Radiative effects of reduced aerosol emissions during the COVID-19 pandemic and the future recovery

Stephanie Fiedler¹, Klaus Wyser², Joeri Rogelj³, and Twan van Noije⁴

¹University of Cologne ²SMHI ³Imperial College London ⁴KNMI Royal Netherlands Meteorological Institute

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Abstract

The pandemic in 2020 caused an abrupt change in the emission of anthropogenic aerosols and their precursors. We provide the first estimate of the associated change in the aerosol radiative forcing at the top of the atmosphere and the surface. To this end, we perform new simulations with the contemporary Earth system model EC-Earth3 participating in CMIP6, and created new data on the anthropogenic aerosol optical properties and an associated effect on clouds for the implemented aerosol parameterization, MACv2-SP. Our results highlight the small impact of the pandemic on the global aerosol radiative forcing in 2020 compared to the baseline of the order of +0.04Wm-2, which is small compared to the natural year-to-year variability in the radiation budget. Natural variability also limits the ability to detect a meaningful regional difference in the anthropogenic aerosol radiative effects. We identify the best chances to find a significant change in radiation at the surface during cloud-free conditions for regions that were strongly polluted in the past years. The new post-pandemic recovery scenarios indicate a spread in the aerosol forcing of -0.68 to -0.38Wm-2 for 2050, which translates to a difference of +0.05 to -0.25Wm-2 compared to the baseline. This spread falls within the present-day uncertainty in aerosol radiative forcing and the CMIP6 spread in aerosol forcing at the end of the 21st century. We release the new MACv2-SP data for studies on the climate response to the pandemic and the recovery scenarios.

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Supporting Information for

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¹University of Cologne, Institute of Geophysics and Meteorology, Cologne, Germany

²Hans-Ertel-Centre for Weather Research, Climate Monitoring and Diagnostics, Bonn/Cologne, Germany

³Rossby Centre, Swedish Meteorological and Hydrological Institute, Sweden

⁴Grantham Institute, Imperial College London, United Kingdom

⁵International Institute for Applied Systems Analysis, Laxenburg, Austria

⁶Royal Netherlands Meteorological Institute, De Bilt, Netherlands

Contents of this file

File specification of supplementary data set S1

Additional Supporting Information (Files uploaded separately)

Data Set S1: SP-covid-input.zip

Data Set S1. Input data for MACv2-SP for COVID-MIP

We provide the input data for the MACv2-SP parameterization in a zip archive. The archive contains netCDF files for each emission scenario (*.nc) and a text file (README.txt) with details on the data generation and version, references, and directions to other MACv2-SP resources.

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¹⁰ Key Points:

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11	•	New COVID-19 data to parameterize anthropogenic aerosol properties are released
12		for use in climate studies.
13	•	First estimate of anthropogenic aerosol radiative forcing for 2020 suggests a change
14		by $+0.04 \text{ Wm}^{-2}$ due to the pandemic.
15	•	Recovery scenarios for 2050 have a spread in anthropogenic aerosol forcing of -0.38
16		to -0.68 Wm^{-2} .

Corresponding author: Stephanie Fiedler, stephanie.fiedler@uni-koeln.de

17 Abstract

The pandemic in 2020 caused an abrupt change in the emission of anthropogenic aerosols 18 and their precursors. We provide the first estimate of the associated change in the aerosol 19 radiative forcing at the top of the atmosphere and the surface. To this end, we perform 20 new simulations with the contemporary Earth system model EC-Earth3 participating 21 in CMIP6, and created new data on the anthropogenic aerosol optical properties and an 22 associated effect on clouds for the implemented aerosol parameterization, MACv2-SP. 23 Our results highlight the small impact of the pandemic on the global aerosol radiative 24 forcing in 2020 compared to the baseline of the order of $+0.04 \,\mathrm{Wm^{-2}}$, which is small com-25 pared to the natural year-to-year variability in the radiation budget. Natural variabil-26 ity also limits the ability to detect a meaningful regional difference in the anthropogenic 27 aerosol radiative effects. We identify the best chances to find a significant change in ra-28 diation at the surface during cloud-free conditions for regions that were strongly polluted 29 in the past years. The new post-pandemic recovery scenarios indicate a spread in the 30 aerosol forcing of -0.68 to -0.38 Wm⁻² for 2050, which translates to a difference of +0.0531 to $-0.25 \,\mathrm{Wm^{-2}}$ compared to the baseline. This spread falls within the present-day un-32 certainty in aerosol radiative forcing and the CMIP6 spread in aerosol forcing at the end 33 of the 21st century. We release the new MACv2-SP data for studies on the climate re-34 sponse to the pandemic and the recovery scenarios. 35

