# Minimal climate impacts from short-lived climate forcers following emission reductions related to the COVID-19 pandemic

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## Key Points:

- Emission reductions are likely to have led to a global reduction in short-lived climate forcers and tropospheric oxidising capacity.
- Reductions in $O_3$ and aerosol from both lower emissions and decreased sulphate oxidation resulted in a net negative radiative forcing.
- The radiative impacts are small and short-lived. Longer term climate impacts must come through future sustained emission reductions.

## Abstract

We present an assessment of the impacts on atmospheric composition and radiative forcing of short-lived pollutants following worldwide decrease in anthropogenic activity and emissions comparable to what has occurred in response to the COVID-19 pandemic, using the global composition-climate model UKCA. Changes in emissions reduce tropospheric hydroxyl radical and ozone burdens, increasing methane lifetime. Reduced $SO_2$ emissions and oxidising capacity lead to a decrease in the sulphate aerosol burden and increase in aerosol particle size, with accompanying reductions to cloud droplet number concentration. However, large reductions in black carbon emissions increase the albedo of aerosols. Overall, the changes in ozone and aerosol direct effects (neglecting aerosol-cloud interactions) result in an instantaneous radiative forcing of -31 to -74 $mWm^{-2}$. Upon cessation of emission reductions, the short-lived climate forcers rapidly return to pre-COVID levels, meaning these changes are unlikely to have lasting impacts on climate assuming emissions return to pre-intervention levels.

## Plain Language Summary

As a result of the global COVID-19 pandemic, unprecedented lockdown measures have been imposed worldwide to reduce the spread of the disease, causing huge reductions in economic activity and corresponding reductions in transport, industrial and aviation emissions. As well as lowering emissions of long lived greenhouse gases, such as carbon dioxide, this has resulted in a dramatic reduction in the emissions of components which affect climate in the short term. In this study we have used state-of-the-art computer simulations to quantify how changes in these components are likely to impact the chemical make-up of the atmosphere and the likely short-term impacts on climate. Despite large decreases in nitrogen dioxide and atmospheric particles, we find these changes result in a very small impact on the energy balance of the atmosphere but one that would act to cool the planet, without considering the knock-on impacts on clouds. However, these effects are all likely to be short-lived if emissions return to pre-lockdown levels.


## 1 Introduction

The outbreak of the COVID-19 coronavirus disease in China in December 2019 and its global spread in early 2020 has led to the most deadly and disruptive pandemic in recent memory. As of 8 June, there have been 6.8 million confirmed cases and 395,000 deaths globally (WHO). In response, governments around the world have implemented varying lockdown measures. The resulting decreases in transport and economic activity have led to the unprecedented reduction of anthropogenic emissions of carbon dioxide ($CO_2$) (Le Quéré, 2020) and short-lived climate forcers (SLCF) (Zhang et al., 2020). The SLCFs include sulphur dioxide ($SO_2$), nitrogen oxides (NO and $NO_2$, which together form $NO_x$), carbon monoxide (CO), and organic carbon and black carbon (OC and BC respectively). Such species perturb the oxidant balance of the atmosphere (O'Connor et al., 2020), the ozone budget (Young et al., 2018) and aerosol burden (Karset et al., 2018), and thus the radiative balance of the atmosphere and climate (Myhre et al., 2013). This paper aims to assess how the perturbations to atmospheric composition arising from changes to emissions of SLCFs due the COVID-19 pandemic affect parameters important for climate.

There remains uncertainty in the temporal, spatial, and composition changes to emissions arising from the restrictions imposed. Le Quéré et al (2020) calculated reductions in daily $CO_2$ emissions of between 11 and 25% by April 2020 relative to April 2019. Despite this uncertainty there exists common themes to emissions changes on which this study focuses.

