Response to Referee Comments on "Global response of parameterised convective cloud fields to anthropogenic aerosol forcing"

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We are grateful to the two anonymous referees for their time and constructive comments on our original manuscript and during the public discussion. We have made a number of alterations in a revised manuscript to address the points raised by both reviewers during the discussion phase, and we hope that the manuscript is now clearer as a result. Responses to individual points, and details of changes to the manuscript, are given below.

Response to reviewer #1

> *This paper addresses a neglected topic, the global impact of aerosols on the full range of convective clouds. While many climate models consider aerosol effects on clouds, they mostly consider this only on clouds formed by large-scale condensation in the model, and generally neglect the impact on convective (for example mixed-phase) clouds. This could be important not only by contributing to cloud radiative effects, but also by altering rainfall. Thus the current contribution is useful. The results do rely heavily on a convection scheme that may not represent the convective-scale dynamics very well, but the authors explain how this scheme works and how its assumptions play into the results obtained; the study is a useful advance even though conditional on the scheme. The results qualitatively support previous suggestions based on more localised modelling approaches.*

> *My chief concern with this paper is that I am not sure 10 years is long enough to see the impact of aerosols on rainfall, due to its high internal variability. This impact is subtle compared to the large dynamical influences on convection, as acknowledged by the authors, and the results are not straightforward, with opposite-signed changes in different regions that defy any simple explanation as an aerosol impact and look noisy. I don't see any significance testing applied to the claimed impacts, but the authors need to do this – for example by considering each year as an independent sample and computing a t-statistic on the differences in mean rainfall or cloud property, either at the pixel or region level or aggregated in some other way to improve the statistics.*

This is an excellent point, and for all the plots illustrating PD−PI differences we have now included an indication of statistical significance at the 95% level, based on a two-sided t-test. The value for each of the 10 years is treated as an independent sample from the underlying distribution, as suggested by the reviewer, with the PD and PI values for a given year being matched in a "paired-samples" t-test.

For maps of differences, the areas of significance are shown with stippling; likewise for the 2D histograms a dot is placed in each shaded bin where the difference is significant. For the zonal-mean difference plots, the corresponding 95% confidence interval is shaded, indicating significance where the shaded region does not cross zero.

This analysis reassuringly shows that many (though not all) of the coherent features that show up in the results do indeed have statistical significance based on 10 years of simulation. We have updated the text to describe the methodology applied (extending Section 3.2), and to indicate the statistical significance of the major features in the results to which the discussion refers (throughout Sections 4.1 and 4.2), and metion this in the conclusions.

We also believe that identifying the statistically significant responses, and separating them from the noise, helps to address some of the points raised by Reviewer #2 (see below).

Detailed comments.

86: Please clarify whether new particle formation is included in this model. Here it says the gas-phase chemistry model is not active for this study, but later (l174) the manuscript speaks of precursor emissions, which would seem to be irrelevant if there is no gas-phase chemistry or new particle formation predicted.

The full MOZ chemistry scheme is not included in the model configuration used here; however the ECHAM–HAM configuration still contains a simple sulphate precursor chemistry driven by DMS and SO_2 emissions. Oxidation from DMS to SO_2 to H_2SO_4 follows a simplified parameterisation in the absence of full oxidant chemistry, and sulphate aerosol can then be produced by new particle formation, condensation of H_2SO_4 onto existing particles, and by parameterised aqueous oxidation within cloud droplets. We have clarified this point in the text.

175-ish: please specify what SSTs were used (are they the same each year for the 10 years?)

Sea surface temperatures use a monthly climatology derived from years 1979–2008 of the AMIP2 SST dataset, so the interannual variability is not included here. We have clarified this in the text.

212–214: It is a common misconception that precipitation generated by the convective scheme is "convective" and that generated by the grid-scale scheme is "stratiform." The convective scheme simply represents the net effect of all air motions below the grid scale. For example as the model resolution increases, the fraction of total P produced by the convective scheme should steadily decrease, but the model is not predicting that rain is physically becoming more stratiform. Since convective motions in nature mathematically project onto the grid scale circulation, some of the grid-scale condensation will be attributable to convection, no matter what the resolution.

The reviewer is of course correct, in that the difference between "convective" and "stratiform" in a model such as this is really one of resolved vs sub-grid-scale motions, and does not necessarily correspond to physical cloud types. It is not our intention to suggest otherwise, and this is why we make clear that we are talking about the split between the *paramteterisations*, and that this is somewhat arbitrary; however we have updated the text to make this point more explicit.

Fig 1. caption: might be helpful to (re)define PD and PI in the caption.

We have done this as suggested.

Response to reviewer #2

Kipling et al. use a model with parameterized deep convection to study aerosol effects on deep convection. They do so in an atmosphere-only model setup that does not allow sea surface temperatures (SSTs) to respond to the aerosol radiative forcing. The main advantage of this study is that they take into account feedbacks from the large scale circulation (or at least those effects which are not mediated by SST changes). Unfortunately, however, in spite of many nice and useful diagnostics, the discussion of aerosol effects in the strongly forced regions ultimately still seems fairly superficial. I think that in order to better understand the overall effect of taking into account aerosol-deep-convection interactions, potential reasons for the qualitative difference of the CCFM effects between the India region and the Amazon region should be explored in this study. A specific suggestion can be found below, but I hope that perhaps the authors can add to this. To me, the explanation that "[i]n a strongly-forced deep convective environment, there may be sufficient energy input that any aerosol modulation of the latent heat release will have little effect" seems overly simplistic regarding the qualitative difference between the CCFM effects in the strongly forced regions in Figure 5. I think that after some additional analysis to address the differences between aerosol effects in strongly forced regions, this study will ultimately be a useful addition to the literature on the interesting and important topic of aerosol effects on deep-convection. I recommend major revisions. It should be noted that convective invigoration could in principle affect precipitation intensity while the time mean precipitation amount remains constant.

