# The Climate Response to Emissions Reductions due to COVID-19: Initial Results from CovidMIP

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## Key Points:

- Lockdown restrictions during COVID-19 have reduced emissions of aerosols and greenhouse gases
- 12 CMIP6 Earth system models have performed coordinated experiments to assess the impact of this on climate
- Aerosol amounts are reduced over southern and eastern Asia but there is no detectable change in annually averaged temperature or precipitation

## Abstract

Many nations responded to the COVID-19 pandemic by restricting travel and other activities during 2020, resulting in temporarily reduced emissions of $CO_2$, other greenhouse gases and ozone and aerosol precursors. We present the initial results from a coordinated Intercomparison, CovidMIP, of Earth system model simulations which assess the impact on climate of these emissions reductions. Twelve models performed multiple initial-condition ensembles to produce over 300 simulations spanning both initial condition and model structural uncertainty. We find model consensus on reduced aerosol amounts (particularly over southern and eastern Asia) and associated increases in surface shortwave radiation levels. However, any impact on near-surface temperature or rainfall during 2020-2024 is extremely small and is not detectable in this initial analysis. Regional analyses on a finer scale, and closer attention to extremes (especially linked to changes in atmospheric composition and air quality) are required to test the impact of COVID-19-related emission reductions on near-term climate.

## Plain Language Summary

Many nations responded to the COVID-19 pandemic by restricting travel and other activities during 2020. This caused a temporary reduction in emissions of $CO_2$ and other pollutants. We compare results from twelve Earth system models to see if the emissions reductions affected climate. These twelve models performed over 300 experiments using multiple initial-conditions. We find a consensus that aerosol amounts were reduced, especially over southern and eastern Asia, during 2020-2024. This led to increases in solar radiation reaching the surface in this region. However, we could not detect any associated impact on temperature or rainfall. We recommend more analyses on regional scales. We also suggest that analysis of extreme weather and air quality would be useful to test the impact on climate of emission reductions due to COVID-19.

# 1 Introduction

## 1.1 Impact of COVID-19 lockdown on emissions

The COVID-19 pandemic led to widespread measures restricting travel, industrial, and commercial activity during 2020. The effects of these changes in socioeconomic activity on atmospheric composition have been widely studied including estimates of emissions and concentrations of species that directly or indirectly affect climate.

The impacts of COVID-19 measures on long-lived greenhouse gases have been inferred from both bottom-up estimates using activity data and top-down analysis of atmospheric observations. Bottom-up estimates using sector activity have estimated global $CO_2$ emissions reductions of 8.8% during the first 5 months of 2020 (Liu et al., 2020) and annual reductions from 4% to 7% (Le Quéré et al., 2020). Top-down assessments have found some indications of a decrease in $CO_2$ growth rate during 2020 (Buchwitz et al., 2020), with examples of substantial local and regional $CO_2$ and methane ($CH_4$) emissions reductions inferred from surface observations (Tohjima et al., 2020; Turner et al., 2020). However, existing satellite products could not provide the required coverage to reliably detect changes in $CO_2$ column densities at the magnitude expected to be occurring in 2020 (Buchwitz et al., 2020; Chevallier et al., 2020). Expected growth rates in atmospheric $CO_2$ fractions vary too much from year to year due to internal climate variability (Jones and Cox, 2005; Betts et al., 2016) for the effects of emission reductions on the order of 8% to be clearly detected from observations of $CO_2$ column densities (Sussmann and Rettinger, 2020; Tohjima et al., 2020). The long lifetime of $CO_2$, and to a lesser extent $CH_4$, means that the small impact of emissions reductions is likely to be long-lived, and may still exert a non-negligible climate impact on decadal timescales (Forster et al., 2020).