³⁶ Plain Language Summary

Anthropogenic aerosols, released into the atmosphere due to human activities, af-37 fect the climate by scattering and absorbing sunlight and changing the properties of clouds. 38 The socio-economic impact of the pandemic in 2020 reduced the amount on anthropogenic 39 aerosols. We here estimate the total reduction of anthropogenic aerosols for 2020 and 40 the implication for the radiation budget of our planet. Overall we find only a small im-41 pact on the radiation budget due to the change in anthropogenic aerosols in 2020. The 42 post-pandemic recovery pathway influences, however, the magnitude of the total anthro-43 pogenic radiative forcing which for instance also accounts for changes in atmospheric green-44 house gas concentrations. 45

46 **1** Introduction

The aerosol burden in 2020 is affected by reduced emissions of anthropogenic aerosols 47 and their precursors associated with the global COVID-19 pandemic. Many countries 48 have witnessed a reduction in socio-economic activities and lockdowns. The associated 49 decline in traffic and industrial productivity have led to marked regional reductions in 50 atmospheric pollution improving the air quality (e.g., van Heerwaarden et al., submit-51 ted; Ranjan et al., 2020). Figure 1 illustrates the change in the aerosol burden as the ob-52 served anomaly in the mid-visible aerosol optical depth, τ' , for northern hemisphere spring 53 in 2020 against the 20-year spring climatology from NASA's MODIS satellite product 54 (Acker & Leptoukh, 2007; Platnick et al., 2015). Pronounced negative τ' in spring 2020 55 are identified for Eastern and Southern Asia as well as the Northwest Pacific. Even re-56 gions with typically relatively low aerosol burden like Europe and North America had 57 less aerosol burden. The pandemic restrictions in most of the European countries for in-58 stance occurs in parallel with exceptionally blue skies and new extremes in surface ir-59 radiance (van Heerwaarden et al., submitted). 60

The emission reductions due to the COVID-19 pandemic are thought to potentially influence climate (e.g., Forster et al., 2020a), but the emission reductions are not considered in the contemporary climate simulations of the Coupled Model Intercomparison Project phase 6 (CMIP6, Eyring et al., 2016), used for assessing climate changes by the Intergovernmental Panel on Climate Change (IPCC). The construction of the CMIP6 scenarios of anthropogenic emissions has therefore been revisited (Forster et al., 2020b).



Figure 1. Observed anomaly in aerosol optical depth for northern hemisphere spring 2020. Shown is the anomaly in the aerosol optical depth (τ') at 550 nm for March–May 2020 against the climatology of the same months for 2000–2020 from MODIS.

Based on the new emission data, the scientific community plans to investigate the co-67 occurrence of climate anomalies and the COVID-19 impacts on global air quality. To this 68 end, a new climate model inter-comparision project for 2015–2050 with the revised emis-69 sion scenarios is planned (COVID-MIP Lamboll, et al., in prep.) under the umbrella of 70 the Detection and Attribution Model Intercomparison Project (DAMIP, Gillett et al., 71 n.d.) endorsed by CMIP6. Some of the participating models use the simple plumes aerosol 72 parameterization MACv2-SP (Fiedler et al., 2017; Stevens et al., 2017) and therefore need 73 new MACv2-SP input data consistent with the new emission data to participate in COVID-74 MIP. We here derive these new input data for MACv2-SP and provide it for use in cli-75 mate studies. 76

The aim of the present study is to give a first estimate of the impact of the COVID-77 19 pandemic on the radiative forcing of anthropogenic aerosols for the pandemic year 78 2020 and the recovery scenarios from 2020 to 2050. We further derive and describe the 79 new MACv2-SP data for the anthropogenic aerosol optical properties and an associated 80 effect on clouds for 2015–2050 from the revised aerosol emissions (Forster et al., 2020b). 81 These emission data cover different recovery pathways after the pandemic ranging from 82 fossil-fuel based to green developments into the future. We use the here newly constructed 83 MACv2-SP data in the CMIP6 model EC-Earth3 (Doescher, et al., in prep.), which uses 84 MACv2-SP as standard to represent anthropogenic aerosols. EC-Earth3 simulates aerosol-85 radiation and aerosol-cloud interactions including cloud adjustments from MACv2-SP. We perform new atmosphere-only experiments with EC-Earth3 and estimate the effec-87 tive radiative forcing (ERF) of the anthropogenic aerosols in 2020 and 2050 for both the 88 top of the atmosphere and the surface. Details of our methods are given in Section 2, 89 followed by our results in Section 3, and our conclusions in Section 4. 90

91 2 Methods

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2.1 Emissions of SO₂ and NH₃

Forster et al. (2020b) developed five scenarios to explore the impact of the COVID-19 pandemic on current and future emissions. These scenarios are:

• A baseline scenario (*base*) without any impact of the COVID-19 pandemic and the measures to contain it;



Figure 2. MACv2-SP τ_a in 2050. Shown is the annual mean in anthropogenic aerosol optical depth (τ_a) at 550 nm for the (a) fossil-fuel based, (b) moderate green, and (c) strong green scenario. Orange symbols mark the centers of the aerosol plumes associated with industrial pollution (circles) and emissions from both industry and biomass burning (rectangles).