Major comments:

1) India region: I suggest to analyze ocean and land in the India region separately. As far as I can see, the change regarding LS ACI + ARI in the India region in the Figure S5 is at odds with many studies of aerosol effects over India. Figure 2 suggests that this could in part be due to changes in the Arabian Sea and the Bay of Bengal.

The reviewer makes a good point that the change in this region could be a mixture of quite different effects over the land and ocean portions of the box. To answer this, we have therefore repeated the analysis restricted to "land" points using the model's land–sea mask (see Figures A1, A2 and A3 in this response. This does indeed appear to remove an additional set of large-scale processes that are showing up in the cloud-field and rain-production responses. Because this makes the overall results cleaner, we have changed the definition of the "India" region to refer to the land only (which was always the intended focus rather than the ocean which falls into the same rectangular box).

2) Amazon region: As far as I can see, Figure S2 suggests some invigoration in CCFM-microphys in the Amazon region which is partially compensated by CCFM-anvil. Please discuss.

The changes in the Amazon region due to CCFM show only marginal statistical significance, and look quite noisy/patchy over the CTP-radius distribution rather than indicating any clear invigoration or suppression effect in our view. The large-scale effects, on the other hand, show a quite coherent suppression of deep convection overall, consistent with our interpretation that aerosol effects on convection in the model in this region are being driven primarily by modulation of the large-scale forcing. In updating the text to refer to significance following Reviewer #1's comments, we have noted in the text that the effects in the deep convective regimes are mostly noisy and not statistically significant.

3) I think that the reasons for the apparent convective suppression due to including aerosol effects in CCFM in the India region should be analyzed and discussed in more detail.

Again, this is a case where there is little statistical significance to the apparent signal coming from CCFM effects in Figure 5; the only regions where a coherent significant effect is visible are the Caribbean (a clear invigoration signal that dominates the total effect), and the Congo (a smaller but significant invigoration that is nevertheless outweighed by the large-scale effects).

Although the cloud field morphology changes in Figure 5 are not that significant here, there *is* a clear decrease in rain production from the CCFM microphysics effects in Figures 6 and S5. This can be explained in terms of aerosol increasing CDNC and suppressing autoconversion, although it is interesting that the effect on the cloud field is weak here (unlike in the Caribbean case where suppression of autoconversion leads to clear convective invigoration). However, this fits with the idea that aerosol can push shallower cloud into transition, but its effect on already-deep cloud regimes is more limited overall even if it does reduce warm rain production.

We have updated the final paragraph of Section 4.2 to take account of this.

4) Because the CCFM effects are defined as CCFMall_ari−CCFMfix_noari, I don't understand why the CCFM effects over India still seem to compensate the large scale effects in such a rather systematic manner (see Fig. 2 and Fig. 6, discussion in line 294 and elsewhere). Please explain.

Note that the CCFM effects are defined as CCFMall_ari−CCFMfix_ari, as per Table 2 (not CCFMfix_noari as stated in the comment).

This is not specifically a feature of the behaviour over India, but the same partial compensation which is noted in many of the regions, with one scale of processes tending to oppose the other, although it is the large-scale processes which dominate the overall response in most cases.

Minor comments:

l. 6: what does "explicitly simulate" mean here?

We have changed this to "simulate. . . complete with microphysics and interactions between clouds" for clarity.

l. 12: "rather small" compared to large-scale effects? Fig.6 suggests similar magnitudes for India.

This statement is talking about the convective cloud field morphology, as shown in Figure 5, which is affected much more strongly by the large-scale effects than those via CCFM itself. The reviewer is correct, however, that there is nevertheless a strong decrease in rain production (Figure 6) from the CCFM effects that does not translate into a significant modification of the cloud field itself, which we have discussed above.

l 25: Yes, "total precipitation is constrained to balance evaporation and by energetic constraints". The problem here is that sea surface temperatures are fixed. In coupled climate models aerosol does affect sea surface temperature and consequently also evaporation. When the sea surface temperatures cannot respond to the aerosol forcing, a large part of the precipitation response that one would see in a coupled climate model is lost. In other words, it is not possible to fully simulate the effects of aerosol on global mean precipitation in the setup used here. I think this point should already be stressed in the introduction and later also be taken into account in the results section (especially in Sect. 4.1) as well as in the conclusion section.

We fully agree that there are limitations in the feedback processes which can be captured in an uncoupled atmosphere-only model (especially with respect to those operating on longer timescales and for maritime convection). Nevertheless, the approach still allows many inter-scale feedbacks via atmospheric processes alone to be represented, and it is more the effects on *regional* precipitation and cloud fields than on global-mean precipitation which are the focus of this paper. We have updated the text to acknowledge the limitations of an atmosphere-only model in this context, and suggest that further studies using a coupled atmosphere–ocean model might provide further insight, though with a greater computational cost (final paragraph of introduction, extending Section 4.1, and in the second paragraph of the conclusions).

l 310: it seems odd to me that the effect of aerosol on global mean precipitation is emphasized in the conclusion section. When SSTs are allowed to respond to forcing, global mean precipitation changes. When it is not, global mean precipitation stays more or less constant. An exception to this are model runs in which the forcing is from greenhouse gases which by definition absorb longwave radiation. Greenhouse gases affect precipitation more directly than scattering aerosol via their influence on the radiation budget. I think that instead of discussing changes of global mean precipitation in quite some detail, the consequences of keeping SSTs fixed should be discussed. It should also be noted somewhere that convective invigoration could affect precipitation intensity while time mean precipitation remains constant.