The largest changes in observed composition attributed to COVID-19 restrictions were for nitrogen dioxide ($NO_2$), with concentration reductions at both national- and city-scales typically on the order of 20-60% in China, India, Europe, and the United States (Goldberg et al., 2020; Keller et al., 2020; Menut et al., 2020; Miyazaki et al., 2020; Ordóñez et al., 2020; Venter et al., 2020; Zhao et al., 2020). The $NO_2$ decreases have been attributed largely to changes in the transport sector (Bao and Zhang, 2020; Diamond and Wood, 2020; Lian et al., 2020b; Venter et al., 2020). The rapid changes in emissions and complex dynamics of short-lived pollutants have complex and non-uniform implications for climate. In areas where background $NO_x$ concentrations were high, reduced $NO_x$ emissions led to increased tropospheric ozone ($O_3$) concentrations in many regions and cities (Keller et al., 2020; Le et al., 2020; Lian et al., 2020a; Ordóñez et al., 2020; Sicard et al., 2020; Venter et al., 2020). Elsewhere, tropospheric ozone may have decreased during lockdowns leading to short-term estimated changes of radiative forcing by -33 to -78 $mWm^{-2}$ (Weber et al., 2020).

Some studies report substantial decreases in particulate matter (PM) on the order of 10-30% (Filonchyk et al., 2020; Le et al., 2020; Silver et al., 2020; Venter et al., 2020; Xu et al., 2020), but analyses accounting for long-term trends generally found no lockdown impacts on aerosol optical depth (AOD) or PM concentrations (Diamond and Wood, 2020; Field et al., 2020; Zangari et al., 2020). In some regions, PM concentrations increased as a result of altered dust or biomass burning emissions or as a consequence of changes in emissions and meteorology

(Le et al., 2020; Venter et al., 2020). Notably, northern China experienced an increase in haze during the spring lockdown due to enhanced formation of ozone, which, in combination with favorable meteorological conditions and changes in heterogeneous chemistry, contributed to enhanced secondary aerosol formation (Chang et al., 2020; Le et al., 2020; Wang et al., 2020b).

### 1.2 Impact of emissions reductions on climate

The reduction in emissions is expected to have regional impacts on atmospheric composition, and therefore could have implications for weather and climate. Different species have very different lifetimes from hours-to-days for aerosols, to decades or longer for long-lived greenhouse gases, and very different spatial scales, with some being very localized and others globally well-mixed.

For example, Yang et al. (2020) examined climate responses to aerosol emission reductions during the COVID-19 lockdown, back-to-work and post-lockdown stages throughout the year 2020 based on CESM1 model simulations. They reported that an anomalous surface warming appeared over the Northern Hemisphere continents due to the fast climate response to aerosol reductions. Fyfe et al. (2021) examine a large ensemble of simulations with CanESM5 under an idealized modelling framework of the COVID emission reduction and conclude that any signal from such short-lived emissions changes is likely to be small or even undetectable. Forster et al. (2020) developed a two-year COVID-19 emissions reduction scenario for long- and short-lived species based on mobility data and the bottom-up approach of Le Quéré et al. (2020) for some sectors and then assumed a recovery over the subsequent two years. Using the FaIR climate emulator, they simulated the effect of these emissions reductions and found a rapid short-term warming due to reduced aerosols, which was offset by a slightly slower, but also near-term cooling due to reduced tropospheric ozone. On longer timescales, well-mixed GHGs, especially $CO_2$ became important, and their simulations showed that the net effect of these emissions changes by 2030 was negligible: a global cooling of about 0.01 ± 0.005 °C.

However, because FaIR cannot capture regional climate effects, internal variability or complex interactions of atmospheric composition and biogeochemistry, there remain unanswered questions about the possible climatic impact of emissions reductions on regional air quality and climate. These are beginning to be addressed by single model studies (e.g. Yang et al., 2020 analyse an atmospheric model with prescribed sea surface temperature, and ; Fyfe et al, 2021 analyse a large ensemble of coupled atmosphere-ocean simulations with the CanESM5 model), but would benefit greatly from being analyzed across an ensemble of Earth system models (ESMs) run under a common protocol. Hence it was decided that this scenario would form the basis of a multi-Earth system model intercomparison project (MIP). This paper presents an initial analysis of the first results coming from this new activity, called CovidMIP. The emissions estimates and modelling protocol used are described in section 2, results shown in section 3 and discussed in section 4 in the context of ongoing climate change.

