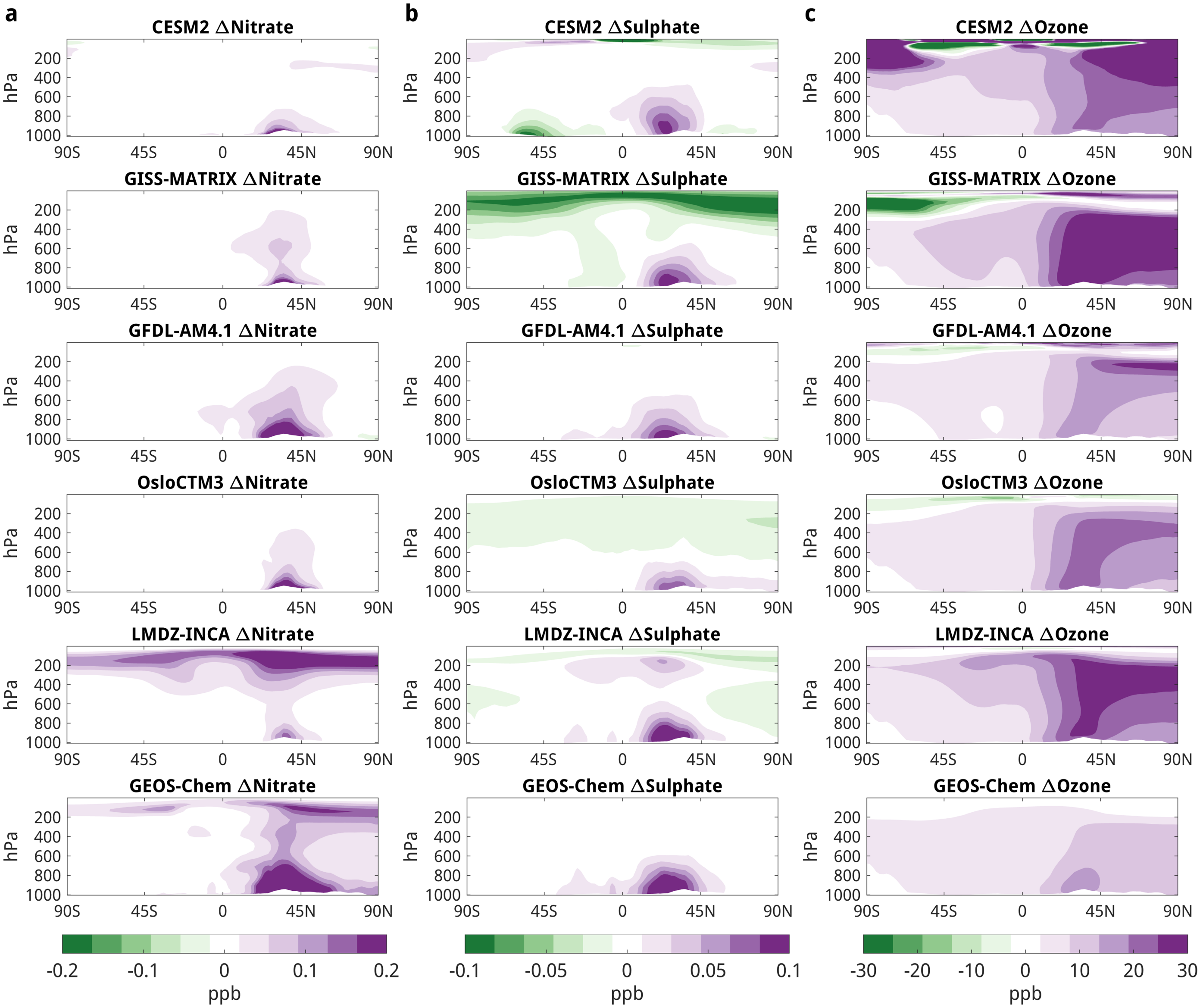