It is not our intention to "emphasize" the effect on global mean precipitation; rather we present this as the global context in which the regional precipiation and cloud-field changes which *are* the focus of the manuscript are discussed. We hope that the changes made in respect of the previous point, acknowledging that the overall balancing-out of the global-mean response follows from the use of fixed SSTs, address this concern. The possibility to modulate precipitation intensity while keeping total precipitation fixed is already mentioned at the end of the first paragraph of the introduction.

l. 256: quasi-equilibrium: I am not convinced that this is actually a problem here since the deep convective heating is applied to the large scale circulation and since large scale water vapor is also modified. More active deep convection may result in less large-scale condensation, but there would still be a shift in precipitation production from "stratiform" cloud microphysics to the deep convection parameterization, which would then constitute the signature of deep convective invigoration. In my opinion, fixed SSTs are potentially more problematic than using the quasi-equilibrium assumption in the deep convection parameterization.

The problems of fixed SSTs and the quasi-equilibrium hypothesis are somewhat similar, in that both will limit the feedback mechanisms that are captured by the model (though of course in different ways). We have updated the text to reflect the fact that fixed SSTs may also be a limitation here.

l. 1: references?

Appropriate references are those cited in the first paragraph of the introduction – in the interest of conciseness, however, we do not believe it is appropriate to duplicate them in the abstract.

l. 33: "we are probably decades away from having the computer power to run convection-resolving global climate models for more than short time periods": Could you please cite a reference or provide some backing for this statement in the reply to this comment. This does not have to be included in the manuscript.

This is our impression of the current state of global climate modelling, however in the absence of a specific reference, we've revised this to "we are some way from having the computer power to routinely run convection-resolving global climate models for more than short time periods" which we hope is less controversial than estimating how long it might take to reach that point.

l. 67: "still lacking non-local interactions": I reviewed Wang et al. (2011), but I don't understand what the authors are referring to. Please explain.

In the superparameterisation approach, although convective elements are explicitly resolved on e.g. a 2D grid within each host-model column, they are able to interact only "locally", i.e. between elements within the same host-model column – interactions with convective elements in neighbouring columns occurs only via the host model fields. We have updated the text to explain our understanding of the non-locality issue.

l. 109: what does "explicit" mean here? Maybe explain briefly how this differs from A+S74.

We have changed this to "an entraining plume model for each type of cloud with embedded aerosol activation and cloud microphysics" for clarity.

l. 142: if I understand this right, the anvil effects includes the effect from detrainment into the large scale. Does this have consequences for the separation between CCFM and large scale effects? Please clarify.

Yes, that is exactly the effect that is being referred to here – changes to the droplet/ice-particle size at detrainment will not directly affect the convective clouds themselves, but will feed back by changing the microphysics in the large-scale cloud scheme, thus acting as a modulation of the LS ACI effects.

This highlights the fact that there isn't a clean separation between the effects – as each of them is "switched on" going down the list in Table 1, it may trigger feedbacks by modifying the processes above which are already active, as well as its own direct impact.

l. 142: please also explain briefly how the effect of detrainment on CDNC (and ICNC?) is treated.

The two-moment detrainment, explicitly passing a number of droplets or ice crystals to the large scale rather than just a bulk mass, is implemented using the same mechanism as in Lohmann (2008): if a convective cloud detrains liquid or ice with a number concentration greater than that of any existing large-scale cloud, the large scale CDNC or ICNC will be increased to match (though it will never be decreased by convective detrainment). We have added the explanation in the text.

l. 156: a fixed CDNC is assumed in all CCFM convective clouds <- how many CDNC?

The fixed value is $100\,\mathrm{cm}^{-3}$ globally in both PD and PI CCFMfix simulations. We have clarified this in the text.

l. 214f: based on my understanding, having a more inactive deep convection scheme leads to more stratiform precipitation and vice versa. Sometimes, this behavior can be influenced by tuning parameters in the convection scheme. The potential explanation given here is, however, fine with me.

Yes, given that (as discussed elsewhere) the total precipitation is constrained, any change in tuning parameters that alters the amount from one scheme must cause a balancing change in the other. The tuning of this balance is certainly something which could be the subject of further investigation, but is not a focus of the present study.

l. 263f: I don't understand how this explanation fits with the CCFM results for India in Figure 5 and 7.

As discussed above, the CCFM effect on the cloud field itself (Figure 5) is small compared to the large-scale effects. Figures 6 and 7 show that microphysical effects are changing the autoconversion and glaciation processes, but without causing significant changes to the dynamics of the already deep convective regime in the way that happens in the more susceptible shallow convection case.

> *l. 301: Please repeat which idealized studies this refers to.*

This refers back to the discussion in the penultimate paragraph of Section 4.2, and we have now repeated the citations here for clarity.

> *l. 301: I can see a number of potential problems with limited area studies, and I think that it is important to perform the type of study presented here. For example, applying a large scale forcing in a limited-area model means that in a strongly forced case, precipitation will more or less simply equal the large scale vapor large scale forcing. At the same time, it is not directly clear to me why phase changes due to precipitation formation delays should be less important in a strongly forced case, unless CCN are depleted by precipitation.*

As touched on above, the key argument here relates to the "tipping point" of glaciation – if a shallow convective cloud is in a state where it is not quite glaciating but an additional delay in warm rain production would cause it to do so, then it may be particularly susceptible to an aerosol-induced CDNC increase and this will lead to convective invigoration.