# 2 Materials and Methods

## 2.1 CovidMIP protocol

The emissions estimates assembled by Forster et al. (2020) were collated and gridded, and made available in Inputs4MIPs data format for use by CMIP Earth system models (Lamboll et al., 2020). A modelling protocol was agreed, and is incorporated into DAMIP (the Detection and Attribution MIP; Gillett et al., 2016), which is also described in Lamboll et al. (2020), but the main points are noted here for convenience.

Because any climate signal due to COVID-19-induced emissions reductions was considered likely to be small, it is advantageous to carry out large initial-condition ensembles which have been shown to enable detection of even small regional climate signals (e.g. Banerjee et al., 2020). But cognizant of the computational cost and time required for producing such large ensembles, a pragmatic recommendation was made that model groups perform at least 10 initial-condition ensemble members. This was hoped to maximize the number of modelling groups participating but still produce enough members to enable meaningful analysis.

The protocol uses the SSP2-4.5 scenario (O'Neill et al., 2016) as a baseline against which to apply the emissions reductions. Simulations are run parallel to ssp245, but branching from that simulation on 1 January 2020 and following the new forcing in line with emissions reductions. The results will be published on the CMIP6 archive (Earth System Grid Federation) under experiment name ssp245-covid. Forcing is provided as concentrations of greenhouse gases and emissions of aerosols and aerosol and ozone precursors. For models with interactive chemistry, ozone can be simulated otherwise it has been provided as concentrations. Similarly, models can simulate aerosols or they can be represented with the MACv2-SP parametrisation (Stevens et al., 2017; Fiedler et al., 2020).

In this manuscript we focus on the immediate term impact (from 2020-2024) of the "two year blip" scenario under which emissions revert to the baseline levels by the end of 2022. In addition to this, Forster et al. (2020) created a set of scenarios spanning possible future economic recovery strategies: a reduction in anthropogenic $CO_2$ emissions post-2020 consistent with enhanced investment in environmentally friendly technologies (moderate or strong "green stimulus"), no effect after 2022 (continuation of "two year blip" studied here with emissions reverting to ssp245) or an increase in anthropogenic $CO_2$ emissions relative to ssp245 after 2020 consistent with an investment in more traditional fossil-fuel based energy production (or "fossil-fuelled recovery"). All of these scenarios have become part of the CMIP6 set of experiments, under the detection and attribution activity (DAMIP: Gillett et al., 2016).

## 2.2 Participating Earth system models

The protocol is open to all models participating in CMIP6 and to date twelve models have provided data for analysis (Table 1). A particular value of a multi-model ensemble is being able to incorporate different levels of process complexity, but this also brings challenges of interpreting results.

Some models prescribe aerosols and ozone, either using their own climatology or MACv2-SP and/or prescribed ozone 3D concentrations taken from the OsloCTM3 chemical transport model (Lamboll et al., 2020). Others may simulate either aerosols or ozone interactively in response to their primary or secondary emissions. The MPI -ESM1-2-LR model simulated interactive $CO_2$ while the other models used prescribed $CO_2$ concentrations. Models have differing complexity and species richness of aerosols, representing both natural and anthropogenic species such as sulphates, black carbon, organic carbon, sea-salt and mineral-dust, but many still lack representation of nitrate aerosols.

In terms of biogeochemistry many ESMs now represent land and marine ecosystems and the carbon cycle (Boysen et al., 2020; Séférian et al., 2020; Thornhill et al., 2020). On the near-term studied here, the carbon cycle is unlikely to have a large effect on climate but impacts of emissions reductions may show up in terms of changes in carbon fluxes, stores and partitioning across realms of the Earth system.

To generate initial conditions some models (ACCESS-ESM1-5, CanESM5, EC-Earth3, MIROC-ES2L, MPI-ESM1-2-LR, UKESM1-0-LL) drew on existing ssp245 simulations which followed on from initial-condition ensembles of the CMIP6 historical simulations. Others perturbed conditions at the end of the historical period (CESM1, E3SM-1-1, GISS-E2-1-G), or mixed the two approaches by inflating existing ensembles with additional perturbations applied (MRI-ESM2-0, CNRM-ESM2-1, NorESM2-LM) or by running on different super-computers (NorESM2-LM).