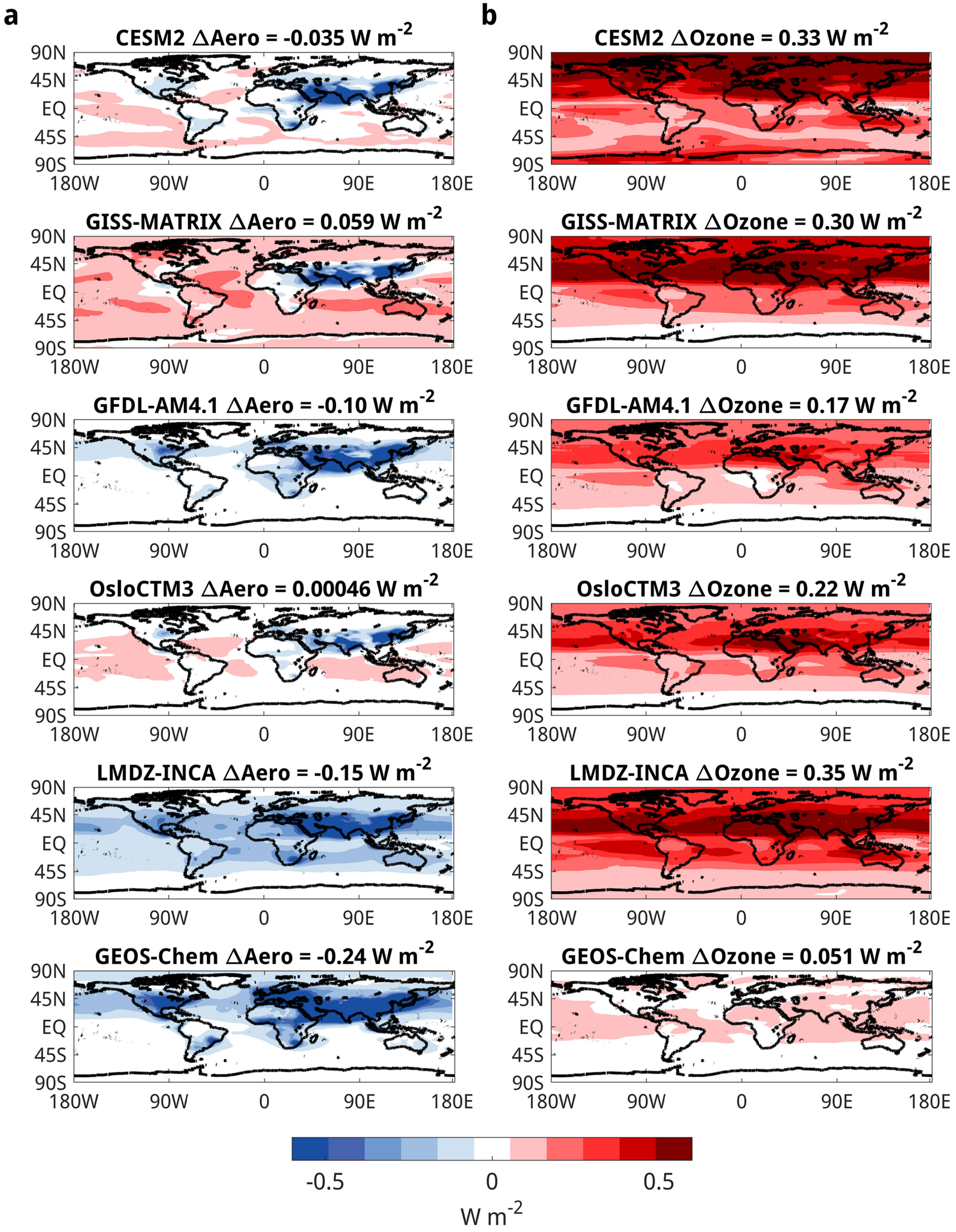