## 2 Methods

### 2.1 Model description

Five experiments were performed using the United Kingdom Chemistry and Aerosols Model (UKCA) run at a horizontal resolution of 1.25°×1.9° with 85 vertical levels up to 85 km (Walters et al., 2019) with the fully interactive stratospheric and tropospheric chemistry (Archibald et al., 2020), and GLOMAP-mode aerosol scheme which simulates sulphate, sea-salt, black carbon, organic matter, and dust but not currently nitrate aerosol (Mulcahy et al., 2020). Emissions were from the CMIP6 CEDS inventories (Hosely et al. 2018). Emissions of methane ($CH_4$) and carbon dioxide ($CO_2$) were not simulated, rather a prescribed value is applied for $CO_2$ and a lower

boundary condition (fixed surface concentration) used for methane. The simulations were run using nudging (Telford et al., 2008) to atmospheric reanalyses from ECMWF (Dee et al., 2011) to constrain the simulations to consistent meteorology enabling a small ensemble of three different years: 2012, 2013, and 2014. The years chosen were the most recent CMIP6 emissions available at the time, and were averaged to filter out the influence of interannual meteorological variation. Nudging prevented temperatures and horizontal winds from responding to the forcings produced by the emissions changes, thus preventing changes in aerosols from affecting clouds and the subsequent impacts on the radiation budget (Zhang et al., 2014).

### 2.2 Scenario descriptions

Five scenarios were considered, each with different perturbations to emissions (Table 1). Emitted species are specified in Table S1. The perturbation scenarios A1-A4 were developed by reducing global anthropogenic emissions in the aviation, surface transport, and industrial sectors by a set factor. In all perturbation scenarios, emissions were held at the control run values until mid-February before declining linearly until mid-March to their minimum value. They remained at their minimum value until mid-May before increasing linearly to the control levels by mid-June (Fig. S1). We made the approximation of all countries in the world making parallel emission reductions. As these scenarios were developed early in the COVID-19 pandemic when information on the impact of the lockdown on all sectors was unknown, we drew on available information from a number of sources to compile emission reduction scenarios that span likely representative changes in emissions. See Text S1 for further details.

**Table 1 - Scenarios and emission changes**

| **Scenario** | **Transport** | **Aircraft** | **Industry** | **% Global change in surface emissions during "lockdown period" (March-May)** | | | |
|---|---|---|---|---|---|---|---|
| | | | | NO | $SO_2$ | BC | OC |
| Control | No reduction | No reduction | No reduction | No reduction | No reduction | No reduction | No reduction |
| A1 | -50% | -50% | -25% | -15.8 | -8.84 | -11.88 | -3.66 |
| A2 | -50% | -25% | -25% | -15.8 | -8.84 | -11.88 | -3.66 |
| A3 | -75% | -50% | -25% | -22.2 | -9.48 | -16.48 | -4.52 |
| A4 | -50% | -50% | No reduction | -12.8 | -1.27 | -9.19 | -1.73 |

The scenarios were designed to allow a comparison between the effects of decreasing different sectors on emissions. By comparing A1 with A3 and A4, we saw that global $NO_x$ emissions were

approximately twice as sensitive to surface transport emissions than industrial emissions, while the majority of $SO_2$ emission decreases were due to industrial emissions. Comparing the primary aerosol emissions, BC was more sensitive to the surface transport sector, whilst OC was more sensitive to industry. While reducing aviation emissions resulted in a negligible decrease in the total mass of emissions, these emissions were injected directly into the free troposphere which is more sensitive to NOx emissions (Stevenson et al., 2004). These reductions are in line with those in the recently published study by Le Quéré et al (2020) which estimates decreases in aviation of 50-90%, in surface transport of 40-75% and various industrial emissions such as Chinese coal (40%) and US steel (35%).

## 3 Results

In all cases we combined the results from the simulations with different years of meteorology to generate an ensemble mean, and compared the results of the different scenarios (A1-A4) to the control case. In all the scenarios the effects of emissions changes were short lived and atmospheric composition returned to control levels within a couple months of the emissions reductions ceasing. In the following analyses we focus on the lockdown period (mid-March to mid-May), where emissions are prescribed to be at their lowest, and quantify changes in composition and average instantaneous radiative forcing (IRF) from $O_3$ and aerosol direct effects.

### 3.1 Evaluation of $NO_2$ Column

Observations of tropospheric $NO_2$ columns have exhibited significant reductions globally (Bauwens et al., 2020, Zhang et al., 2020) with decreases in excess of 20% over many major cities. Figures 1 and S2 show $NO_2$ column changes from observation (Bauwens et al., 2020) and model scenarios.

