

1 **Stronger Response to the Aerosol Indirect Effect due to**  
2 **Cooling in Remote Regions**

3 **Linnea Huusko<sup>1</sup>, Angshuman Modak<sup>1</sup>, Thorsten Mauritsen<sup>1</sup>**

4 <sup>1</sup>Department of Meteorology, Stockholm University, Stockholm, Sweden

5 **Key Points:**

- 6 • The forcing efficacy from an enhanced aerosol indirect effect is larger than unity  
7 • The aerosol indirect effect induces remote cooling at mid- to high latitudes, in contrast  
8 to the local cooling from the direct effect  
9 • The different spatial patterns of temperature change from the aerosol direct and  
10 indirect effects excite different feedbacks

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Corresponding author: Linnea Huusko, [linnea.huusko@misu.su.se](mailto:linnea.huusko@misu.su.se)

## 11 **Abstract**

12 It is often assumed that effective radiative forcings, regardless of forcing agent, are addi-  
13 tive in the temperature change. Using climate model simulations with abruptly applied  
14 aerosol forcing we find that the temperature response per unit forcing is larger if induced  
15 by aerosol-cloud interactions than directly by aerosols. The spatial patterns of forcing and  
16 temperature change show that aerosol-cloud interactions induce cooling over remote oceans  
17 in the extratropics, whereas the effect of increased emissions is localized around the emis-  
18 sion sources primarily over tropical land. The results are consistent with ideas of how the  
19 patterns of sea surface temperature impact radiative feedbacks, and a large forcing efficacy  
20 of aerosol-cloud interactions could help explain previously observed intermodel spread in  
21 the response to aerosols.

## 22 **Plain Language Summary**

23 Aerosols, small particles suspended in the atmosphere, emitted by humans tend to cool  
24 the climate. They do this directly by reflecting incoming sunlight, and indirectly by affecting  
25 cloud properties foremost such that clouds reflect more sunlight. Here, we investigate how  
26 the global surface air temperature responds to changes in the two types of aerosol interaction  
27 with solar radiation. We find that the cloud effect causes a relatively larger global mean  
28 temperature change than the direct effect of the aerosol particles. Interactions between  
29 aerosols and clouds are difficult to represent in climate models and are sometimes excluded  
30 entirely. Our results highlight the importance of including the cloud effect to get an accurate  
31 representation of the Earth's climate.

## 32 **1 Introduction**

33 The state of the climate system is determined by the radiative balance at the top of the  
34 atmosphere: a positive imbalance causes warming of the system, and vice versa. The largest  
35 contributor of uncertainty to the total imbalance is the radiative effect from anthropogenic  
36 aerosols, particularly from aerosol-cloud interactions (Forster et al., 2021). When studying  
37 the temperature response to an applied radiative forcing a linear energy balance framework  
38 is often used, where the global mean top of atmosphere (TOA) radiative imbalance,  $N$ ,  
39 is a function of an external effective radiative forcing,  $F$ , and the resulting surface air  
40 temperature change,  $\Delta T$  (relative to an unforced reference state), according to

$$N = F + \lambda \Delta T, \quad (1)$$

where  $\lambda$  is a feedback parameter (Gregory et al., 2004). It is usually assumed that the feedback parameter,  $\lambda$ , is universal, such that the individual effective radiative forcings that make up  $F$  can be added linearly without scaling. This assumption is used by the Intergovernmental Panel of Climate Change (IPCC) in their Sixth Assessment Report (AR6) (Forster et al., 2021), among other things to make projections of global warming in the 21st Century.

It has, however, been shown that in global climate models the temperature response per unit forcing varies depending on the type of forcing, both in idealized scenarios with abruptly applied forcing (e.g., Hansen et al., 2005; Modak et al., 2016, 2018; Modak & Bala, 2019; Richardson et al., 2019; Shindell et al., 2015) and in transient scenarios (e.g., Zhao et al., 2019). The concept of *forcing efficacy* has been introduced to account for these differences in the temperature response (Hansen et al., 2005). Several studies have argued that the intermodel variation in the efficacy of different forcing agents likely causes discrepancies in estimates of the equilibrium climate sensitivity (ECS), defined as the equilibrium temperature response to doubled CO<sub>2</sub> concentration over preindustrial levels, between model based estimates and constraints from observational data (Kummer & Dessler, 2014; Marvel et al., 2016; Richardson et al., 2019). These studies have highlighted the importance of including forcing efficacy in the linear energy balance framework.