Extended Data Fig. 1 | Pre-industrial to present-day (1850 to 2019) change in burden due to anthropogenic Nr. Nitrate fine-mode aerosols (**a**), sulphate aerosols (**b**), and ozone (**c**) for each of the five models in this study and for GEOS-Chem results from ref. 1. It is unclear whether the GEOS-Chem results show fine-mode or total nitrate.



Extended Data Fig. 2 | Pre-industrial to present-day (1850 to 2019) zonal mean change due to anthropogenic Nr. Nitrate fine-mode aerosols (**a**), sulphate aerosols (**b**), and ozone (**c**) for each of the five models in this study and for GEOS-Chem results from ref. 1. It is unclear whether the GEOS-Chem results show fine-mode or total nitrate.



Extended Data Fig. 3 | Pre-industrial to present-day (1850 to 2019) radiative forcing (RF) due to anthropogenic Nr. Direct aerosol RF (**a**) and ozone RF (**b**) for each of the five models in this study and for GEOS-Chem results from ref. 1. The aerosol RF includes contributions from nitrate, sulphate and ammonium.

Matters arising

Reply to: Uncertain climate effects of anthropogenic reactive nitrogen

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REPLYING TO: **Ø. Hodnebrog et al.** ***Nature*** **https://doi.org/10.1038/s41586-025-09337-9 (2025).**

The main purpose of Gong et al.[1] is to show that anthropogenic reactive nitrogen (Nr) has a net cooling influence on climate, which has important implications for future emissions mitigation strategies. We welcome that in the accompanying Comment[2], Hodnebrog et al. confirm the net cooling influence of anthropogenic Nr. However, Hodnebrog et al. argue that Gong et al. underestimate the uncertainties in individual effects, such as in aerosol, ozone (O_3) and methane (CH_4) radiative forcing (RF) from Nr emissions. Here we show that the varied differences of each component will not influence the estimates of the net climate effect under future projections, and we find that biases and uncertainties in Hodnebrog overemphasize differences between our and their estimates.

Although we disagree that the central estimates in Hodnebrog et al. are comparable to those of Gong et al.[1] (see below), we first apply their central estimates of each component to estimate the sensitivities of RF to carbon dioxide (CO_2), nitrous oxide (N_2O), CH_4 concentrations, or ammonia (NH_3) and nitrogen oxide (NO_x) emissions, respectively, and reproduce the assessment of future impacts (Fig. 5 in Gong et al.[1]). Figure 1 shows that this update provides similar patterns (in terms of magnitude and trend across the three scenarios) in RF change as in Gong et al., where the differences between the updated and original trends are fully covered by the original uncertainty ranges in Gong et al. We acknowledge that these future estimates are based on simple calculations and, as already written in Gong et al., we encourage further work to integrate more dynamic feedbacks into future projections of the net climate effect of anthropogenic Nr. However, our new analysis indicates that the associated uncertainties will not “carry important implications for future projections” as Hodnebrog et al. argued.

An important uncertainty in Hodnebrog et al.[2] is that the RFs of aerosols and O_3 are not calculated by the online radiative transfer modules in each chemistry–climate model, but by prescribed monthly three-dimensional maps of aerosol and O_3 kernel ‘radiative efficiency’ (united by Watts per gram change in aerosol loading (W/g) or Watts per Dobson unit change in O_3 (W/DU)) generated from OsloCTM3. Such a simplified method fails to account for the inter-model differences in the particle physical properties (for example, sizes, humidity and mixture), cloudiness distributions and surface albedo, all of which have very high temporal heterogeneity and thus introduce uncertainty into the assessment of the short-lived greenhouse components aerosol and O_3.

Hodnebrog et al.[2] argue that aerosol cooling effect induced by anthropogenic Nr is substantially weaker than that in Gong et al.[1]. Although we have explicitly acknowledged in the main text that “the negative radiative forcing of nitrate aerosol may be overestimated, as the GEOS-Chem model tends to overestimate nitrate aerosol concentrations”[3–5], we find that the enhancements of fine-mode nitrate loadings in CESM2 (0.068 Tg yr^{-1}) and OsloCTM3 (0.089 Tg yr^{-1}) are also at the low end relative to the ranges given by AeroCom III multi-models[6]. The positive sulfate aerosol RFs in GISS-MATRIX and OsloCTM3 are also questionable and require more validation. Furthermore, Hodnebrog et al. assume all sulfate exists in the form of ammonium sulfate ($(NH_4)_2SO_4$) when calculating RF, which may enhance global pre-industrial aerosol mass in the No_allNr experiment and further weaken the present-day aerosol RF, as the dominant sulfate phase under an ammonia-poor environment (for example, in the form of H_2SO_4) has lower molecular weight than $(NH_4)_2SO_4$.