Future studies will be able to take into account the model complexity and how this affects the simulated results. For example, are changes in atmospheric circulation or surface climate affected differently between models with simulated and prescribed ozone and aerosols? How does the model treatment of interactions between atmospheric composition (such as fraction of diffuse light or surface ozone) affect vegetation productivity and carbon storage? In this analysis such considerations are out of scope and we give an overview on each model's results for the climate response for 2020-2024. The reader is referred to Table 1, which documents the spatial resolution and the process complexity of each participating model as well as the number of ensemble members utilized in this study.

## 3 Results

### 3.1 Indicators of global change

Our analysis draws on different sized ensembles from 12 ESMs. Throughout, we base analysis on ensemble mean anomalies from each model, calculated from a pair-wise difference between simulations with COVID-19-related emissions reductions ("ssp245-covid") and simulations using the standard, baseline SSP2-4.5 scenario ("ssp245").

Globally, for 2020, all models show a reduction in aerosol optical depth (at 550 nm) in their ensemble mean with 7 out of 11 models which reported this variable having a reduction greater than 1 standard deviation (Figure 1). In 2021, the AOD anomalies of 10 out of 11 models remain negative with ACCESS-ESM1-5 showing near-zero deviation. From 2022 onwards there is no robust global signal in AOD as emissions reductions in this simulation recover to levels in the baseline scenario and aerosol amounts quickly recover too.

This behavior is reflected in the amount of solar radiation reaching the surface, which is generally simulated to have increased, with all models (of the 11 for whom this variable was available for this analysis) having a positive anomaly in downwards shortwave (SW) radiation for both 2020 and 2021 (Figure 1, panel b). Although only MRI-ESM2-0 simulated an ensemble mean global increase greater than 1 standard deviation. As for AOD, the anomaly quickly recovers and becomes very small from 2022 onwards. We have not yet investigated the extent to which surface shortwave is directly affected by aerosol absorption or by aerosol-induced changes in cloud cover. Future studies will also assess impacts and implications of aerosol-cloud interactions in driving the changes seen here.

*Figure 1. Annual mean, ensemble average output from ESMs. Each panel shows anomalies from the simulations with COVID-19-related emissions reductions compared to the baseline SSP2-4.5 simulations ("ssp245-covid" minus "ssp245"). (a) Global aerosol optical depth at 550nm; (b) downwards SW radiation at the surface; (c) Global surface air temperature; (d) Global precipitation. Coloured lines show ensemble average results from each model, and paler plumes show ensemble spread for each model calculated here as ±1 standard deviation across each model's ensemble. Vertical bars to the left of each panel show each model spread (mean ±1 standard deviation) for the first year, 2020. Each model has performed a different number of ensemble members as listed in Table 1 and shown in square brackets in the caption.*

The impact of this, however, on surface climate at a global scale is very small. Figure 1 panels (c) and (d) show globally averaged surface air temperature and precipitation respectively. No model shows any significant change in either of these quantities at a global level for any year.

## 3.2 Patterns of regional changes

Figure 2 shows the regional patterns of the changes in aerosol optical depth for each model. It is apparent that models agree that the largest response is in Asia, predominantly over India and China where almost all models show a marked decrease in aerosols as an average over the 5-year period 2020-2024. Some models also show some patches of aerosol increases, for example CanESM and E3SM-1-1 over the Himalayan region, and MIROC-ES2L over regions of North Africa. Reasons for these changes are not explored further here and we do not yet know if they are caused by changes in anthropogenic or natural sources, such as dust, which can be very sensitive to variations in windspeed.

*Figure 2. Model by model simulated changes in aerosol optical depth (at a wavelength of 550 nm). For each model we plot the ensemble mean response from 2020-2024 inclusive. Blue colours denote a decrease in AOD. Each model has performed a different number of ensemble members as listed in Table 1 and shown in square brackets in the caption. The black box shows the region analysed in Figure 3.*

To see if these regional changes in aerosol loading affect regional climate properties, we define a region bounded by 60-160$^{o}$E and 0-50$^{o}$N which has been chosen subjectively after considering all models to cover the main AOD anomalies across models (marked as black boxes in Figure 2). We assess annual changes in surface SW radiation, temperature and precipitation in this region. Figure 3 shows a similar response to the global metrics shown in Figure 1 but with greater magnitudes of average response. Again, there is a strong model agreement of reduced aerosols, with all models agreeing on this in their ensemble mean for 2020 and 7 out of 11 having reductions greater than 1 standard deviation. Averaged across models, global AOD reduction in 2020 is -0.0027±0.0012, while in southern and eastern Asia it is -0.0097±0.0034. The associated increase in downwards SW radiation is also apparent, and stronger here: globally models show an increase of 0.21±0.10 Wm$^{-2}$ while in southern and eastern Asia it is 0.69±0.31 Wm$^{-2}$.