Forcing efficacy can be incorporated into the linear framework as a factor  $E$ , using CO<sub>2</sub> as a reference:

$$E = \frac{\lambda_{2 \times CO_2}}{\lambda}, \quad (2)$$

where  $\lambda_{2 \times CO_2}$  is the feedback parameter in a simulation with abruptly doubled atmospheric CO<sub>2</sub> concentration. Under the assumption of a time-invariant  $\lambda$  the efficacy can be approximated as

$$E = \frac{\Delta T / F}{\Delta T_{2 \times CO_2} / F_{2 \times CO_2}}, \quad (3)$$

where  $\Delta T$  and  $F$  are defined as in equation (1), and  $\Delta T_{2 \times CO_2}$  and  $F_{2 \times CO_2}$  are the corresponding quantities under a doubling of the CO<sub>2</sub> concentration. This approximation is used by Richardson et al. (2019) and is adopted here.

70 The concept of forcing efficacy is not new, yet the aerosol forcing efficacy remains diffi-  
71 cult to constrain. Richardson et al. (2019) studied forcing efficacy in a set of global climate  
72 models and found a considerable spread in the response to aerosol forcing. Nevertheless, re-  
73 cent studies based on the models that participated in the sixth phase of the Coupled Model  
74 Intercomparison Project (CMIP6) show an enhanced climate response to aerosol forcing  
75 (Salvi et al., 2022; Smith & Forster, 2021). Salvi et al. (2022) suggested that the strong  
76 temperature response, compared to the corresponding response to CO<sub>2</sub> forcing, stems from  
77 the latitudinal distribution of the aerosol forcing.

78 Aerosols affect the radiative balance of the climate system both through direct inter-  
79 action with radiation (direct effect) and through aerosol-cloud interactions (indirect effect),  
80 for example by increasing the cloud reflectivity by distributing the cloud water on more  
81 abundant but smaller droplets (*Twomey effect*, Twomey, 1974). However, insight into the  
82 relative contributions from the direct and indirect effects from aerosols to the climate re-  
83 sponse are lacking in the literature. In this study, we systematically investigate the climate  
84 response to aerosol forcing by disentangling the aerosol direct and indirect effects. Using  
85 MPI-ESM1.2 we run idealized simulations with aerosol forcing applied abruptly and held  
86 constant to assess the climate response. We show that the direct effect causes local cooling  
87 and has a forcing efficacy close to unity, while an enhanced indirect effect causes a stronger  
88 global mean temperature response per unit forcing. The behavior is related to a remote  
89 response at mid- to high latitudes and consistent with ideas of how the patterns of change  
90 influence radiative feedbacks.

## 91 **2 Background: Pattern Effects**

92 How large the temperature response to an applied forcing is depends on the feedback  
93 mechanisms in the climate system. The spatial pattern of temperature change is believed to  
94 affect the feedback mechanisms that are activated following an initial change in the surface  
95 temperature and the idea of so-called pattern effects has gained much attention (e.g., Armour  
96 et al., 2013; Ceppi & Gregory, 2017; Dong et al., 2019, 2020).

97 Various explanations have been suggested for how pattern effects influence the global  
98 climate. Pierrehumbert (1995) pointed to the importance of "radiator fins" over areas  
99 with cold sea surface temperatures (SSTs), where subsidence makes the air dry and clear,  
100 in stabilizing the climate. Building on this idea, Ceppi and Gregory (2017) argued that

101 changes in tropospheric temperatures aloft govern changes in the global mean feedback  
102 parameter with time, and that this is controlled by areas with comparatively warm SSTs,  
103 such as the West Pacific warm pool region, where the tropospheric stability depends directly  
104 on the local SST. In other regions the stability depends on the SST relative to that in the  
105 warmer areas, because heat is advected from warm areas in the free troposphere, leading  
106 to temperature inversions over areas with lower SSTs. Using a Green’s function approach,  
107 Dong et al. (2019) likewise identified temperature change in the tropical West Pacific region  
108 as important for the global mean energy balance. A similar effect has been found in studies  
109 showing cooling from low clouds forming below inversions (e.g., Mauritsen, 2016; Zhou et  
110 al., 2016).

111 The mechanisms of pattern effects are typically discussed in the context of time-varying  
112 feedbacks under CO<sub>2</sub> induced warming, but local temperature change due to a localized  
113 forcing, such as from aerosols, will cause SST patterns that can be studied analogously.  
114 Studies where the climate has been forced with inhomogeneous patterns of carbon dioxide,  
115 aerosols, or SSTs suggest that the location of a radiative forcing affects the location and  
116 strength of the temperature response (e.g., Dong et al., 2020; Forster et al., 2000; Hansen et  
117 al., 1997, 2005; Modak & Bala, 2019; Persad & Caldeira, 2018; Salvi et al., 2022; Stuecker  
118 et al., 2020). Here, we investigate the patterns of forcing and the corresponding response to  
119 the aerosol direct and indirect effects.