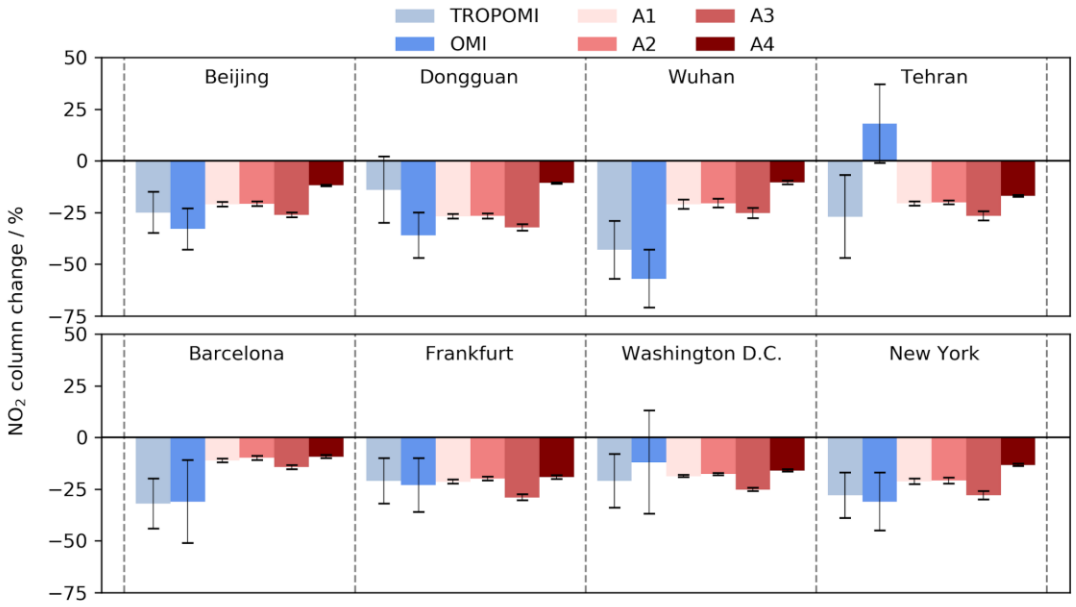

**Figure 1. Observed and modelled tropospheric $NO_2$ column changes. Observations are from TROPOMI and OMI relative to 2019, see Bauwens et al. (2020) for more details. Model results are from the 4 scenarios relative to the control averaged over the period of lowest emissions (mid-March to mid-May).**

Figure 1 highlights that our model simulations are in good agreement with observed $NO_2$ column decreases by Bauwens et al. (2020), with the A1 scenario being within error in most cases. This increases confidence in the representativeness of our emissions scenarios for the COVID-19 changes. However, we note that the model simulations generally underestimate the magnitude of $NO_2$ column changes, suggesting our emission perturbations may be at the lower end of what happened during the pandemic. Shi and Brasseur (2020) showed through surface observation analyses across China that the COVID-19 lockdowns resulted in significant decreases in $NO_2$, but increases in ozone ($O_3$). These local increases in surface $O_3$ in polluted regions are also captured in our simulations, although with a smaller magnitude (Fig. 2), and are driven by the non-linear $NO_x$-VOC chemistry that produces $O_3$ in the troposphere (Monks et al., 2016). However, all scenarios exhibited a general decrease in global tropospheric $O_3$, attributed to the reduction in $NO_x$ emissions.

### 3.2 Reduction in Oxidant Burden

Globally averaged, the changes to emissions from transport, industry and aviation led to decreases in the tropospheric $O_3$ burden of 2.0-3.2 % (Fig. 2, S3), which recovered quickly once emissions increased. The OH concentration was also simulated to have decreased (Fig. 2). The reduction in tropospheric $O_3$ was most pronounced in A3 where localised decreases exceeded 7%, illustrating the large impact of reducing surface transport emissions. The Northern Hemisphere midlatitudes, the location of the largest absolute change in emissions, saw the greatest reductions. Spatial heterogeneity in OH and $O_3$ depletion between scenarios revealed the importance of emissions from surface transport and aviation (Fig. S4). The additional decreases in low altitude $O_3$ and OH in Scenario A3 relative to A1 were attributed to the greater reduction in surface transport emissions in A3, while smaller decreases in mid altitude $O_3$ and OH in A2 were due to the smaller reduction in aviation emissions. The similarity in $O_3$ and OH between scenarios A1 and A4 signified the tropospheric oxidant budget is relatively insensitive to industrial emissions.