We are also concerned about the result of the simplified method applied by Hodnebrog et al.[2] to derive changes in CH_4 concentration from NO_x emissions. The implied lifetime changes of CH_4 for a change in NO_x loading, derived from inverting the calculation of CH_4 concentration in Hodnebrog et al. (see their methods) suggests that NO_x reduces CH_4 lifetime in the GISS-Matrix model by approximately 50%. This is clearly outside the range of a 22–34% reduction in CH_4 lifetime as a result of the NO_x emission changes between 1850 and 2000 using a multi-model ensemble[7]. The other models, including our own estimates, are either at the upper (CESM, LMDZ) or lower (OsloCTM, GFDL, as well as our own estimate) end of this range. This finding is also consistent with the NO_x-induced forcing due to CH_4-lifetime changes in the multi-model ensemble in ref. 8 (-0.2 W m^{-2} to -0.37 W m^{-2}), which identifies the GISS-MATRIX model used in Hodnebrog et al. as an extreme outlier (-0.53 W m^{-2}) for GISS-MATRIX)), whereas the CESM and LMDZ are at the high end. The additional effects considered by Hodnebrog et al. but not in Gong et al.[1] – that is, CH_4 impacts on tropospheric O_3

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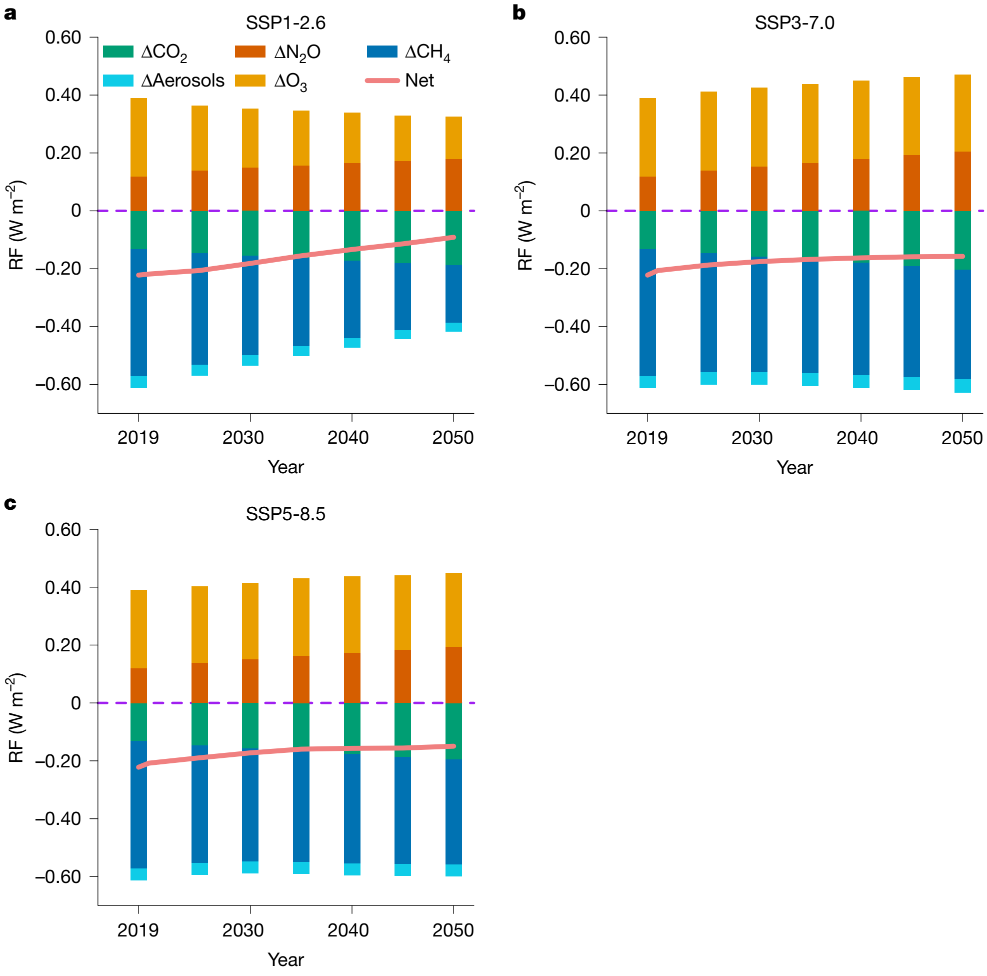