### 120 **3 Model and Methods**

121 We have run simulations with the Max Planck Institute for Meteorology Earth System  
122 Model version 1.2 (MPI-ESM1.2). The next two sections describe the model and the pa-  
123 rameterization of the Twomey effect. The third section explains how the experiments were  
124 set up.

#### 125 **3.1 MPI-ESM1.2**

126 MPI-ESM1.2 is a state-of-the-art Earth system model (Mauritsen et al., 2019). The  
127 model was used here because it has a simple aerosol scheme (described below) and can be run  
128 at a low resolution, and still accurately simulates aerosol forcing close to the best estimate  
129 of the IPCC AR5 and a historical global warming in close agreement with observations  
130 (Mauritsen et al., 2019). We ran MPI-ESM1.2 at its lowest resolution (*coarse resolution*,

131 CR; see Mauritsen et al., 2019), as a higher resolution would limit the number of simulated  
 132 years and thus restrict the comprehensiveness of the analysis. To verify the results from  
 133 the CR model we also ran a few key experiments in the LR version, but it should be noted  
 134 that the model versions differ in more than just the resolution as some important tuning  
 135 parameters were also set differently.

### 136 **3.2 A Parameterized Twomey Effect**

137 The complexity of aerosol and cloud interactions makes their climate impact challenging  
 138 to constrain (Bellouin et al., 2020; Forster et al., 2021). In models with sophisticated  
 139 interactive aerosol modules the cloud interactions are difficult to isolate and control, whereas  
 140 in MPI-ESM1.2, which uses the simple plume implementation of the second version of the  
 141 Max Planck Institute Aerosol Climatology (MACv2-SP), this is relatively simple. In this  
 142 model the aerosol emissions are represented by nine plumes in major source regions, and  
 143 skewed Gaussian functions are used to represent the spatial distribution of aerosol optical  
 144 depth (Stevens et al., 2017). In the MACv2-SP, aerosol-cloud interactions are represented  
 145 entirely by the Twomey effect (Stevens et al., 2017; Twomey, 1974). The exclusion of other  
 146 cloud effects from anthropogenic aerosols, such as the cloud lifetime effect (Albrecht, 1989),  
 147 was based on the argument that they are too poorly understood (Fiedler et al., 2017).  
 148 However, here we enhance the Twomey effect as a proxy for representing other uncertain  
 149 indirect effects. This is reasonable in so far as cloud processes, such as rain formation, are  
 150 more susceptible to aerosols where also the Twomey effect dominates, i.e., where aerosol  
 151 concentrations are relatively low.

152 In MACv2-SP, the strength of the Twomey effect, as described by the cloud droplet  
 153 number density ( $N$ ), depends on the optical depth of both natural background aerosol ( $\tau_{bg}$ )  
 154 and anthropogenic aerosol ( $\tau_a$ ), according to

$$155 \quad \frac{N}{N_{1850}} = \frac{\ln(b_N(\tau_a + \alpha\tau_{bg}) + 1)}{\ln(b_N\alpha\tau_{bg} + 1)}, \quad (4)$$

156 where  $b_N$  is a model parameter. The scaling parameter  $\alpha$  has been introduced here to enable  
 157 altering of the assumed optical depth of the background aerosol for an enhanced Twomey  
 158 effect: a reduced background aerosol optical depth ( $\alpha < 1$ ) gives a stronger Twomey effect  
 159 than with the original formulation.

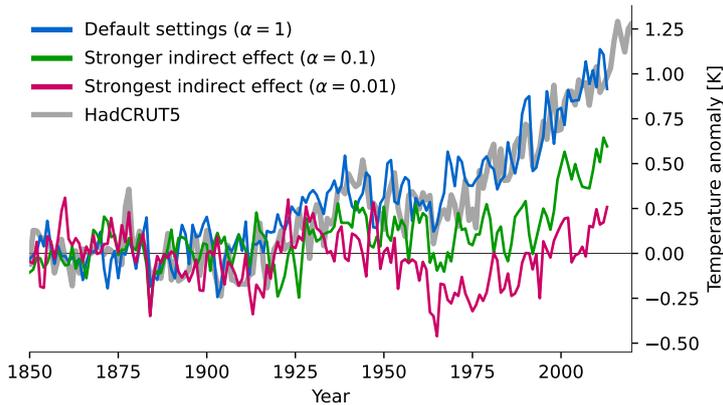
160 This simple parameterization of the Twomey effect makes it possible to adjust the  
161 strength of the aerosol-cloud interactions in MPI-ESM1.2 (Fiedler et al., 2017; Stevens et  
162 al., 2017). One could argue that a more complex aerosol module with interactive aerosols  
163 would be better for studying the climate response to aerosol-cloud interactions (e.g., Ekman,  
164 2014), but running a model with an interactive aerosol module is computationally expensive  
165 and each change would in principle require a re-tuning and a new spin-up of the model  
166 (Golaz et al., 2013). The simplicity of MACv2-SP makes it computationally lightweight  
167 and it does not require re-tuning, yet it produces an evolution of aerosol forcing in line  
168 with past estimates (Mauritsen et al., 2019). This allows us to perform a large number of  
169 simulations, enabling systematic investigation of the climate response to aerosol forcing of  
170 different strengths.