97	• A two-year-blip scenario (blp) that assumes emissions return to the baseline sce-
98	nario after a two-year reduction in emissions due to temporary societal lockdowns
99	and disruptions;
100	• A fossil-fuel recovery scenario (ff) that assumes the recovery from the COVID-
101	19 economic downturn preferentially supports polluting fossil-fuel-based economic
102	sectors;
103	• A moderate and strong green recovery scenario (called <i>mg</i> and <i>sg</i> , respectively)
104	that assume different levels of preferential stimulus of green sectors during the re-
105	covery from COVID-19 (e.g., see Andrijevic et al. (2020)) that would lead to lim-
106	iting global mean temperature increase relative to preindustrial levels to well be-
107	low $2^{\circ}C$ and to $1.5^{\circ}C$, respectively (Forster et al., 2020b).

The near-term evolution of SO₂ and NH₃ during the COVID-19 lockdown period uses 108 the activity scaling method of (Forster et al., 2020b). For the extensions beyond the COVID-109 19 lockdown period and until 2050, the large-scale global relationships between green-110 house gases, aerosols and aerosol precursors as found in detailed emissions scenarios de-111 rived with integrated assessment models were used (Lamboll et al., 2020). Emissions evo-112 lutions of SO_2 and NH_3 compatible with each of the above scenario have been estimated, 113 based on the relationships found in the scenario ensemble compiled and assessed as part 114 of the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Global 115 Warming of $1.5^{\circ}C$ (Rogelj et al., 2018; Huppmann et al., 2018). 116

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2.2 Anthropogenic aerosol parameterization

We use the emissions of SO_2 and NH_3 from Forster et al. (2020b) to create the new 118 input data for the novel simple-plumes parameterization MACv2-SP (Fiedler et al., 2017; 119 Stevens et al., 2017) in use for representing anthropogenic aerosol effects in climate mod-120 els of CMIP6 je.g., Mauritsen2019. MACv2-SP prescribes month-to-month and year-to-121 year changes of the three dimensional fields of anthropogenic aerosol optical properties 122 and associated effects on clouds. Temporal changes from 1850 to 2100 have been derived 123 by scaling the anthropogenic aerosol optical depth of 2005 with the CMIP6 emission amounts 124 of SO₂ and NH₃ (Stevens et al., 2017; Fiedler et al., 2019b). This scaling did not account 125 for the effect of the pandemic on anthropogenic emissions. We therefore create here new 126 MACv2-SP input data, based on the new emission data sets for 2015–2050, which ac-127 count for the COVID-19 pandemic and four recovery scenarios (Forster et al., 2020b). 128

For creating the new MACv2-SP data, we scale the anthropogenic aerosol optical depth and the effect on clouds from 2005 to other years by multiplying scaling factors



Figure 3. Example of the scaling factors for the aerosol optical depth in the centre of the aerosol plumes for two scenarios. Shown are the annual scaling factors for the color-coded plumes calculated from the (a) baseline and (b) two-year-blip emission data for the years provided in the data. The pandemic period 2019–2023 is marked with grey shading.

in the centre of the plumes, marked in Figure 2a. Mathematical functions in MACv2SP use the values in the plume centers to create the three dimensional distribution of
the aerosol extinction. As an example, Figure 2 shows the maps of the mid-visible anthropogenic aerosol optical depth in 2050 from MACv2-SP for three scenarios that we
derive here. Technically, we create annual scaling factors for each plume center and each
year to be represented in MACv2-SP. A comprehensive technical description of MACv2SP is given by Stevens et al. (2017).

Our method for constructing the scaling factors for MACv2-SP is similar to the method for the CMIP6 scenarios (Fiedler et al., 2019b). The anthropogenic aerosol optical depth τ_i in each plume center i = 1, ..., 9 is scaled with the emission scaling factor E_i for the years t with:

$$\tau_i(t) = E_i(t)\tau_i(2005) \tag{1}$$

We use $\tau_i(2005)$ at 550 nm from Stevens et al. (2017). The scaling factors $E_i(t)$ are constructed from the anthropogenic emission ϵ_{ik} of the species k. These are the gridded emission data for SO₂ and NH₃ from the emission data version 4 (Forster et al., 2020b). The calculation of $E_i(t)$ follows Fiedler et al. (2019a):

$$E_i(t) = \frac{\sum_{k=1,2} w_k[\epsilon_{ik}(t) - \epsilon_{ik}(1850)]}{\sum_{k=1,2} w_k[\epsilon_{ik}(2005) - \epsilon_{ik}(1850)]}$$
(2)

The emissions of 1850 and 2005 are taken from the CMIP6 historical emission data. We 146 consider emissions from all anthropogenic sectors provided by Forster et al. (2020b), and 147 include open burning emissions from the CMIP6 scenario SSP2-45. SSP2-45 is the base-148 line for the experiments to be carried out in COVID-MIP (Lamboll, et al., in prep.). The 149 anthropogenic emissions ϵ_{ik} are integrated values over the 10x10 grid boxes surround-150 ing the plume center. The weights w_k for the two species are $w_1 = 0.645$ for SO₂ and 151 $w_2 = 0.355$ for NH₃, representing the forcing ratio of sulphate against ammonia for present 152 day (Stevens et al., 2017). 153

Figure 3 shows examples of the scaling factors for each of the nine aerosol plume centers *i*. Contrasting the baseline against the two-year-blip data illustrates the reduction of E_i for 2020–2021. The reduction for E_i is particularly strong for the plumes over India and South America. Comparably smaller changes are seen in areas where the an thropogenic aerosol burden has been relatively small in the past decade, i.e., Europe and
 North America, and where biomass burning contributes more to the aerosol burden than
 other anthropogenic sources, namely in the African plumes.