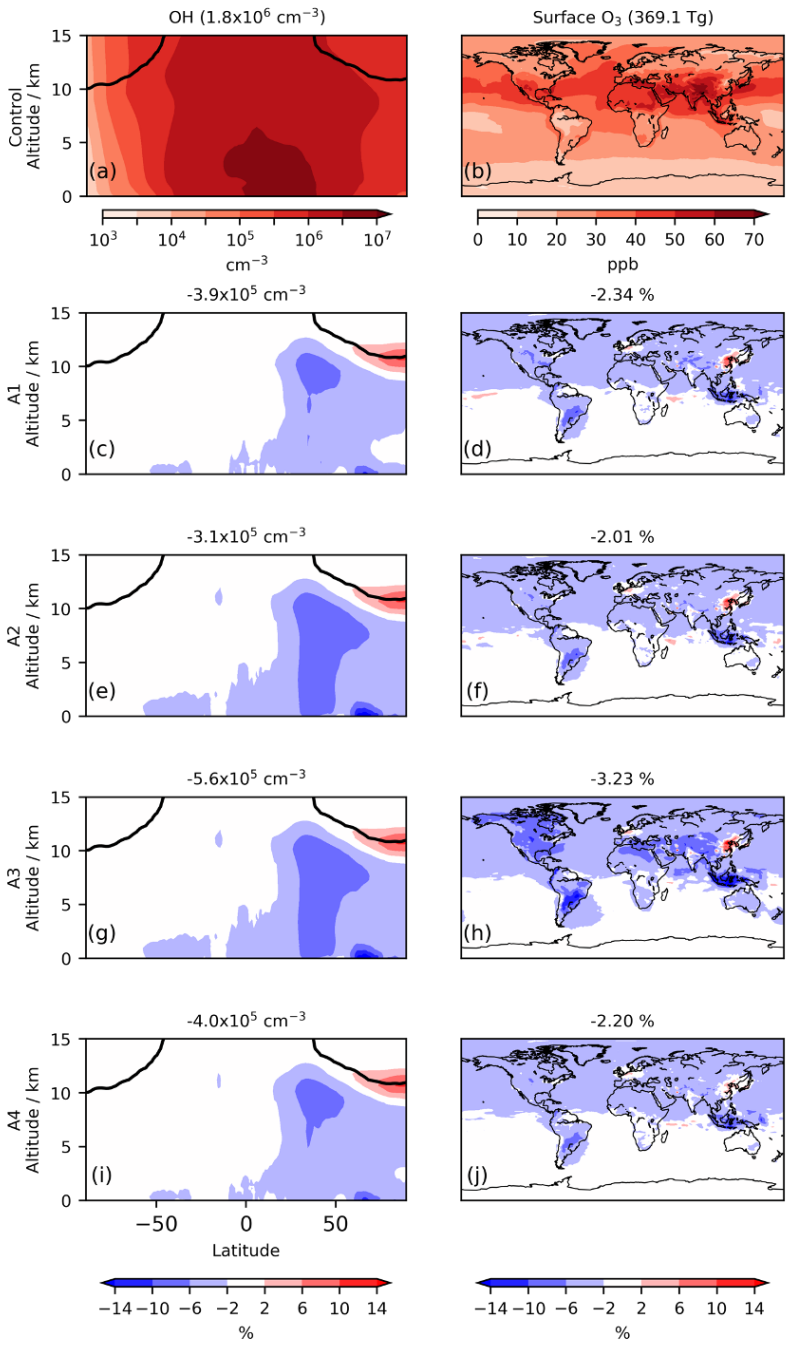


**Figure 2. Zonal mean OH and surface $O_3$ mixing ratios in control runs and respective changes (mid-March to mid-May). Model results are the ensemble mean for each scenario. Black lines in the OH plots show the tropopause. Titles in the left column show mean tropospheric air-mass-weighted [OH] in control (top) and change (lower panels). Titles in the right column show mean tropospheric $O_3$ burden in control (top) and change (lower panels).**

The decrease in tropospheric OH did not affect model methane concentration due to the fixed methane surface boundary condition. However, the change in methane concentration, c, which

would have occured can be calculated from the methane lifetime (Eq.1) (Thornhill et al., 2020), where f=1.33 is methane's feedback on its own lifetime (Fiore et al., 2009).

$$\frac{\Delta c}{c} = \left(\frac{\Delta \tau}{\tau} + 1\right)^f - 1 \approx f\frac{\Delta \tau}{\tau}$$

**Equation 1**

Methane lifetime increased by 2-2.5% (A1-2, A4) and 4% (A3) over the period of emissions reduction (Fig. S5). This would correspond to increases in methane concentration of ~20-40 ppb if steady state were reached. However, given the perturbations' brevity, much smaller increases of 1-2 ppb were calculated as an upper bound (Text S2). We therefore conclude the effect on methane concentration and the associated forcing are negligible.