171 Figure 1 shows simulations of the historical period (1850 to present day) with MPI-  
172 ESM1.2, with standard settings and with an enhanced indirect effect. There is good  
173 agreement between the observed warming and the simulated temperature change with the  
174 standard setting, in part because the model has been tuned to the observational record  
175 (Mauritsen & Roeckner, 2020). An enhanced Twomey effect clearly gives a too cold tem-  
176 perature evolution with the present climate sensitivity; however, different combinations of  
177 aerosol cooling and climate sensitivity can be used to achieve a temperature evolution that  
178 matches the observational record (e.g., Golaz et al., 2013; Kiehl, 2007).

### 179 **3.3 Experimental Setup**

180 To analyze the climate response to aerosol forcing, idealized simulations were run with  
181 forcing applied abruptly and held constant for 150 years. The spatial pattern of aerosol  
182 emissions of year 2005 was used in all simulations, and the forcing was strengthened using a  
183 combination of enhanced aerosol-cloud interactions (enhanced indirect effect) and increased  
184 aerosol emissions (enhanced direct effect). The experiments with abruptly applied aerosol  
185 forcing are here called *abrupt-aerosol* experiments. For the increased emissions, the 2005  
186 emission levels were scaled by a common factor in all nine emission regions.

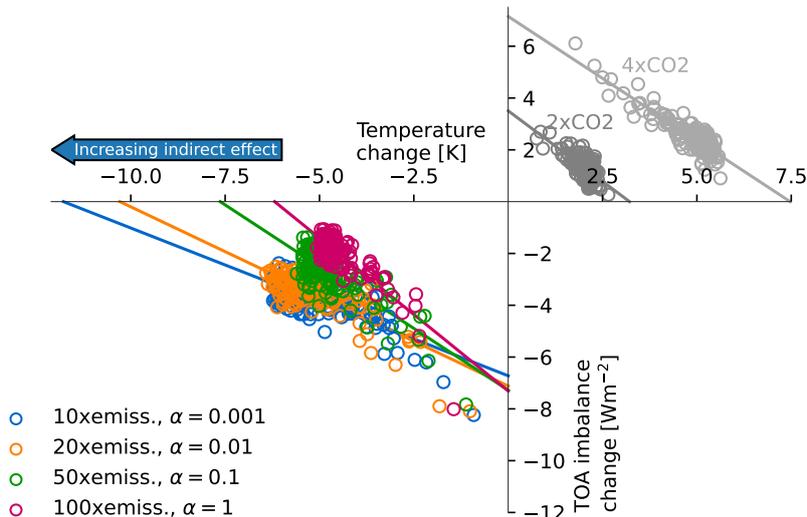
187 Most simulations were run with very strong aerosol forcing. Previous studies looking  
188 into different aspects of the forcing and climate response following the shift in the aerosol  
189 emission pattern between the 1970s and present day in MPI-ESM1.2 have found it difficult  
190 to distinguish a signal from the internal variability of the model (Fiedler et al., 2017, 2019;



**Figure 1.** Temperature change over the historical period (1850 to present day) simulated by MPI-ESM1.2, relative to the 1850-1900 mean. The blue line shows the standard settings in MPI-ESM1.2 and the green and pink lines show simulations with enhanced aerosol indirect effect (using the scaling parameter  $\alpha$  in equation (4)). For comparison the figure also includes the HadCRUT5 data set of observed surface temperature over the historical period.

191 Fiedler & Putrasahan, 2021). Therefore, we strongly enhanced the forcing to get a better  
 192 signal-to-noise ratio. Furthermore, to investigate the importance of the location of aerosol  
 193 emissions we ran additional simulations with emissions from one single region at a time,  
 194 with emissions from all other plumes turned off.

195 All simulations were run with a fully coupled model to assess the radiative forcing, tem-  
 196 perature response and feedbacks, using the linear regression method suggested by Gregory  
 197 et al. (2004). Some simulations were also run using only the atmospheric component,  
 198 ECHAM6.3, with prescribed SSTs fixed in a preindustrial pattern, to obtain the spatial  
 199 distribution of radiative forcing (Hansen et al., 2005). All coupled runs were 150 years long,  
 200 while the fixed-SST simulations were 150 years for the simulations with all emissions and  
 201 30 years for simulations with emissions from a single source region. To achieve a stronger  
 202 signal-to-noise ratio, five-member ensembles were used for some coupled runs. The ensem-  
 203 bles were created by running simulations from different initial conditions, selected at ten  
 204 year intervals from a preindustrial control simulation.