MACv2-SP typically uses one $E_i(t)$ per decade with linear interpolation in between. 161 This is the same here, except that we also construct the scaling factors for the individ-162 ual years around 2020 for consistency with the COVID-19 emission data. We note that 163 the observed small-scale structures in the aerosol burden, e.g., like in local observations, 164 cannot be created with MACv2-SP owing to the design and purpose of this parameter-165 ization (Stevens et al., 2017). As such results from using these individual years in later 166 studies should be interpreted as estimates for the large-scale influence and not as local 167 constraints of the forcing for individual years. 168

Aerosol absorption is prescribed with the single scattering albedo of $\omega_0 = 0.93$ for industrial plumes and $\omega_0 = 0.87$ for plumes additionally affected by biomass burning, marked in Figure 2a. The asymmetry parameter, $\gamma = 0.63$, is constant. MACv2-SP uses the Angstrom exponent $\alpha = 2$ to interpolate the aerosol optical properties for different wavelengths.

Additionally to the aerosol optical properties, MACv2-SP prescribes aerosol effects on the cloud droplet number concentrations N. The latter is induced with the prefactor η_N to be multiplied with N in the host model:

$$\eta_N = 1 + \frac{dN}{N} = \frac{\ln[1000(\tau_a(\phi, \lambda, t) + \tau_b(\phi, \lambda, t)) + 1]}{\ln[1000\tau_b(\phi, \lambda, t) + 1]}$$
(3)

The background aerosol optical depth (τ_b) is a simplified representation that follows the plume structure for τ_a to parameterize the aerosol effect on clouds. Host models can multiply η_N with N in the radiation transfer calculation to induce a Twomey effect only, e.g., in MPI-ESM1.2, or in the cloud microphysics to allow further rapid adjustments of clouds, e.g., in EC-Earth3. Additional documentation of MACv2-SP and details on the application in climate studies is given elsewhere (e.g., Fiedler et al., 2017; Stevens et al., 2017; Fiedler et al., 2019a).

The new MACv2-SP input data are provided as supplementary material for use in climate studies, e.g., in COVID-MIP (Lamboll, et al., in prep.). It covers the baseline and scenarios that assume recoveries after COVID-19 that intensify the use of fossil fuels, follow a moderate or strong green pathway, and return to a business as usual pathway after the assumed two-year interruption by the pandemic in 2020 and 2021.

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2.3 Model experiment strategy

We estimate the ERF of the anthropogenic aerosol reduction in 2020 and the ERF 190 spread associated with the recovery scenarios in 2050 from the new data. To this end, 191 we perform atmosphere-only simulations with EC-Earth3 and compute the ERF of the 192 anthropogenic aerosols at the top of the atmosphere and the surface, i.e., the instanta-193 neous radiative effects plus the rapid adjustments in the atmosphere. EC-Earth3 is an 194 Earth system model participating in CMIP6. It is based on the atmosphere and land-195 surface model from ECMWF's IFS cycle 36r4, and the ocean and sea-ice model NEMO 196 version 3.6. The implementation of MACv2-SP in EC-Earth3 (Doescher, et al., in prep.) 197 is such that the model accounts for aerosol-radiation interactions and aerosol-cloud in-198 teractions, including aerosol albedo and cloud lifetime effects (Fiedler et al., 2019a). 199

Our simulations use annually repeating aerosol optical properties and associated effects on clouds for the years 2020 and 2050. We run experiment with the setups:

Table 1. Global means from the new MACv2-SP data and EC-Earth3 experiments. Shown are the ERF at the top of the atmosphere (ERF_{TOA}) and at the surface (ERF_{SFC}) calculated against pi as the mean \pm 95% confidence interval. (*) marks differences to the baseline that are statistically significant at the 95% level.