### 3.3 Reduction in Sulphate Aerosol Burden

The perturbation to oxidants reduced the oxidation flux of $SO_2$ beyond the change due to the reduction in $SO_2$ emissions alone, illustrating the coupling between emissions, oxidants and sulphate aerosol, an important climatic forcer. $SO_2$ production fluxes (emissions plus chemical production) decreased by around 8% (A1-A3) and 1.3% (A4), highlighting the sensitivity of $SO_2$ to industrial emission reductions. However, the corresponding drop in $SO_2$ burden (5.4% (A1-A3) and 0.1% (A4)) (Fig. 3(a)) was smaller than the production flux decrease due to a reduction in chemical loss driven by oxidant decreases. This effect was most pronounced with the tropospheric gas phase OH + $SO_2$ flux which decreased by 8-9.5% (A1-A3) and 2.6% (A4) (Fig. 3(b)) and showed significant spatial similarity to [OH] change and exceeded the changes in $SO_2$ alone (Fig. S5).

The other $SO_2$ oxidation pathway, aqueous oxidation by $H_2O_2$ and $O_3$, decreased by only 4% (A1-A3), meaning relatively more $SO_2$ was oxidised via aqueous phase chemistry. This is important because in UKCA, the $H_2SO_4$ produced via OH + $SO_2$ oxidation can nucleate new particles and thus affects aerosol number and size distribution. However, the aqueous phase pathway only adds mass to existing particles. The different reductions in gaseous and aqueous flux causes an additional perturbation to the aerosol size distribution resulting in fewer, larger aerosols (Fig. 3 (c, e)).

We calculated a reduction in sulphate aerosol burden (with rapid post-lockdown recovery) with non-uniform reduction across the aerosol modes and largest changes in the mid latitude Northern Hemisphere (Figs. S6,7). The largest decrease in mass occurred in the accumulation mode (Fig. 3(c)) and the largest decrease in number in the nucleation mode (Fig. 3(d)). This perturbation to the size distribution produced an increase in the mean aerosol effective radius ($r_{eff}$) of 1-4% (Fig. 3(e)) and is attributed in part to the greater relative reduction of gas phase oxidation of $SO_2$ (and thus new particle nucleation) than aqueous phase oxidation: a further illustration of coupling between composition and climatically-relevant agents.

The perturbation to the aerosol size and number distribution resulted in cloud droplet number concentration (CDNC) decreases of up to 4% globally (Fig. 3(f)), with localised decreases exceeding 10% (Fig. S8) and commensurate increase in effective cloud droplet radius of 0.25-0.4% (Figs. S9, S10). The drop in CDNC is likely to reduce cloud albedo (Twomey, 1977) and thus contribute a positive forcing but this has not been calculated here.