In strongly-forced deep convection, however, extra aerosol might modify the exact microphysical details inside the cloud (rebalancing warm vs cold rain for example) but providing glaciation still occurs, the impact on the overall convective dynamics may be minor. An exception would be if, in spite of delayed autoconversion, the delayed freezing of smaller droplets causes some clouds in the ensemble to lose buoyancy before they glaciate, leading to convective suppression – however there is little indication of that happening in these simulations. Where large-scale forcing is strong, it is able to maintain deep convection irrespective of the amount of aerosol.

> *l. 309: what does "via energetic and water-budget constraints" mean? Please be more specific.*

Having already expanded the discussion of this elsewhere in reference to fixed SSTs etc. we don't feel it's necessary to include this phrase here and have deleted it.

> *l. 310: Although invigoration might not change the time average amount of precipitation, it could still have an impact on precipitation intensity. Please discuss.*

We completely agree, and although the precipitation intensity is not the subject of this manuscript, we might expect to see some correlation between changes in the intensity distribution and the cloud-field distributions presented here. Although somewhat out of scope here, the baseline precipitation intensity distribution in CCFM was discussed in Labbouz et al. (2018), and an analysis of how this varies with aerosol perturbations could be a worthwhile topic for a future study. We have now noted this in the conclusions.

> *Fig 1: does this depend strongly on the model run?*

No: although the CCN distribution is of course modulated by changes in scavenging, this does not significantly change what is shown here. We have updated the caption to note that these are from the CCFMall_ari simulations, but that others look very similar.

> *Fig. 4: I think it would be good to explain the x-axis better. Perhaps you could mention the number of ensemble members in CCFM somewhere. I would like to obtain a rough idea about how the values on the x-axis come about without having to consult additional literature.*

A paragraph has been added to Section 2.2 explaining this, and a note to the captions of Figures 4 and 5. (There are 10 members in the ensemble in the CCFM configuration used here.)

> *Technical:*
> *l. 98: uses -> is diagnosed (and remove diagnostic in line 99)*

Changed as suggested.

> *l. 177: months' -> should it just be months without the apostrophe?*

Changed to "15 months of spin-up".

Other corrections

line 64: "considers attempts" ⟶ "attempts".

Figures 2, 3 and S1. These had been incorrectly drawn using the _noari simulations to extract the CCFM response. We have corrected this to use the _ari simulations as indicated in Table 2, which provides for a logical progression of enabling successively more processes, is consistent with what is shown in the other figures, and does not change the conclusions drawn.

Table 1. We have updated this to show the correct set of simulations referred to in Table 2 (in particular, the large scale radiative effects are activated before the CCFM processes, not after). This was an oversight in updating from an earlier draft. The actual sets of differences listed in Table 2, however, were correct.

References

Labbouz, L., Kipling, Z., Stier, P., and Protat, A.: How Well Can We Represent the Spectrum of Convective Clouds in a Climate Model? Comparisons between Internal Parameterization Variables and Radar Observations, Journal of the Atmospheric Sciences, 75, 1509–1524, doi:10.1175/JAS-D-17-0191.1, 2018.

Lohmann, U.: Global anthropogenic aerosol effects on convective clouds in ECHAM5-HAM, Atmos. Chem. Phys., 8, 2115–2131, doi:https://doi.org/10.5194/acp-8-2115-2008, 2008.

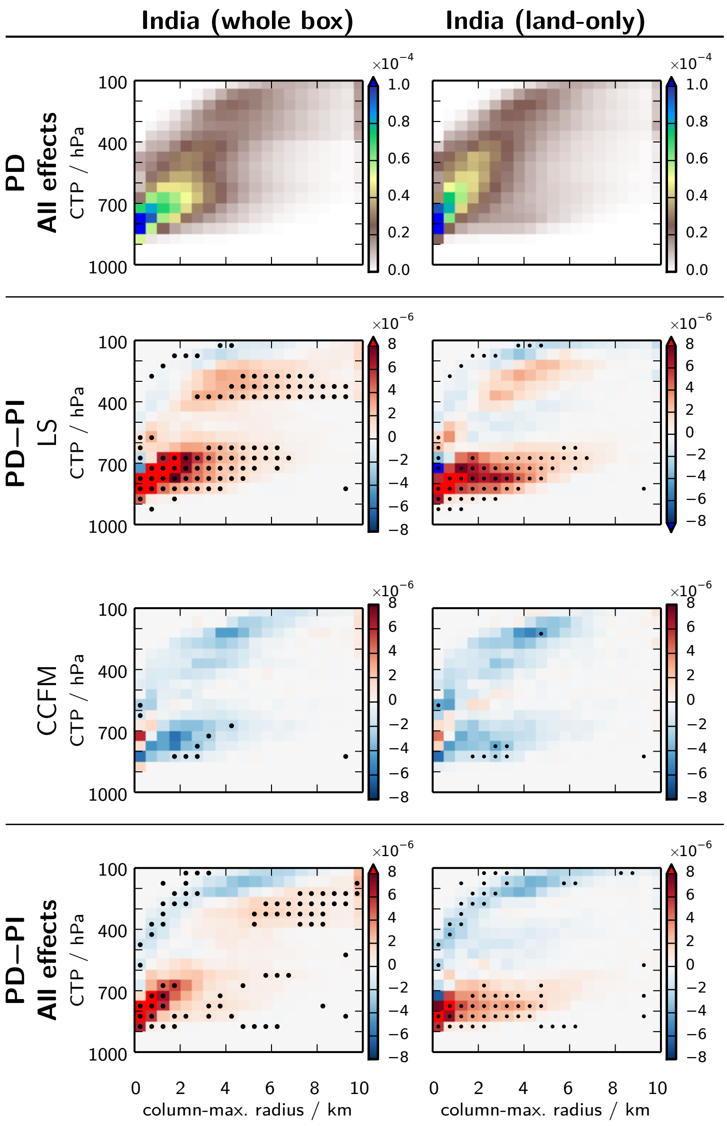

Figure A1: Modified version of Figure 5 from the manuscript, showing how the regional cloud field response differs for the India region when it is restricted to land points only.