**Figure 2.** Gregory plot of four *abrupt-aerosol* experiments with varying direct and indirect aerosol effect. The standard *abrupt-2xCO2* and *abrupt-4xCO2* simulations with MPI-ESM1.2-CR are shown for reference.

## 205 4 Results and Discussion

206 In the following sections we present the simulated global mean temperature response  
 207 to aerosol forcing and the implications for forcing efficacy, as well as the spatial patterns  
 208 of forcing and temperature change. All presented values are anomalies compared to time-  
 209 averages from corresponding preindustrial control simulations.

### 210 4.1 Global Mean Response to Aerosol Forcing

211 We first inspect four idealized experiments with similar forcing strength, achieved  
 212 through different combinations of enhanced direct and indirect effects, as shown in Fig-  
 213 ure 2. The four experiments show a clear difference in their slopes, meaning that they have  
 214 different values of the feedback parameter ( $\lambda$ ). This indicates a difference in forcing efficacy,  
 215 since the efficacy describes the magnitude of the feedback parameter compared to that of  
 216 carbon dioxide (equation (2)). The feedback parameter is consistently smaller (less nega-  
 217 tive), and hence the efficacy is larger, for an enhanced indirect effect than for an enhanced  
 218 direct effect. Thus, for a given effective radiative forcing the cooling is stronger when the  
 219 ratio of indirect to direct aerosol cooling is large.

220 For the purpose of illustration the forcing in all four simulations is large compared to  
221 the present-day aerosol cooling (Forster et al., 2021). This helps obtaining a clear signal:  
222 in weaker-forcing scenarios the weak signal-to-noise ratio makes it difficult to distinguish  
223 the direct and indirect effect experiments from each other (see Figure S1 in the Supporting  
224 Information). However, due to the state dependency of climate feedbacks (Bloch-Johnson  
225 et al., 2015; Meraner et al., 2013), the value of the feedback parameter depends on the  
226 forcing strength. Therefore, we use five-member ensembles to enable distinction between  
227 the direct and indirect effects also in cases with smaller forcing strength (around  $-2.2$  to  
228  $-3.2 \text{ Wm}^{-2}$ , see Figure S2), confirming that there is a difference in efficacy between the  
229 direct and indirect effect also in cases where the forcing strength is closer to the lower bound  
230 of estimates of the present-day value (Forster et al., 2021).

## 231 4.2 Model Dependence

232 Next, we ask whether this behavior is model dependent, or if it is more likely to be a  
233 general behavior. There is some indication in the results of Richardson et al. (2019) that  
234 the aerosol forcing efficacy is larger in models which perturb aerosol emissions rather than  
235 concentrations. Models with perturbed emissions are typically also models that include an  
236 indirect effect through complex representations of aerosol-cloud interactions, thus supporting  
237 the results obtained here.

238 To further investigate the model dependence we compared two versions of MPI-ESM1.2  
239 and found that in the LR version of the model the variation in the feedback parameter  
240 with the strength of the indirect effect persists, see Figure S3 and Table S1. The overall  
241 pattern is the same in both model versions, although the feedback parameter values in the  
242 corresponding cases are not the same (Table S1): the effect is larger in the CR model.  
243 The two versions of MPI-ESM1.2 differ by more than resolution, most importantly, certain  
244 tuning parameters are not set the same way. The CR model version was finalized before the  
245 LR model version and uses a much smaller value of a parameter that enhances the amount  
246 of marine stratocumulus clouds. The large parameter value was set in MPI-ESM1.2-LR  
247 because it was found to induce a negative stratocumulus cloud feedback, and so dampened  
248 the very high climate sensitivity of MPI-ESM1.2-LR (Mauritsen & Roeckner, 2020). The  
249 MPI-ESM1.2-CR version instead has a weaker radiative forcing from  $\text{CO}_2$ , which by chance  
250 results in a similar climate sensitivity to that of MPI-ESM1.2-LR. Our interpretation is that  
251 the negative stratocumulus cloud feedback in MPI-ESM1.2-LR dampens the remote region

252 surface cooling, resulting in less sensitivity of the efficacy to aerosol indirect effects. Since  
253 the observational estimates of the stratocumulus cloud feedback is weak but positive (Myers  
254 et al., 2021) one could argue that the behavior of MPI-ESM1.2-CR in this regard is more  
255 realistic than that of the LR version.