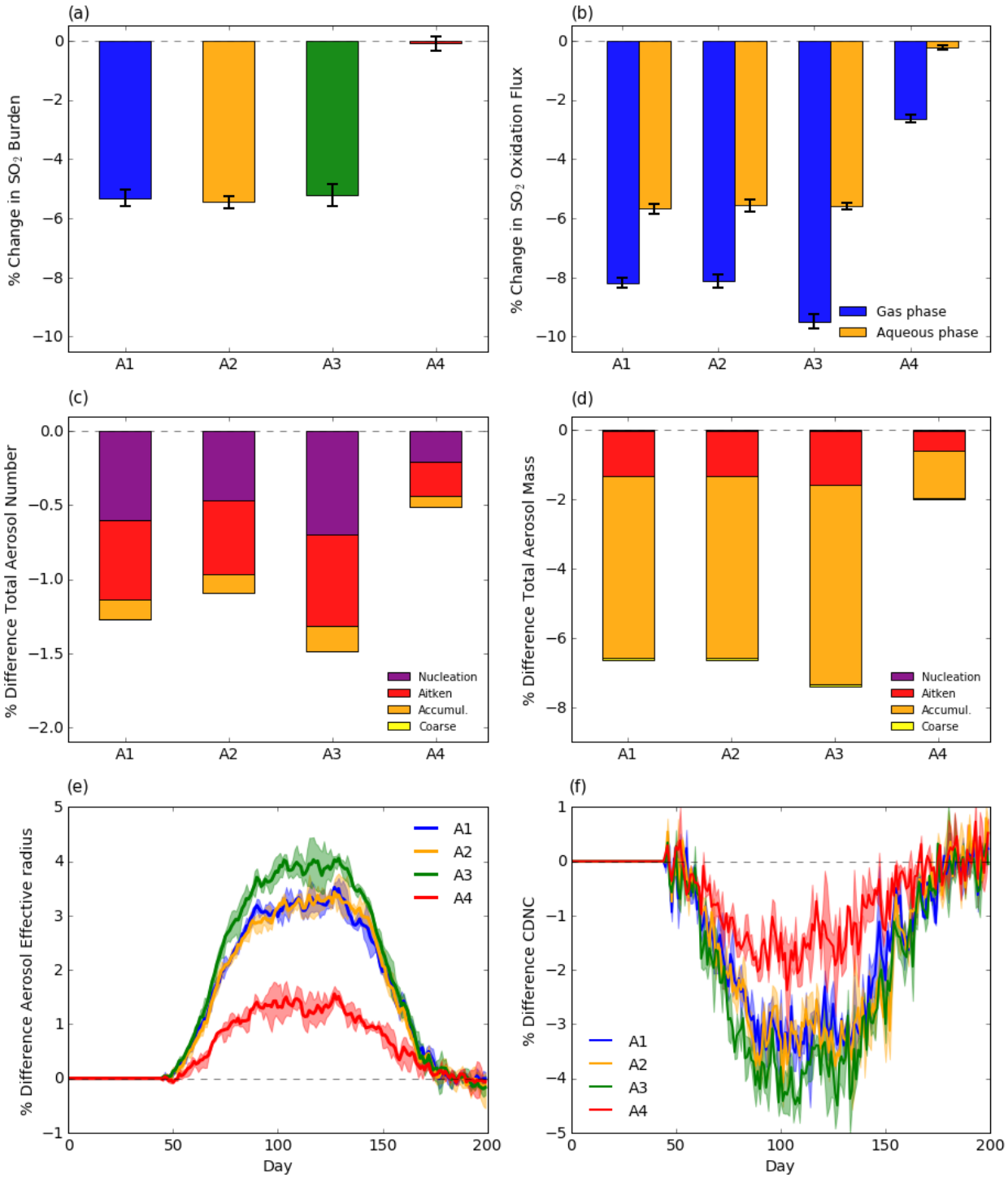


**Figure 3 - Mean change in (a) $SO_2$ burden, (b) $SO_2$ oxidation flux, (c) sulphate aerosol number, and (d) mass burden split by aerosol size (March to May). Mean change in (e) $r_{eff}$ and (f) CDNC (error bars and shading show ensemble range).**

### 3.4 Aerosol Optical Depth

The decrease in simulated sulphate aerosol burden and emissions of primary aerosol (BC, OC) results in decreases in aerosol optical depth (AOD) at 550 nm across most terrestrial regions in scenarios A1-A3 (Fig. S11) with rapid increase upon emission increase. Eastern China exhibits the largest absolute decreases (Fig. S12) while A4 showed much smaller decreases, highlighting the major contribution of industrial $SO_2$ emissions to AOD. Observed AOD changes between 2017-2019 and 2020 from VIIRS (Sayer et al., 2018) were analysed (Fig. S13) but showed little significant sign due to considerable noise.

## 4. Radiative Effects

The impact of ozone reduction (Fig. S14) was estimated using the conversion factor of 0.042 $Wm^{-2}$ $DU^{-1}$ (Stevenson et al., 2013). The IRF resulting from aerosol direct radiative effects, $IRF_{DRE}$, was calculated by comparing the total outgoing flux, $F$, and outgoing clean air flux, $F_{clean}$, between the perturbed and control runs (Eq. 2) following Ghan (2013).

$$IRF_{DRE} = \Delta(F - F_{clean})$$

**Equation 2**

The $IRF_{DRE}$ was calculated to be significantly smaller than the $O_3$ forcings in A1 and A2 but comparable in A3 and A4. Despite the warming effect expected from the reduction in sulphate aerosol, the global aerosol IRF was simulated to be negative in all scenarios (Table 2).