Although most models simulate a slight warming signal in this region in their ensemble mean (Figure 3, panel c), the magnitude is very small – less than 0.1 $^{o}$C, and in all models smaller than the standard deviation across ensemble members (typically of the order 0.2$^{o}$C).

*Figure 3. indicators of change in southern and eastern Asia (defined here as 60-160$^{o}$E and 0-50$^{o}$N). As for figure 1 results are plotted as annual mean anomalies, with coloured lines denoting ensemble means from each model and grey shading 1-standard deviation for each model. (a) Aerosol optical depth; (b) surface downwards shortwave radiation; (c) surface air temperature; (d) precipitation.*

Outside of this region, models show patchy temperature changes, indicative of random changes, and internal variability of modes such as NAO or ENSO. This residual signal of internal variability is not eliminated in limited ensemble size and demonstrates the weak signal-to-noise ratio (see figure 1 in Supplementary Info). These changes do not appear to be systematic, with some regions exhibiting both apparently strong warming and cooling signals in different models. The region of northern East Asia often displays a strong temperature signal in the model results, with CESM1 displaying a warming as reported in Yang et al. (2020), although that study performed simulations with fixed sea-surface temperatures. GISS-E2-1-G and E3SM-1-1 also show strong warming patterns here and UKESM1-0-LL, MPI-ESM1-2-LR and CanESM5 some warming too. But NorESM2-LM shows a strong cooling and ACCESS-ESM1-5, MIROC-ES2L and MRI-ESM2-0 having mixed signals. Models show marked differences elsewhere e.g. MPI-ESM1-2-LR and MRI-ESM2-0 have opposite patterns of warming over North America while in South America CanESM5 and UKESM1-0-LL show a cooling but GISS-E2-1-G and NorESM2-LM show a warming.

When looking at regional patterns of precipitation and surface SW radiation (S.I. figures 2 and 3) there are no robust signals or consistent patterns of change across models. Even the increase in surface SW radiation shown in Figure 3 is very hard to see by eye in the patterns of change, due to the influence of clouds which can easily mask any signal from changes in aerosols. This, and similar incoherent patterns of rainfall change, indicate the substantial variability in these quantities and the challenges in detecting robust signals of change under conditions of relatively small forcing. Despite a large number of ensembles, it is evident that at these smaller regional scales, variability in meteorology prevents robust detection of signals in clouds and rainfall.

## 4 Discussion and Conclusions

Here we have only begun to scratch the surface of the results becoming available from the CovidMIP simulations. We stress that this work has been the result of a very rapid response of the Earth system modelling community. It often takes several years to design and perform coordinated MIP experiments, and process the data for publication in a community archive. This activity has taken place in only a matter of months. This paper is just the very first analysis of initial results and therefore serves only as a first indication of how the climate system has responded to the perturbations to emissions in response to the COVID-19 pandemic. It is not possible at this stage to analyze all of the responses, nor the processes responsible for changes across the whole system. But this study sets the scene and informs priorities for future analysis.

We have shown that the imprint of COVID-19-related changes in societal activity is visible in atmospheric composition – notably aerosol optical depth over southern and eastern Asia, and in the amount of solar radiation reaching the planet's surface. Over this most affected region, the 2-year average effect was more than 0.5Wm$^{-2}$. More locally and on shorter timescales it could be substantially higher. However, despite these changes in the make-up of the atmosphere, no detectable change in surface temperatures or rainfall could be found. We conclude that the emissions reductions were too small in magnitude and time to have a significant effect on global climate, and that larger, sustained changes on a much longer timescale are required in order to have observable effects (Samset et al., 2020; Tebaldi et al, 2020). The CovidMIP protocol will be extended to include an additional "four year blip" simulation so that future work can also consider the impact if lockdown restrictions were prolonged or recovery delayed due to new strains of the Coronavirus.