Experiment	$\overline{\tau_a}$	$\overline{\eta_N}$	$ERF_{TOA} \; [\mathrm{Wm}^{-2}]$	ERF_{SFC} [Wm ⁻²]
2020-base 2020-blp	$0.021 \\ 0.019$	$1.060 \\ 1.056$	$\begin{array}{c} -0.661 \pm 0.087 \\ -0.622 \pm 0.072 \end{array}$	$\begin{array}{c} -1.449 \pm 0.047 \\ -1.338 \pm 0.038 \ (*) \end{array}$
2050-base 2050-ff 2050-mg 2050-sg	$\begin{array}{c} 0.019 \\ 0.020 \\ 0.012 \\ 0.014 \end{array}$	$1.054 \\ 1.057 \\ 1.038 \\ 1.040$	$\begin{array}{l} -0.631 \pm 0.068 \\ -0.675 \pm 0.081 \\ -0.382 \pm 0.080 \ (*) \\ -0.461 \pm 0.069 \ (*) \end{array}$	$\begin{array}{c} -1.324 \pm 0.035 \\ -1.409 \pm 0.041 \ (*) \\ -0.875 \pm 0.036 \ (*) \\ -0.987 \pm 0.039 \ (*) \end{array}$

202	• base: new MACv2-SP properties from the baseline for the year 2020 (2020-base)	
203	and $2050 (2050-base)$.	
204	• 2020-blp: new MACv2-SP properties from the two-year-blip for 2020,	
205	• 2050: new MACv2-SP properties for 2050 from the recovery scenarios that are	
206	either primarily fossil-fuel based $(2050-ff)$, moderate $(2050-mg)$ or strong green	
207	(2050-sg), and	
208	• pi : without anthropogenic aerosol effects for calculating the ERF in 2020 and 205	50
209	relative to the pre-industrial.	

The setup of the experiments follows Wyser et al. (2020) and is identical except for the 210 listed changes in the anthropogenic aerosols. We use a pre-industrial experiment setup, 211 as typical for radiative forcing calculations from contemporary climate model experiments 212 (Pincus et al., 2016; Fiedler et al., 2019a; Smith et al., 2020). This means we prescribe 213 annually repeating pre-industrial boundary conditions in atmosphere-only experiments 214 like for a *piClim-control* experiment in the Radiative Forcing Model Inter-comparison 215 project (RFMIP, Pincus et al., 2016), i.e., a monthly climatology for sea-surface tem-216 peratures and sea ice derived from the model's pre-industrial control experiments for CMIP6. 217 All simulations are run for 55 years. The first 5 simulation years are discarded in our anal-218 yses. We compute 50-year averages for ERF to eliminate the impact of natural year-to-219 year variability on the estimate (Fiedler et al., 2019a). 220

221 3 Results

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3.1 Annual means of τ_a and η_N

We show the global annual means of the anthropogenic aerosol optical depth $(\overline{\tau_a})$ 223 and the prefactor for inducing aerosol effects on clouds $(\overline{\eta_N})$ in Figure 4. Both $\overline{\tau_a}$ and 224 $\overline{\eta_N}$ clearly reduce during the pandemic, e.g., by 0.002 for 2020 compared to the baseline 225 and by 0.005 compared to 2005. These translate to a reduction by about 10% and 25%226 for the global $\overline{\tau_a}$ in 2020 and 2050. The associated effect on $\overline{\eta_N}$ is consistent with the 227 change in $\overline{\tau_a}$, with a reduction of $\overline{\eta_N}$ by 0.004 compared to baseline and 0.017 compared 228 to 2005, i.e., a global reduction in η_N by about 0.5–1%. All data sets have the same emis-229 sions for 2015–2023, except the baseline. Hence results from MACv2-SP other than the 230 baseline are identical with the two-year-blip results for this period (Figure 4 and Table 231 1).232



Figure 4. MACv2-SP τ_a in 2015–2050. Shown are the global annual means in (a) the anthropogenic aerosol optical depth (τ_a) at 550 nm and (b) the scaling factor the cloud droplet number concentration (η_N) for the scenarios. The pandemic period 2019–2023 is marked with grey shading. The baseline and two-year blip scenario overlap for 2030–2050. All scenarios except baseline overlap for 2015–2030. The 2005 value from the historical scaling is marked as horizontal line.

The post-pandemic recovery of τ_a and η_N strongly depends on the scenario. The 233 $\overline{\tau_a}$ in 2030 is close to the value in 2005 in the baseline and two-year-blip scenario, larger 234 in the fossil fuel scenario, and substantially smaller for both green scenarios (Figure 4). 235 By 2050 all scenarios point to a decrease of $\overline{\tau_a}$ relative to 2005, with the strongest re-236 duction in the moderate green not the strong green scenario. This might be counter in-237 tuitive since a stronger green scenario might suggest cleaner air. The smaller $\overline{\tau_a}$ in the 238 moderate green scenario is due to the lower emissions of NH₃ compared to the strong 239 green by about -3.5×10^{-6} kg m⁻² s⁻¹ in 2050, integrated over the globe and sectors. Al-240 though the emissions of SO_2 are smaller in the strong green scenario, the total effect of 241 NH₃ and SO₂ on the scaling factor E_i (Section 2) leads to a slightly larger $\overline{\tau_a}$ in the strong 242 green scenarios. 243