**Table 2 - IRF relative to control runs averaged over period of lowest emissions (mid March - mid May).**
**Values in parentheses show the ensemble range.**

| **Instantaneous Radiative Forcing / $mWm^{-2}$** | **A1** | **A2** | **A3** | **A4** |
|---|---|---|---|---|
| **Ozone** | -34 (-37 to -31) | -29 (-32 to -27) | -47 (-50 to -43) | -32 (-35 to -30) |
| **Aerosol Direct Effect IRF** | -4 (-9 to +3) | -2 (-8 to +6) | -27 (-34 to -18) | -44 (-47 to -40) |
| **Ozone and Aerosol IRF** | -38 | -31 | -74 | -66 |

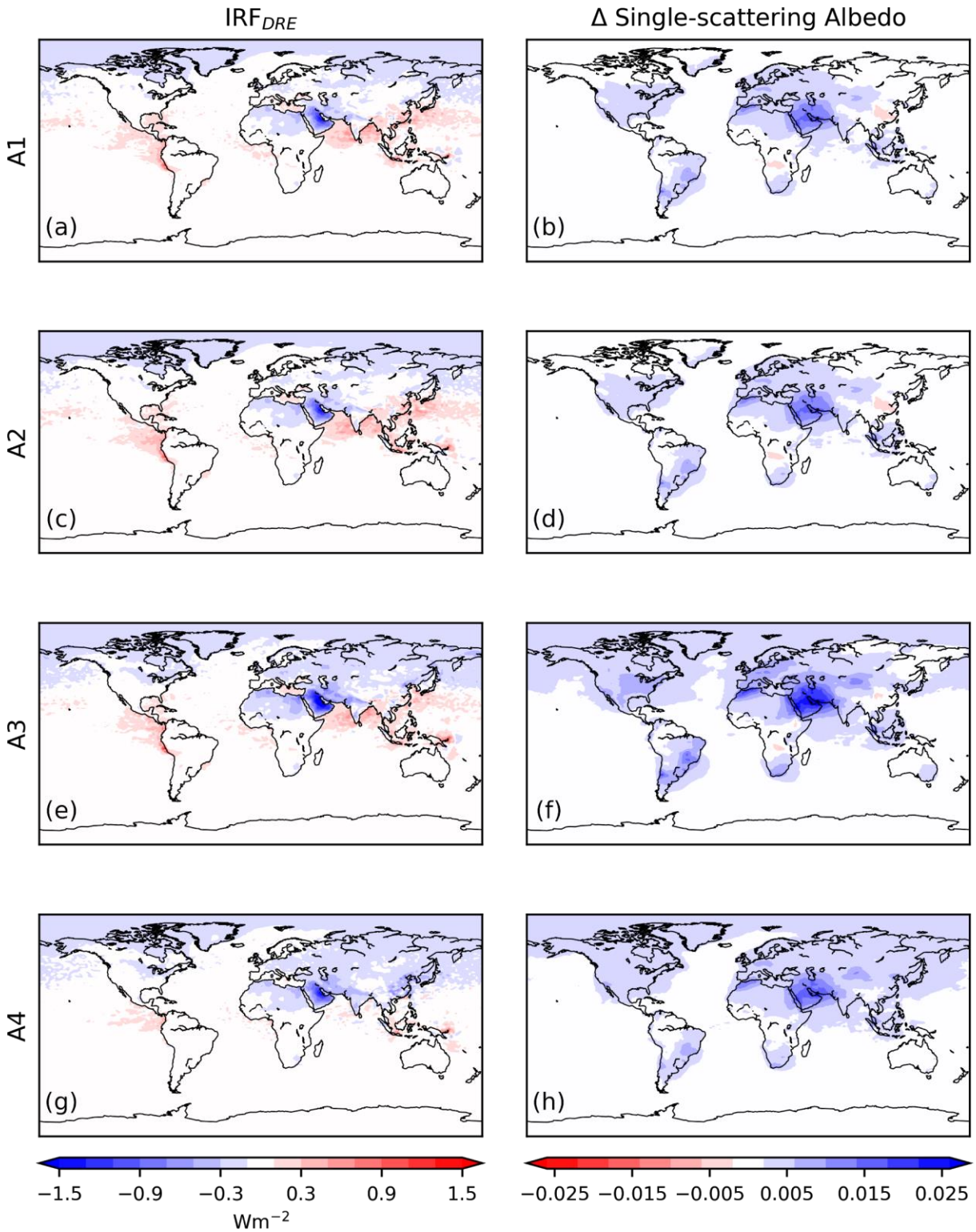


**Figure 4. IRF from aerosol direct effects ($IRF_{DRE}$) and change in single-scattering albedo (March to May) averaged over the 3 years investigated.**