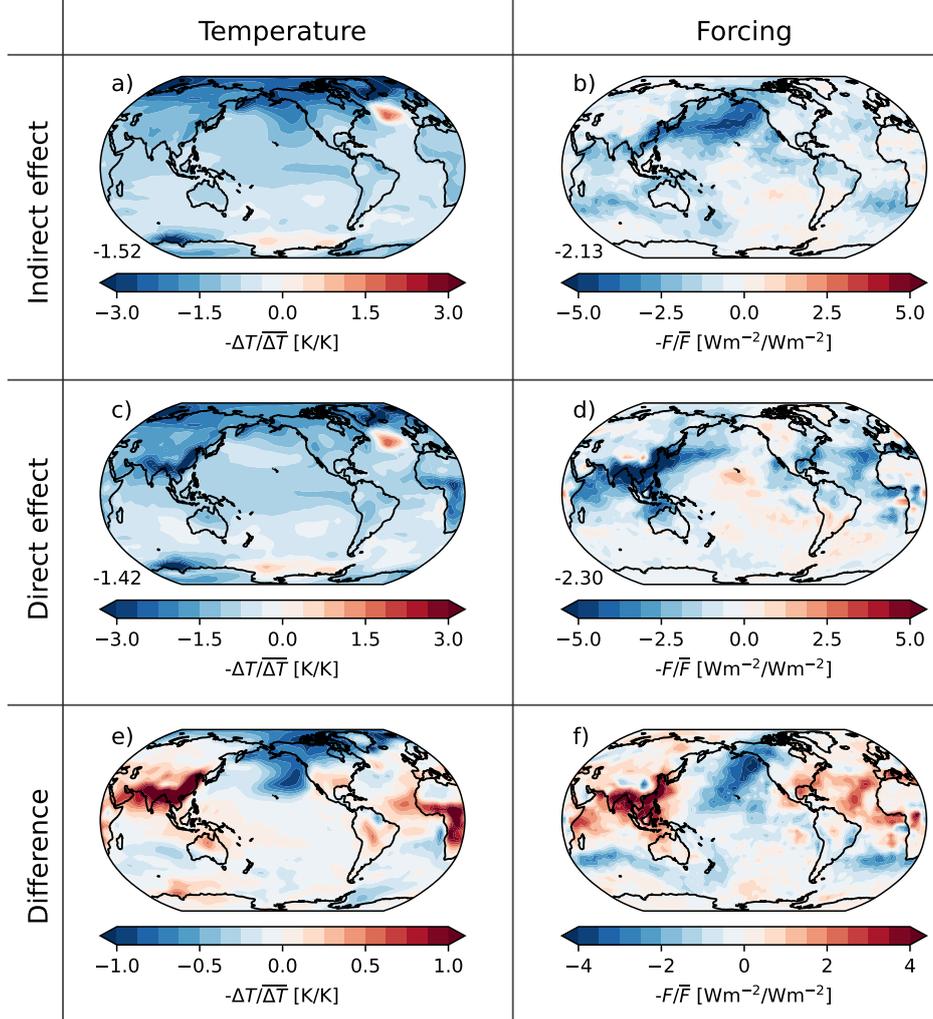
256 In summary, within both model versions we have used, the cooling from an enhanced  
257 indirect effect is larger than the cooling from the direct effect. We find anecdotal evidence for  
258 this also in other models, and therefore there is strong model based evidence that enhancing  
259 the indirect effect causes a larger forcing efficacy.

### 260 **4.3 Spatial Distribution of Forcing and Temperature Change**

261 To identify the mechanisms behind the larger efficacy of the aerosol indirect effect, we  
262 study the spatial patterns of forcing and resulting temperature change. As described in the  
263 following, we find that the indirect effect causes a remote temperature change at mid- to  
264 high latitudes, in contrast to the local tropical response to the direct effect. In addition, we  
265 find that variations in the latitude of the forcing seem to be of importance to the magnitude  
266 of the temperature response.

267 First, we examine the temperature change and forcing in two experiments with similar  
268 global mean forcing strength (*1xemiss.*,  $\alpha = 0.01$  and *5xemiss.*,  $\alpha = 1$ , Figure 3). The aerosol  
269 indirect effect causes a forcing mainly over the North Pacific, likely because aerosols emitted  
270 in South and East Asia, which are the regions with the heaviest emissions in 2005 (Stevens  
271 et al., 2017), are assumed to be transported with the westerlies over the ocean (Figure 3b).  
272 Above the ocean the optical depth of the aerosols is initially small, so enhancing the indirect  
273 effect has a large effect there, consistent with the mechanism of the Twomey effect (Carslaw  
274 et al., 2013). When the background aerosol optical depth scaling factor ( $\alpha$ ) is reduced the  
275 indirect effect becomes stronger, causing strong forcing in the remote regions. The forcing  
276 drives a local cooling, as well as a remote temperature response over the Arctic (Figure 3a).  
277 In contrast, enhancing the direct effect gives a forcing as well as a temperature response that  
278 are localized to major emission source regions, mainly in South and East Asia and Central  
279 Africa (Figure 3c-d).