Based on what we have found we recommend further analysis would be fruitful in the following areas:

- *Effective radiative forcing (ERF) response to the emissions perturbations*. The global patterns of downwards SW radiation anomalies are very noisy in these simulations but the radiation signal would be improved in simulations with fixed-SSTs which reduce interannual variability in the climate system and allow quantification of the ERF due to the emission changes (Pincus et al., 2016; Fiedler et al., 2020). The CovidMIP protocol (Lamboll et al., 2020) defines additional fixed-SST simulations to isolate the effects of ozone, aerosols and even separate black carbon, organic carbon and sulphate aerosols. We recommend model groups perform these complementary simulations to allow the radiative effects of emissions reductions to be assessed more reliably.
- *Attribution of drivers of climate signals*. As part of DAMIP, this activity has a strong interest in performing single-forcing simulations to enable understanding of different drivers and causes of the climate changes seen. Large ensembles have been shown to be successful in detecting and attributing changes, e.g., in recent southern hemisphere circulation changes to stratospheric ozone recovery (Banerjee et al., 2020). Similar techniques could be used here to separate the impacts of emissions reductions of GHGs and aerosols as explored in CanESM5 by Fyfe et al. (2021).
- *Longer term implications of emissions reductions and options for economic recovery*. Forster et al. (2020) compiled a set of hypothetical recovery scenarios

based on moderate or strong green stimulus packages or a fossil-fuel stimulus rebound. The climate impacts by 2050 showed that how the world's economy recovers after 2020 can have profound impacts on our ability to meet long-term climate goals. Multi-model analysis of these simulations will enable clearer understanding of the threats and opportunities arising from the current situation.

- *Quantifying changes in extremes*. In addition to annual mean changes, the climate response in terms of extremes – such as daily maximum or minimum temperatures or daily precipitation rates – may also show important signals (Seneviratne and Hauser, 2020).
- *Influence on atmospheric circulation*. Studies have found a sensitivity of monsoons to changes in emissions of aerosols (Meehl et al., 2008; Li et al., 2016; Lau et al., 2017; Zhao et al., 2019). Analysis of these changes in a multi-model study may be able to detect if COVID-19-related emissions reductions have had a detectable impact on monsoon circulations, especially over Asia.
- *Response and impacts of atmospheric composition*. The response of aerosols is detectable in this ensemble, but we have not yet explored the role of other chemically active components of the atmospheric composition. Especially, the role of ozone and its response to changes in emissions of precursors, is a key components of changes in air quality. Multiple studies have found increases in ozone in populated urban areas during lockdown (e.g. Keller et al., 2020), in contrast to a global decrease in tropospheric ozone (Weber et al., 2020). This MIP provides an opportunity to shed process-level understanding on these changes in a range of models of varying degrees of complexity with regards to atmospheric chemistry.
- *Impact on the global carbon cycle*. There is increasing interest in the ability to make predictions from one year to the next of changes in atmospheric $CO_2$ (Betts et al., 2016; Séférian et al., 2018; Lovenduski et al., 2019; Fransner et al., 2020; Spring and Ilyina, 2020). These studies require knowledge of natural causes of interannual variability – notable from ENSO (Watanabe et al., 2020), but they also require knowledge of up to date estimates of anthropogenic $CO_2$ emissions. These are normally expected to vary relatively little from year to year (Le Quéré et al., 2018) but expected impacts from COVID-19-related emissions reductions allow us to test out ability to forecast this most important metric of climate change, and whether external forcing can affect its variability (McKinley et al., 2020).

The SARS-Cov-2 pandemic of 2020 has created one of the biggest health and economic crises of recent history, but it also presents a remarkable opportunity to study how the climate system responds to changes in emissions of radiatively active species. From regional air quality to global climate this database of ESM outputs will enable advances in our understanding of how the climate system responds to short-term perturbations.