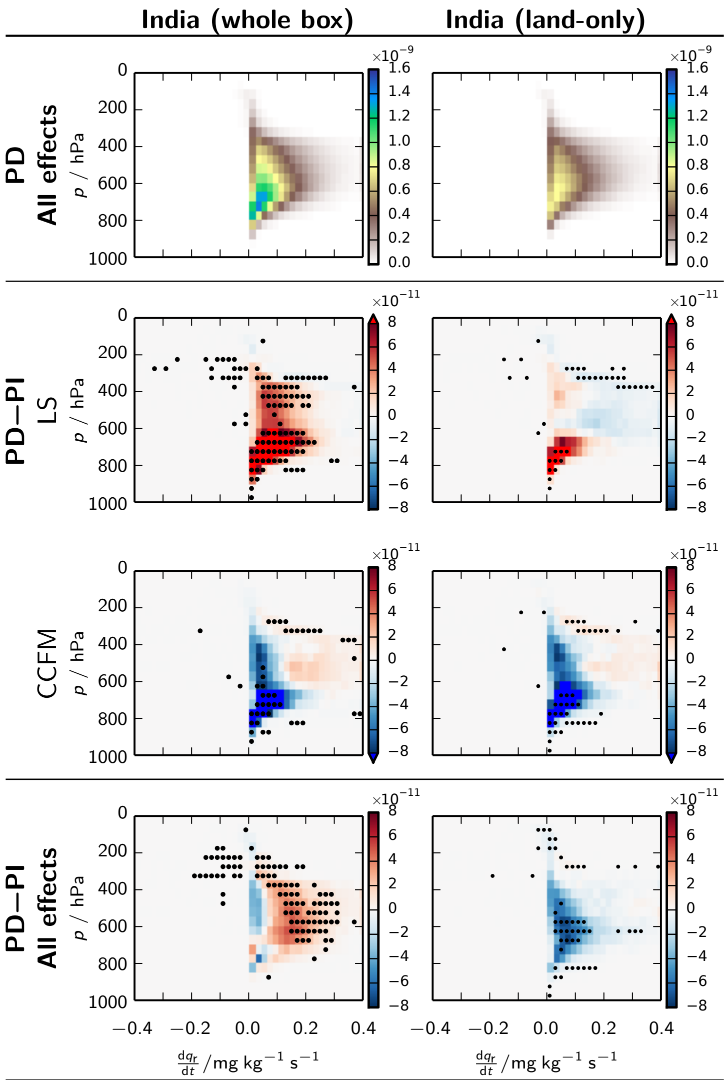

Figure A2: Modified version of Figure 6 from the manuscript, showing how the regional rain production response differs for the India region when it is restricted to land points only.

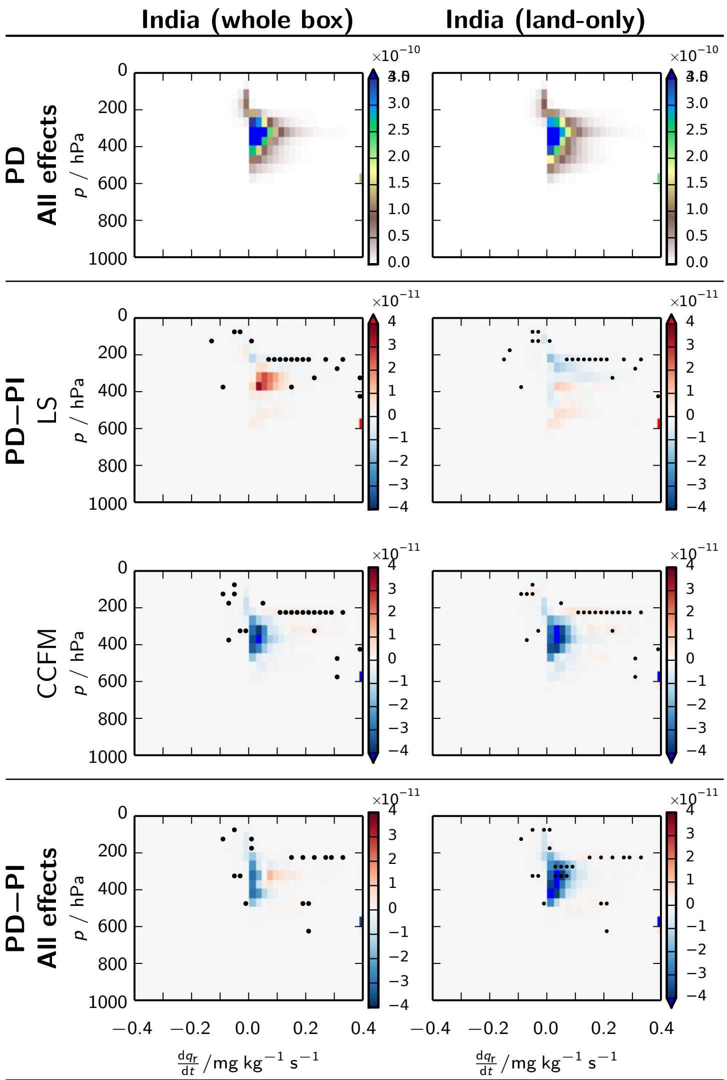

Figure A3: Modified version of Figure 7 from the manuscript, showing how the regional ice production response differs for the India region when it is restricted to land points only.