The assumption of larger NH_3 emissions in the strong green recovery scenario com-244 pared to the moderate green recovery scenario is the result of changes in the structure 245 of the economy in low emissions scenarios, particularly related to agricultural practice 246 and energy provision. Stringent emissions scenarios to an increasing degree rely on more 247 efficient food and biomass production to support a growing world population while gen-248 erating low-carbon energy and enable possibilities of carbon-dioxide sequestration (Popp 249 et al., 2017). The fertilizer use required to achieve this results in an increase in NH_3 emis-250 sions. Furthermore, stringent climate change mitigation scenarios often rely on very high 251 shares of renewable energy, which have intermittent power generation properties and thus 252 require energy storage technologies to bridge gaps in supply. One energy storage tech-253 nology that can store energy across seasons and even multiple years is associated with 254 NH_3 emissions (Society, 2020). The projected increased use of ammonia, as a fuel and 255 for energy storage, results in larger projected emissions of NH_3 due to leakage and due 256 to imperfect transport or storage. Slightly higher NH_3 emissions in the strong green (sg)257 than the moderate (mq) recovery scenarios are hence consistent with the general under-258 standing of the technologies and practices that would be required for a transformation 259 to a strongly decarbonized society. 260



Figure 5. Hemispheric asymmetry for τ_a . Shown is the hemispheric asymmetry (A) as function of the sinus of the geographical latitude for (a) 2030 and (b) 2050 for all scenarios. Baseline and two-year blip are identical for these years. We mark the values of the two-year blip scenario in 2020 as a reference.

$_{261}$ 3.2 Hemispheric asymmetry in au_a

The spatial distribution of τ_a , measured by the hemispheric asymmetry, is qualitatively similar across the scenarios, but the magnitudes differ. Figure 5 illustrates the hemispheric asymmetry A:

$$A = \frac{\overline{\tau_a(\phi)} - \overline{\tau_a(-\phi)}}{2} \tag{4}$$

using the zonal averages $\tau_a(\phi)$ at the same geographical latitudes on the northern (ϕ) and southern hemisphere $(-\phi)$. All scenarios have larger A in the tropics and sub-tropics than further poleward (Fig. 5), consistent with the CMIP6 scenarios (Fiedler et al., 2019a). For 2030, the fossil fuel and baseline scenarios have substantially higher A than for 2020. In the middle of the 21st century, A in the fossil fuel and baseline scenarios are more similar to each other and close to A from 2020.

The temporal behaviour for A in the green scenarios is opposite to the fossil-fuel dominated scenarios, i.e., they are close to A from 2020 in 2030 and differ in 2050. Both green scenarios in 2030 have particularly similar A to 2020 in the tropics and slightly larger differences poleward. In 2050, the green scenarios are still similar to each other, but have overall smaller A compared to 2020, e.g., a reduction by 50% in the maximum around $\phi = 24^{\circ}$. This reflects the decrease in τ_a due to improved air quality in a green recovery (compare Fig. 4).

3.3 Seasonal cycle in τ_a

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The month-to-month changes in τ_a from MACv2-SP is dominated by the biomass burning seasons. These lead to tropical maxima in τ_a between July and October and November and February (Fig. 6a–b). From the sub-tropics to the poles, the seasonal cycle in the scenarios slightly differ from the baseline for 2020. Note here again that all data sets are identical with the two-year-blip in 2020, except the baseline. Overall, the seasonal and zonal patterns are very similar, e.g., seen with the weighting by the global τ_a (Fig. 6c–d) with only marginal changes as we go towards 2050 (not shown).

In 2050, the overall seasonal pattern in τ_a remains qualitatively similar, but the magnitudes strongly depend on the scenario. The green scenarios show the largest re-



Figure 6. MACv2-SP τ_a patterns in 2020. Shown are the annual cycles of the anthropogenic aerosol optical depth (τ_a) at 550 nm as (top) zonal means and (bottom) zonal means weighted by $\overline{\tau_a}$ for the (left) baseline, and (right) two-year-blip scenario.



Figure 7. MACv2-SP τ_a patterns in 2050. Shown is the annual cycles of the anthropogenic aerosol optical depth (τ_a) at 550 nm as (a) zonal mean for the baseline, and (b–c) difference of the green scenarios relative to baseline for 2050.

ductions in τ_a that are primarily projected in the northern hemisphere equatorward of 50°N. Here, the strongest reductions occur between June and October in the moderate green scenario. Again the stronger reduction in τ_a in the moderate than the strong green scenario is associated with the larger emissions of NH₃ in the strong green recovery leading to larger τ_a than for the moderate green scenario.