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## Conflict of interest

The authors declare no competing interests

## Data

Model data is published on the CMIP6 archive available via the Earth System Grid Federation. https://esgf-index1.ceda.ac.uk/search/cmip6-ceda/

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*Table 1. List of participating models, their main properties and number of ensemble members used in this study.*

| Model name | reference | Atmosphere resolution § | Ocean resolution § | ssp245-covid ensemble members | Aerosol processes # | Ozone forcing | Aerosol forcing |
|---|---|---|---|---|---|---|---|
| ACCESS-ESM1-5 | Ziehn et al. (2020) | 250km (N96), L38 | 100km, L50 | 30 | 5; CLASSIC | Prescribed *ssp245-covid* perturbation (Lamboll et al., 2020) * | interactive |
| CanESM5 | Swart et al. (2019) | 500km (T63), L49 | 100km, L45 | 50 | 5; Parameterized using a prognostic scheme for bulk concentrations | Prescribed *ssp245-covid* perturbation (Lamboll et al., 2020) * | interactive |
| CESM1 | Hurrell et al. (2013) | 250km (1.9x2.5), L30 | 100km (gx1v6), L60 | 10 | 6; MAM4 | Prescribed without ssp245-covid perturbation | interactive |
| CNRM-ESM2-1 | Séférian et al. (2019) | 250km (TL127,1.4°), L91 | 100km (eORCA1), L75 | 100 | 5; TACTIC (Michou et al., 2020) | Interactive above 560 hPa, prescribed below ( Michou et al., 2020) | interactive |
| E3SM-1-1 | Burrows et al. (2020) | 100km (NE30), L72 | 60-30 km, L100 | 10 | 7; MAM4 (Wang et al., 2020a) | Prescribed without ssp245-covid perturbation | interactive |
| EC-Earth3 | | 100km (T255), L91 | 100km (eORCA1), L75 | 30 | n/a | Prescribed *ssp245-covid* perturbation (Lamboll et al., 2020) | MACv2-SP (Fiedler et al., 2020) |
| MIROC-ES2L | Hajima et al. (2020); Kawamiya et al. (2020) | 500km (T42), L40 | 100km (360x256), L63 | 30 | 5; SPRINTARS | Prescribed *ssp245-covid* perturbation (Lamboll et al., 2020) | interactive |
| MPI-ESM1-2-LR | Mauritsen et al. (2019) | 250km (T63), L47 | 150km, L40 | 10 | n/a | Prescribed *ssp245-covid* perturbation (Lamboll et al., 2020) | MACv2-SP (Fiedler et al., 2020) |
| MRI-ESM2-0 | Yukimoto et al. (2019); Oshima et al. (2020) | 100km (TL159, 1.125$^{o}$), L80 | 100km (tripolar 1$^{o}$ x 0.3$^{o}$ -0.5$^{o}$), L61 | 10 | 5; MASINGAR mk-2r4c | interactive | interactive |
| GISS-E2-1-G | Kelley et al., 2020; Ito et al., 2020; Bauer et al., 2020 | 250km (2x2.5$^{o}$), L40 | 100km (1x1.25$^{o}$), L40 | 10 | 8; MATRIX | interactive | interactive |

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|---|---|---|---|---|---|---|---|
| NorESM2-LM | Seland et al. (2020); Tjiputra et al. (2020) | 250km ($1.9^{o}$ x $2.5^{o}$), L32 | 100km, L53 | 10 | 5; OsloAero6 | Prescribed without ssp245-covid perturbation | interactive |
| UKESM1-0-LL | Sellar et al. (2019) | 250km (N96), L85 | 100km (eORCA1), L75 | 16 | 5; UKCA MODE | interactive | interactive |

§ shown as CMIP “nominal resolution” in km, “L” denotes number of vertical levels. Grid name or information provided if available.

# number of aerosol species, and name/description of aerosol sub-model

* These models used the first version of the ozone fields that had a small bug in the vertical interpolation of the ozone perturbation, stretching the ozone perturbation to too high altitudes. The models weres not able to re-run the model simulations with the corrected ozone fields. Radiative kernel calculations following Skeie et al. (2020) gave 0.6 $mWm^{-2}$ stronger total ozone radiative forcing in 2020 for the corrected fields compared to the incorrect ozone fields, that are small compared to the total ozone radiative forcing of -37 $mWm^{-2}$ for *ssp245-covid* relative to *ssp245* in 2020.