Fig. 1 | Prediction of the climate effects of anthropogenic Nr to 2050. The present-day RFs of each component are following 'the central estimates' in Hodnebrog et al.[2], which are −0.13 W m^{-2} of CO$_2$, +0.12 W m^{-2} of N$_2$O, −0.44 W m^{-2} of CH$_4$, −0.04 W m^{-2} of aerosols and +0.27 W m^{-2} of O$_3$. The predicted climate effects of anthropogenic Nr are following the scenarios of SSP 1-2.6 (**a**), SSP 3-7.0 (**b**) and SSP 5-8.5 (**c**). The cascading effects of CH$_4$ changes on tropospheric O$_3$ and stratospheric water vapour are included here following Hodnebrog et al.[2] but excluded in Gong et al.[1]. The rest of the method is identical to that in Fig. 5 in Gong et al.[1]. SSP, Shared Socioeconomic Pathway.

and stratospheric water – slightly affect our mean estimate, but remain within the uncertainty range provided in the original paper.

The RF of O$_3$ induced by anthropogenic Nr in Gong et al.[1] (+0.03 W m^{-2} to +0.07 W m^{-2}) is at the lower end boundary of the Intergovernmental Panel on Climate Change Sixth Assessment Report model ensemble[8,9] (+0.07 W m^{-2} to +0.27 W m^{-2}), which we have already noted in Supplementary Table 3 in ref. 1, relative to ref. 8 with a range of 0.2 ± 0.07 W m^{-2}. The comparison brought up by Hodnebrog et al.[2] therefore provides no new information regarding the wide across-model variations in the O$_3$ RF induced by anthropogenic NO$_x$ emissions. We note that the estimates of CESM2, GISS-MATRIX and LMDZ-INCA (around +0.3 W m^{-2} to +0.35 W m^{-2}) exceed the upper boundary of ref. 8, which contributes to exaggerating the differences between our results and ref. 8.

We agree that line-by-line radiative transfer calculations provide the most accurate estimates. However, GEOS-Chem RRTMG is internally consistent in Gong et al.[1] and includes broadband treatment between the different forcing factors. We note that the differences in N$_2$O and CO$_2$ will not significantly change the net climate effects as well as the future projections in our study.

Last but not least, we argue that the accuracy of model predictions should ideally not be determined by the uncertainty ranges of multi-model means, but by their evaluation against observations. Hodnebrog et al. do not cite any evidence that these five models have better performance compared against observations than GEOS-Chem. In particular, four of the five models are climate–chemistry models, and their simulations are affected by uncertainties in meteorology simulations, simplified chemical mechanisms and intricate feedback mechanisms[10–12]. In contrast, the GEOS-Chem model has been widely evaluated across different continents against surface observations, aircraft campaigns and satellite retrievals (for example, refs. 3,13–16).

We acknowledge that the RF values of specific Nr components are subject to uncertainty resulting from using more ensemble members with higher degrees of feedback processes, but the dominant processes associated with the climate effects of anthropogenic Nr have been properly addressed in Gong et al.[1].

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Author contributions C.G. and S.Z. drafted the reply. All authors contributed to and approved the final text.

Competing interests The authors declare no competing interests.

Additional information

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