²⁹³ 3.4 Global radiative forcing

We calculate the global ERF of anthropogenic aerosols from our experiments with 294 the new MACv2-SP data at the top of the atmosphere and at the surface, ERF_{TOA} and 295 ERF_{SFC} . For 2020, the impact of the reduction in anthropogenic aerosols compared to 296 the baseline is a less negative ERF_{TOA} by about $+0.04 \,\mathrm{Wm^{-2}}$ (Table 1). This reduc-297 tion is small compared to the the year-to-year variability in the model, reflected by the 298 confidence intervals about the mean of $\pm 0.07 \,\mathrm{Wm^{-2}}$ to $\pm 0.09 \,\mathrm{Wm^{-2}}$ across our ensem-299 ble of model simulations. Again these estimates are based on fifty years of simulations 300 with annually repeating aerosol patterns. It will therefore be difficult to disentangle any 301 differences in the TOA radiation budget due to reductions in aerosols during the pan-302 demic from differences arising due to natural variability in both observations and small 303 ensembles of simulations. We identify a larger and statistically significant difference in 304 ERF_{SFC} associated with the aerosol reduction during the pandemic compared to the 305 baseline of the order of $0.1 \,\mathrm{Wm^{-2}}$ (Table 1). This implies that radiation observations 306 at the surface and sufficiently many model estimates for ERF_{SFC} can be more informa-307 tive for quantifying the influence of the pandemic on the global radiation and energy bud-308 get than estimates for the TOA. 309

The spread in ERF_{TOA} of anthropogenic aerosols due to the different scenarios for 310 $2050 \text{ is } -0.68 \text{ Wm}^{-2}$ to -0.38 Wm^{-2} (Table 1). Compared to the baseline, these are dif-311 ferences of +0.05 to -0.25 Wm⁻². The least negative ERF_{TOA} occurs for the moderate 312 green scenario, consistent with the lowest τ_a across the MACv2-SP data associated with 313 the lower NH₃ emissions than in the strong green scenario. We obtain ERF_{TOA} of the 314 anthropogenic aerosols for the green scenarios that are statistically significant different 315 compared to the baseline. Baseline and the fossil-fuel based scenarios, however, yield very 316 similar ERF_{TOA} for 2050, consistent with small differences in $\overline{\tau_a}$ and $\overline{\eta_N}$ for the two sce-317 narios (Figure 8a). The ERF_{SFC} for 2050 is more negative than ERF_{TOA} (Figure 8b) 318 and has a smaller 95% confidence interval of about $\pm 0.04 \,\mathrm{Wm^{-2}}$ compared to ERF_{TOA} . 319 We therefore find for all scenarios a statistically significant difference in ERF_{SFC} rel-320 ative to 2050-base (Table 1). 321



Figure 8. Probability density function for the global mean ERF in 2050. Shown are the occurrence frequency of annual mean ERF at (a) the top of the atmosphere (TOA) and (b) the surface (SFC) for the color-coded scenarios in 2050. ERF is calculated from 50 years of data from our EC-Earth3 experiments with anthropogenic aerosols (2050-base, 2050-ff, 2050-mg, 2050-sg) against the pre-industrial control experiment (pi).

322

3.5 Pattern of radiative effects

We assess the spatial distribution of the radiative effects associated with the anthropogenic aerosols. To this end, we calculate the effective radiative effects in all-sky (F_{all}), clear-sky (F_{clr}), and cloudy-sky (F_{cld}) using the relationship:

$$F_{all} = (1-f)F_{clr} + fF_{cld},\tag{5}$$

with the total cloud cover (f). Figure 9 and 10 show the results for the top of the atmosphere (TOA) and at the surface.

For 2020, we find some evidence for regionally significant differences in the radia-328 tive effects at TOA associated with anthropogenic aerosol reductions due to the pandemic, 329 but the spatial extent of these regions is typically small in F_{all} (Figure 9). This is pri-330 marily explained by the strong variability of clouds, leading to only limited areas offshore 331 of major pollution with a significant increase in F_{cld} , hence a less negative (weaker) F_{cld} 332 due to the pandemic. The signal for F_{clr} at TOA is more distinct, and indicates less neg-333 ative radiative effects over larger regions, e.g., offshore of typically polluted regions in 334 Asia. At the surface, the regional differences in the described radiative effects are more 335 pronounced and spatially further extended, covering large parts in Southeast Asia and 336 East Asia both over land and ocean. Surface measurements in these regions could po-337 tentially help to constrain the aerosol effects on climate. Much of the radiative effects 338 occur over oceans, where the measurement network is typically sparse. Efforts to col-339 lect necessary observations during this unique situation could involve sun photometer 340 measurements aboard research vessels as part of the Maritime Aerosol Network (e.g., Smirnov 341 et al., 2009) and in-situ measurements aboard aircrafts based on existing expertises (e.g., 342 Zuidema et al., 2016). 343



Figure 9. Differences in effective radiative effects due to the pandemic in 2020. Shown are differences between 2020-blp and 2020-base for the effective radiative effects in (left) all-sky (F_{all}), (middle) clear-sky (F_{clr}) and (right) cloudy-sky (F_{cld}) at (top) the top of the atmosphere and (bottom) the surface. Black dots mark regions where the differences are statistically significant at the 95% confidence level.



Figure 10. As Fig. 9 but for the differences between the moderate green (2050-mg) against the baseline (2050-base) scenario in 2050.