Global response of parameterised convective cloud fields to anthropogenic aerosol forcing

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Abstract. The interactions between aerosols and convective clouds represent some of the greatest uncertainties in the climate impact of aerosols in the atmosphere. A wide variety of mechanisms have been proposed by which aerosols may invigorate, suppress, or change the properties of individual convective clouds, some of which can be reproduced in high-resolution limited-area models. However, there may also be mesoscale, regional or global adjustments which modulate or dampen such impacts which cannot be captured in the limited domain of such models. The Convective Cloud Field Model (CCFM) provides a mechanism to explicitly simulate a population of convective clouds, complete with microphysics and interactions between clouds, within each grid column at resolutions used for global climate modelling, so that a representation of the microphysical aerosol response within each parameterised cloud type is possible.

Using CCFM within the global aerosol–climate model ECHAM–HAM, we demonstrate how the parameterised cloud field responds to the present-day anthropogenic aerosol perturbation in different regions. In particular, we show that in regions with strongly-forced deep convection and/or significant aerosol effects via large-scale processes, the changes in the convective cloud field due to microphysical effects is rather small; however in a more weakly-forced regime such as the Caribbean, where large-scale aerosol effects are small, a signature of convective invigoration does become apparent.

1 Introduction

The indirect effects of atmospheric aerosol via interactions with cloud and precipitation remain some of the most uncertain contributors to anthropogenic radiative forcing of the earth's climate (Boucher et al., 2013; Myhre et al., 2013). Although the principle behind the cloud albedo effect (Twomey, 1977) is relatively well understood, its magnitude is much less certain, while potential effects on cloud cover and liquid water path and semi-direct effects (Hansen et al., 1997; Ackerman et al., 2000) are more tentative. For convective and mixed-phase clouds, a number of further effects have been proposed relating to enhanced or retarded glaciation and consequent changes in latent heat release (Lohmann and Feichter, 2005; Rosenfeld et al., 2008); Fan et al. (2013) also propose effects based on changes in ice-particle fall speed. Aside from effects on the radiation balance, aerosol–cloud interactions have the potential to alter the distribution of precipitation. Although total precipitation is constrained to balance evaporation and by energetic constraints (Mitchell et al., 1987; Allen and Ingram, 2002), changes in location and frequency of different intensities are possible, which may have significant consequences for drought and flood risk (e.g. Muller and O'Gorman, 2011; Hodnebrog et al., 2016; Myhre et al., 2016).

However, although these mechanisms may be captured in idealised cloud-resolving models (CRMs) and large-eddy simulations (LES) of individual clouds (e.g. Tao et al., 2007; Lee, 2012), there is little robust observational evidence, and it has been suggested that such effects are countered by negative feedbacks or buffering processes on larger spatio-temporal scales (Stevens and Feingold, 2009). Furthermore, evidence from observations may suffer from a lack of significance or correlation between aerosol and the thermodynamics to which convection is much more sensitive (Varble, 2018), and that from CRM and LES studies from uncertainty in the complexities of microphysical parameterisation (White et al., 2017). Many of these topics are covered in more detail in the recent review by Fan et al. (2016).

Studying the effects of aerosol on convection using models at the global scale is challenging, however, as we are probably decades away some way from having the computer power to routinely run convection-resolving global climate models for more than short time periods. Current models therefore all require some form of sub-grid-scale parameterisation of sub-grid-scale physical processes, including convection (e.g. Jakob, 2010). The convective parameterisations used in most current models are of the bulk mass flux variety, representing sub-grid-scale convection by one "average" convective cloud, either with an estimation of the vertical updraught velocity (e.g. Kim and Kang, 2012), or more traditionally without any explicit separation of the total updraught mass flux into horizontal area and vertical velocity (e.g. Tiedtke, 1989; Gregory and Rowntree, 1990; Bechtold et al., 2001). Such schemes are very effective for many purposes, but are unable to represent either the heterogeneity of convective clouds within a grid column, or the detailed microphysics through which indirect aerosol effects may operate (especially the activation process which depends on vertical velocity and supersaturation and is highly non-linear). This is one of the reasons why, although global models may represent the global distribution of *mean* precipitation quite well, both the diurnal cycle and intensity distribution of convective precipitation remain a challenge (Stratton and Stirling, 2012; Kooperman et al., 2018). Current model-based estimates of the effective radiative forcing due to aerosol–cloud interactions (ERFaci) may also be limited by the fact that the models mostly represent only the interactions with large-scale stratiform clouds. These interactions are typically represented by coupling prognostic size-resolved cloud microphysics and aerosol schemes via a parameterisation of the aerosol activation process by which some aerosols act as cloud condensation nuclei (CCN). The activation itself, and thus potentially the overall contribution of ERFaci to climate sensitivity, depends crucially on local vertical velocity and its variability (West et al., 2014; Donner et al., 2016), which as noted above is indeterminate in the convective context for many schemes.