Spatial analysis of the $IRF_{DRE}$ (Fig. 4) revealed a negative forcing over large Northern Hemisphere continental regions except Eastern China, the location of the greatest reduction in $SO_2$ emissions, which exhibited a warming in A1-A3. This warming was attributed to $SO_2$ emission reductions associated with industry as it was not simulated in A4.

The negative forcing was especially strong over the Arabian peninsula. This was attributed to the fact that the reduction in aerosol exposed solar radiation to a surface with a higher albedo than the original aerosol population, resulting in a greater fraction of insolation being reflected (Haywood and Shine., 1995). This effect was compounded on the Arabian peninsula by the large decreases in black carbon emissions from both surface transport and industry sectors (Fig. S16), a strongly absorbing aerosol component with low single-scattering albedo (Bond et al., 2013). Accordingly, the increase in single-scattering albedo (Fig. 4) is most pronounced over the Arabian peninsula and correlates well with the negative $IRF_{DRE}$. In addition, the reduction in $SO_2$ emissions (Fig. S14) was much more modest in this region and therefore the associated warming effects were smaller. Globally these competing aerosol forcing effects almost completely offset in A1 and A2 while the greater reductions in black carbon from surface transport resulted in net cooling in A3. The even larger cooling in A4 was attributed to the combination of BC emissions reduction from transport with the much smaller reduction in $SO_2$ emissions without industry mitigation, resulting in higher aerosol SSA and a negative forcing.

## 5. Conclusion

In this study we investigated the impacts on atmospheric composition and radiative forcing from changes in anthropogenic road transport, aviation, and industrial emissions comparable to those resulting from the response to the COVID-19 pandemic. Our model results have shown these emission reductions led to significant changes in atmospheric composition, driven by the changes in the oxidising capacity of the troposphere and oxidant-aerosol-precursor interactions. Decreases in $NO_x$ emissions reduced tropospheric $O_3$ and as a result the oxidising capacity, with concomitant increases in methane lifetime although a negligible increase in methane forcing. $SO_2$ emission reductions and the reduction in tropospheric oxidising capacity led to decreases in sulphate burden. The reduction in sulphate aerosol number is predominantly manifest in the nucleation mode; attributed in part to the greater relative reduction in gas phase $SO_2$ oxidation compared to aqueous phase oxidation and supported by increases in aerosol effective radius and decreases in CDNC. This highlights the influence of oxidant changes on the aerosol size distribution (as well as aerosol burden), an important climatic parameter.

Despite reduction in the sulphate aerosol burden, decreases in BC emissions resulted in a negative forcing from the aerosol direct effect which, when combined with the negative forcing from tropospheric $O_3$ reduction, led to a small negative forcing of 31-74 $mWm^{-2}$. This change is short-lived and comparable to a *temporary* decrease of 3-6 ppm of $CO_2$. Due to model setup limitations these estimates do not include impacts from aerosol-cloud interactions. However we can speculate from the reductions in aerosol number and CDNC that cloud effects would have a

positive forcing, reducing the overall magnitude of the forcing we calculated and potentially changing its sign.

Our results suggest that temporary changes to SLCF emissions due to the COVID-19 emergency measures are not going to have a significant impact on near-term climate change, implying that changes in $CO_2$ emissions during the lockdown period and following recovery will be more important in determining the lasting impact of the pandemic on climate. Elucidating the full effective radiative forcing, including aerosol-cloud interactions, and the climate response due to emission changes warrants further investigation using longer free-running simulations.

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*Competing Interests: All authors declare that they have no competing interests.*

*Author contributions: JW, YMS and JSS led the experimental design and analysis in the study. All co-authors contributed to writing and reviewing the manuscript.*

*Data availability: All necessary data is in the process of being deposited on the CEDA archive https://arrivals.ceda.ac.uk/uploader/browse/Covid-19_emiss_reduc_study/*

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