280 The radiative forcing from the indirect effect is concentrated over the northern part of  
281 the Pacific Ocean (Figure 3b). Dong et al. (2019) showed that local SST changes in that  
282 area have little to no effect on the global average net TOA radiation balance. This means



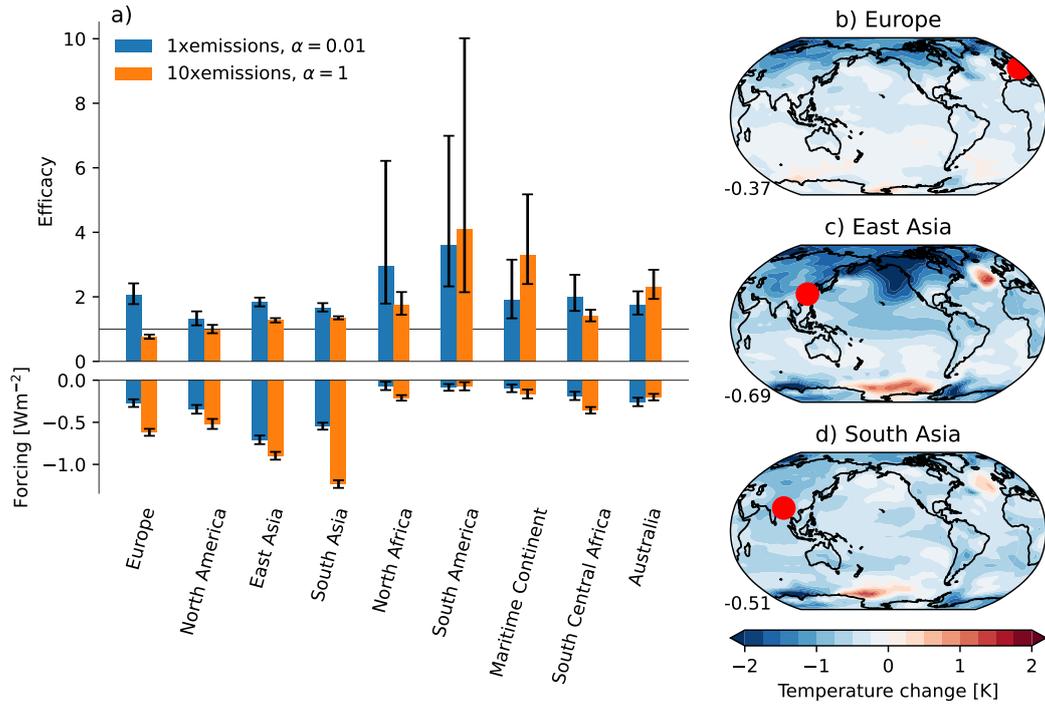
**Figure 3.** Maps showing the temperature anomaly ( $\Delta T$ , first column) and forcing ( $F$ , second column) averaged over the last 30 years of *abrupt-aerosol* experiments with enhanced indirect effect (a-b) and direct effect (c-d). Panels e-f show the difference in temperature and forcing between the two experiments. All values are normalized against the global average to better show the spatial pattern, and multiplied by  $-1$  to get a more intuitive color scale (darker blue signifies stronger cooling than the global average). The forcing was obtained from fixed-SST simulations while the temperature changes are from fully coupled simulations. The numbers in the lower left corner in panels a-d show the global mean, in K and  $\text{Wm}^{-2}$ , respectively. The parameter values are  $1x_{emiss.}$ ,  $\alpha = 0.01$  (indirect effect) and  $5x_{emiss.}$ ,  $\alpha = 1$  (direct effect).

283 that the global mean temperature response per unit forcing will be larger for a forcing there  
284 than in the case of a forcing in the equatorial West Pacific where an SST change is efficiently  
285 propagated throughout the troposphere and hence dampened by negative feedbacks. Since  
286 Dong et al. (2019) forced the system with warmed SSTs they did not chart the effect of a  
287 local temperature change over land, but it seems reasonable to expect a similar response to  
288 changes over South and East Asian land areas as to changes over the northern Indian Ocean  
289 and the tropical West Pacific Ocean. Therefore, the direct effect, with forcing over land in  
290 Asia, results in a stronger change to the TOA radiation balance and thus a small efficacy.  
291 Furthermore, the forcing is located at different latitudes in the two cases, with the indirect  
292 effect causing cooling preferentially at higher latitudes (Figure 3). A connection between  
293 extratropical forcing and a large aerosol forcing efficacy is in line with previous studies (e.g.,  
294 Salvi et al., 2022), and also supported by studies on the latitude dependence of other forcing  
295 agents (e.g., Hansen et al., 1997, 2005; Stuecker et al., 2020). Thus, based on the current  
296 understanding of physical processes and previous studies we argue for the general validity  
297 of our conclusions.