There have been a number of previous attempts to represent aerosol–convection interactions in parameterised convection by a variety of approaches. Nober et al. (2003) used in-situ observed or satellite-retrieved cloud droplet number concentration (CDNC) to modulate the simple microphysics within a Tiedtke-based bulk mass flux scheme. Menon and Rotstayn (2006) introduce simple parameterisations of CDNC or droplet size based on prognostic aerosol into two different GCMs using quite different cloud and convection schemes. Lohmann (2008) goes further, introducing full two-moment microphysics into bulk mass-flux convection, driven by a parameterisation of aerosol activation notwithstanding the lack of explicit information about the convective vertical velocity or its variation amongst updraughts. Another two-moment microphysics parameterisation has been implemented within the Zhang and McFarlane (1995) convection scheme (Song and Zhang, 2011; Song et al., 2012), using a plume model to derive the convective vertical velocity and aerosol activation, but still without representing the diversity of convective clouds (and hence of vertical velocities) that may exist within one model grid cell. Other approaches for parameterising convection include unified schemes which aim to treat all cloud types along with turbulence in a single set of equations: for example CLUBB (Thayer-Calder et al., 2015) applies such an approach in multiple sub-columns to represent a variety sub-grid-scale eddies and clouds. The convective scheme in the GFDL AM3 model (Donner, 1993; Donner et al., 2001, 2011) considers attempts to parameterise some mesoscale structure in addition to the updraughts and downdraughts, using cloud distributions derived from observations. Finally, super-parameterisation uses an embedded cloud resolving model (typically 2D) inside each column of the host model – this approach is well suited to representing aerosol–cloud interactions (e.g. Wang et al., 2011), but at a very high computational cost and still lacking non-local interactions (i.e. the ability for convective elements at the edge of one host-model column to interact with those at the edge of the neighbouring column other than via the large-scale dynamics).

The Convective Cloud Field Model (CCFM), introduced by Nober and Graf (2005) and developed further by Wagner and Graf (2010), provides another approach, representing a spectrum of different convective clouds within the grid cell, with the number of each cloud type dynamically determined by the environment. Each cloud type is represented by a separate realisation of a physical cloud model, with its own horizontal area, vertical velocity and in-cloud microphysics. In Kipling et al. (2017), CCFM was further extended with a sub-cloud dry convection model to describe the triggering of moist convection and determine the cloud-base vertical velocity crucial for aerosol activation, and evaluated in the global model ECHAM6–HAM2 both against observations, performing comparably to the standard Tiedtke–Nordeng bulk mass-flux convection scheme used in that model and showing an improvement in the diurnal cycle of convection in certain regions. The CCFM cloud spectra themselves have been evaluated against observations by Labbouz et al. (2018).

We use CCFM here to study the impact of anthropogenic aerosol emissions on convective clouds in a model which can represent both local variations in the convective cloud field and feedbacks via the global atmosphere (though still not those via the ocean, without moving to a coupled atmosphere–ocean GCM). In this way, we quantify the responses of the parameterised convective cloud fields in several regions to changing aerosol, and ask which physical processes are dominating these responses.

2 Model description

2.1 The ECHAM–HAMMOZ global composition–climate model

The modelling framework used here is as in Kipling et al. (2017); further details can be found there but we repeat the main points here for clarity. ECHAM–HAMMOZ is built upon the global atmospheric general circulation model ECHAM6.1 (Roeckner et al., 2003; Stevens et al., 2013), coupled to the interactive aerosol module HAM2.2 (Stier et al., 2005; Zhang et al., 2012). The system also includes a gas-phase chemistry model (the “MOZ” part), but this is not active in the configuration used here which includes only a simplified sulfate precursor scheme driven by DMS and SO_2 emissions which drives condensation and new particle formation.

Developed at the Max Planck Institute for Meteorology, ECHAM6 (Roeckner et al., 2003; Stevens et al., 2013) is based around a spectral dynamical core using a vorticity–divergence formulation. In the vertical, a hybrid sigma/pressure coordinate is used. The physical parameterisations are implemented on a Gaussian grid corresponding to the spectral truncation, with advection in grid-point space based on the semi-Lagrangian scheme of Lin and Rood (1996).

The aerosol module HAM2 (Stier et al., 2005; Zhang et al., 2012) uses a two-moment modal approach to resolve the particle size distribution, which is based on M7 (Vignati, 2004) with four soluble and three insoluble modes. The particles in each mode are an internal mixture of up to five aerosol components (sulfate, sea salt, black carbon, particulate organic matter and mineral dust).

As in many models, clouds are divided into large-scale stratiform clouds and convective clouds. The former use a two-moment microphysics scheme (Lohmann et al., 2007; Lohmann and Hoose, 2009) with prognostic variables for liquid water content, ice content, droplet number concentration and ice particle number concentration CDNC and ice crystal number concentration (ICNC). Cloud cover fraction uses the Sundqvist et al. (1989) diagnostic scheme is diagnosed based on relative humidity (Sundqvist et al., 1989). In standard ECHAM–HAM, convective clouds are parmeterised with a bulk mass-flux scheme (Tiedtke, 1989; Nordeng, 1994) – we use this for "control" simulations, but our main results are based on replacing this with the Convective Cloud Field Model (CCFM) described in Section 2.2.

In this study, we use version ECHAM6.1–HAM2.2–MOZ0.9 in ECHAM–HAM configuration (i.e. with the MOZ chemisty switched off) at T63L31 resolution. This corresponds to about $1.875°$, with 31 vertical levels and a model top at $10\,\mathrm{hPa}$. As in Kipling et al. (2017), on top of the "standard" configuration, we use the Abdul-Razzak and Ghan (2000) aerosol activation scheme for stratiform clouds, including a multi-bin distribution of updraught velocities following West et al. (2014).