The scenario differences in F_{all} at TOA for 2050 are largest in South, Southeast 344 and East Asia (Figure 10). Here, F_{clr} shows significant differences with less negative ra-345 diative effects in the moderate green scenario compared to the baseline by up to $3 \,\mathrm{Wm^{-2}}$. 346 The pattern of F_{cld} is again more inhomogeneous than F_{clr} . The overall pattern for F_{all} 347 differences at the surface is again qualitatively similar, but the magnitude and spatial 348 extent are larger. Based on these results, significant scenario differences for the radia-349 tive effects associated with anthropogenic aerosols are primarily confined to the trop-350 ics and sub-tropics close to hotspots for industrial activity at present. 351

352 4 Conclusion

We show the anthropogenic aerosol optical properties and the associated effect on clouds based on the new COVID-19 emission data. Our results point to a reduction in the global anthropogenic aerosol optical depth by 10% due to the pandemic compared to the baseline. Scenarios for the post-pandemic recovery indicate a continuous increase in aerosols until 2030 in half of the scenarios and a general decrease for 2030—2050. The spread in the anthropogenic aerosol optical depth in 2050 is 0.012 to 0.02, which is lower than in 2005. These values fall within the lower end of the spread in 2050 obtained from the original CMIP6 aerosol scenarios (Fiedler et al., 2019b).

First estimates of the effective radiative forcing (ERF) associated with the new an-361 thropogenic aerosols are calculated from several hundred years of atmosphere-only sim-362 ulations with EC-Earth3. The results highlight a weaker (less negative) aerosol ERF of 363 the order of 10% during the pandemic relative to the baseline. Such small ERF differ-364 ences require long averaging, hence our 50 years of simulations for each aerosol pattern 365 assessed here. The small change in aerosol ERF for the time of the pandemic is not ex-366 pected to induce a global climate response that is clearly detectable in light of model-367 internal variability. Even regional radiative effects are rather difficult to detect at the 368 top of the atmosphere. We find, however, more significant effective radiative effects at 369 the surface in regions typically more strongly polluted by aerosols. Any attempt to use 370 the pandemic period to constraint aerosol effects should therefore focus on areas in South 371 and East Asia, primarily focusing on effects at the surface. This may involve station ob-372 servations, but our experiments suggest that much of the aerosol signal is expected off-373 shore of land with major pollution in the past decades. We therefore propose to also use 374 other measurements, e.g., from sun photometers aboard research vessels or in-situ in-375 struments aboard aircrafts. Measurements outside of clouds might be particularly ben-376 eficial, although much research focuses on aerosol-cloud interactions. Our model results 377 indeed suggest that there are better chances to obtain a signal in clear sky conditions 378 at the surface rather than in cloudy and all sky. We mostly find poor prospects to mea-379 sure a meaningful regional effect on clouds due to the strong influence of natural vari-380 ability. 381

For 2050, we obtain an ERF spread of -0.68 to -0.38 Wm⁻², which is smaller than 382 the ERF from the same model for 2005 and 1975 (Fiedler et al., 2019a). These ERF es-383 timates for 2050 fall within the ERF spread for 2095 associated with the emission path-384 ways from CMIP6 and uncertainty in aerosol-cloud interactions (Fiedler et al., 2019b). 385 Interestingly, the stronger green scenario does not yield the smallest anthropogenic aerosol 386 optical depth and least negative forcing, but the moderate green recovery does. This is 387 associated with a relative increase in NH_3 emissions due to intense land-use paired with 388 an energy system primarily relying on renewable sources. Such a pathway implies a slightly 389 stronger warming due to weaker aerosol cooling in the strong green than the moderate 390 green scenario. We expect, however, a stronger reduction in greenhouse gas emissions 391 in the strong green pathway. Taken together the anthropogenic warming in the strong 392 green scenario is therefore expected to be the weakest. Regionally, our simulations sug-393 gest the largest differences in the aerosol radiative effects across sub-tropical and trop-394 ical regions. 395

Our global ERF estimates for the anthropogenic aerosols fall within the plausible 396 range of the present-day aerosol ERF (Bellouin et al., 2020) underlining the still large 397 uncertainty in our understanding of aerosol effects compared to our ability to estimate 398 a change in ERF from different emission pathways from a complex model. We expect 399 that models participating in COVID-MIP will show diversity in their aerosol ERF ow-400 ing to model-internal variability and model biases, even when they use the same emis-401 sions or MACv2-SP data (e.g., Fiedler et al., 2019a; Smith et al., 2020). Reasons for the 402 model diversity in aerosol ERF include not only uncertainties in the aerosol parameter-403 izations, but also the ability of the host model to accurately simulate important processes 404 influencing the aerosol life cycle and therefore ERF, e.g., the parameterization of clouds 405 and the representation of circulation. Future research should therefore also address the 406 relative contributions from host model biases to the model diversity in ERF, e.g., using 407

simulations performed in the framework of the Radiative Forcing Model Inter-comparison
 Project (RFMIP, Pincus et al., 2016) endorsed by CMIP6.

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