#### 298 **4.4 Emissions from Single Source Regions**

299 The latitude dependence can be further investigated in simulations with emissions from  
300 one source location at a time. Figure 4a shows the forcing efficacy in simulations with  
301 emissions from each of the nine source regions in MACv2-SP. In the cases that show a  
302 signal that is distinguishable from the noise, the efficacy of an enhanced indirect effect is  
303 consistently larger than that of an enhanced direct effect (in Europe, East and South Asia,  
304 and, to some extent, North America). Emissions from Europe stand out with a very large  
305 efficacy from aerosol-cloud interactions.

306 The patterns of temperature change resulting from an enhanced indirect effect in the  
307 three cases with the strongest emissions (Europe and South and East Asia) are shown in  
308 Figure 4b-d. The forcing and temperature change from all emission source regions with  
309 enhanced direct and indirect effect, respectively, are shown in Figures S4-S7. The results  
310 show a strong Arctic response from both the European and East Asian emissions. However,  
311 whereas the global mean forcing is the strongest from East and South Asian emissions,  
312 European emissions contribute disproportionately to the global mean temperature change due  
313 to the strong cooling in the Arctic. The enhanced Arctic response suggests that mechanisms  
314 related to the Arctic amplification or ocean energy transport (e.g., Pithan & Mauritsen,



**Figure 4.** a) Forcing efficacy (equation (3)) (upper part) and global mean radiative forcing (lower part) in simulations with emissions from each region separately, and b-d) the spatial pattern of temperature change from emissions in the three regions that cause the largest global mean temperature change, with  $\alpha = 0.01$ . Error bars in panel a) show the 68% range and were obtained using Monte Carlo sampling for the efficacy, and the standard deviation of the mean in the final 20 years of fixed-SST simulations for the forcing.

315 2014; Acosta Navarro et al., 2016) are likely to dominate the temperature response to  
316 European aerosol emissions.

317 There are large statistical uncertainties in the efficacy in some of the regions (North  
318 Africa, South America, the Maritime Continent, South Central Africa, and Australia). In  
319 those regions the emissions in 2005, and thus also the forcing, are weak (Figure 4a). There-  
320 fore, the signal is obscured by the internal variability of the climate system and no conclusion  
321 can be drawn regarding the forcing efficacy from emissions in those regions.

## 322 5 Conclusions and Implications

323 We have shown that in MPI-ESM1.2, aerosol forcing from an enhanced aerosol indirect  
324 effect causes a temperature response per unit forcing that is larger than the corresponding  
325 response to forcing from increased aerosol emissions. In other words, the aerosol forcing  
326 efficacy is larger when the ratio of indirect to direct effect is large. The response to the  
327 enhanced indirect effect is dominated by remote oceans and an Arctic-amplified cooling, in  
328 contrast to the direct effect which causes a radiative forcing and a resulting temperature  
329 response localized to major emission source regions. Indirect effects from European emis-  
330 sions contribute disproportionately to the strong Arctic cooling, while the overall stronger  
331 emissions in South and East Asia dominate the total response.

332 We provide a mechanistic explanation for the enhanced remote response to the aerosol  
333 indirect effect. An enhanced indirect effect induces stronger forcing in mid- to high latitude  
334 remote ocean regions where the aerosol optical depth is low to begin with, and a forcing  
335 in the mid- and high latitudes generally leads to a larger forcing efficacy compared to a  
336 forcing closer to the equator (e.g., Hansen et al., 1997, 2005; Salvi et al., 2022; Stuecker et  
337 al., 2020).

338 A larger-than-unit aerosol forcing efficacy reported in recent studies (Salvi et al., 2022;  
339 Smith & Forster, 2021) could be related to a large efficacy of the aerosol indirect effect in the  
340 models applied in those studies. Furthermore, our results could help reconcile intermodel  
341 differences in the temperature response to aerosol forcing (e.g., Richardson et al., 2019). A  
342 larger aerosol forcing efficacy also has implications for estimates of the climate sensitivity  
343 based on the historical warming (e.g., Otto et al., 2013), and projections of future aerosol  
344 forcing when emissions from fossil fuel burning eventually decline.

## 6 Open Research

### 6.1 Data Availability Statement

The source code for MPI-ESM1.2 is available through <https://mpimet.mpg.de/en/science/models/mpi-esm> (Mauritsen et al., 2019). The output data used to produce the figures for this paper, and the accompanying Python scripts, are available through Zenodo at <https://doi.org/10.5281/zenodo.7057855> (Huusko et al., 2022). The observational temperature data presented in Figure 1 was downloaded via <https://crudata.uea.ac.uk/cru/data/temperature/> (Morice et al., 2021).

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