2.2 The Convective Cloud Field Model (CCFM)

CCFM is a spectral convective parameterisation which aims to represent the large-scale effects of an ensemble of multiple convective cloud types within each GCM column. This is based on the framework of Arakawa and Schubert (1974), coupled with an explicit entraining plume model for each type of cloud with embedded aerosol activation and cloud microphysics. The heterogeneous cloud types are forced by their grid-scale environment, and each has an impact on this shared environment via entrainment and detrainment; these impacts can in turn produce a feedback on other cloud types. The resulting interactions, characterised in terms of competition for convective available potential energy (CAPE), form a set of Lotka–Volterra type equations. If convective quasi-equilibrium is assumed, these equations can be solved to determine the number of clouds of each type in the ensemble.

The individual cloud types are represented by a steady-state entraining plume model following Simpson and Wiggert (1969) and Kreitzberg and Perkey (1976), with an entrainment coefficient inversely proportional to the cloud radius. Cloud microphysics within the plume are calculated according to the one-moment bulk scheme used in ECHAM5 (Lohmann and Roeckner, 1996; Zhang et al., 2005). Without implementing a full two-moment microphysics scheme, this has been extended with a simple treatment of the evolution of CDNC within the rising parcel as in Labbouz et al. (2018) – whereas in Kipling et al. (2017) CDNC was assumed to remain constant from activation at cloud base to cloud top. In the revised scheme, the CDNC derived from cloud-base activation is updated as the parcel rises with accretion, autoconversion, freezing and dilution by entrainment acting to reduce CDNC. (The activation of additional droplets above cloud base is not currently included).

The set of possible cloud types in CCFM is specified according to a range of starting radii between 200 m and the depth of the planetary boundary layer (PBL); an ensemble of 10 different entraining plumes is run over this range, each of which will develop differently as it rises in terms of its radius, velocity, moisture content and microphysics etc.

Further details of CCFM can be found in Wagner and Graf (2010) and Kipling et al. (2017).

2.3 Aerosol coupling

There are a number of mechanisms by which, without CCFM, ECHAM–HAM already supports aerosol effects on climate: direct radiative effects by scattering and absorption; semi-direct effects as cloud (both large-scale and convective) adjusts to the modified thermal profile; the cloud albedo effect due to changes in CDNC in the large-scale cloud scheme; and effects on (large-scale) cloud microphysics due to changes in CDNC, e.g. enhanced liquid water path due to rain suppression.

When using the standard Tiedtke–Nordeng convection scheme, there is no explicit coupling of aerosols and convection; however both the direct radiative effects and those on the large-scale cloud scheme (Lohmann et al., 2007) may nevertheless invoke a convective feedback. As mentioned above, Lohmann (2008) introduced aerosol-aware two-moment microphysics experimentally into this convection scheme, subject to the limited information available on vertical velocity and variation between clouds. With CCFM, these latter points can be taken into account much more explicitly since cloud-base vertical velocity is estimated directly from the sub-cloud triggering model, and the variation across the cloud spectrum represented explicitly (Kipling et al., 2017).

Activation at cloud base for each CCFM cloud type is calculated using the parameterisation of Abdul-Razzak and Ghan (2000), as in the large-scale cloud scheme, but using the convective-scale updraught velocity to determine CDNC at cloud base. This gives rise to two distinct types of aerosol–convection effects:

microphysics effects due to changes in droplet number propagating through the convective cloud microphysics, including changes in autoconversion rates, glaciation and associated latent heat release etc. (Heikenfeld et al., 2019), which affect the development of a given cloud type as the parcel rises, in turn potentially changing the balance of different cloud types in the competition for CAPE.

anvil effects due to changes in the number (and thus size) of droplets and ice particles detrained from CCFM into the large-scale cloud scheme, which implemented as in Lohmann (2008) so that if convective cloud detrains with a greater CDNC or ICNC than that of any pre-existing large-scale cloud, then the large-scale CDNC or ICNC will be increased to match (though never reduced). This does not directly affect the development of the convective plumes but will alter their radiative effects, potentially feeding back on subsequent convection via changes to the thermodynamic profile and circulation. (The parameterised updrafts themselves do not interact with the radiation scheme directly, only via the detrained condensate as is the practice in many other models.)

In addition to these effects arising from aerosol interacting directly with convective cloud, there are the semi-direct effects due to aerosol–radiation interactions altering the thermodynamic profile and hence the CAPE and convective inhibition (CIN) in the environment. Particularly in the context of heating due to absorbing aerosol, these effects have been shown to have a significant effect on convective behaviour (e.g. Ackerman et al., 2000; Yamaguchi et al., 2015) which may dominate over the microphysical pathway in certain regimes.

In both the CCFMall_* and CCFMµphy_* simulations, the modelled CDNC is used in the microphysical parameterisations of the CCFM cloud model, enabling the microphysical effects; in CCFMall_* it also controls the number of droplets detrained into the large-scale cloud scheme, enabling the anvil effects, while in CCFMµphy_* only the bulk condensate is detrained without any explicit CDNC or size distribution (as when Tiedtke–Nordeng is used in standard ECHAM–HAM). In CCFMfix_*, the activation calculation is bypassed altogether; a fixed CDNC of $100\,\mathrm{cm}^{-3}$ is assumed in all CCFM convective clouds, and bulk condensate is detrained.

CCFM is only able to represent a subset of the possible aerosol effects on convective microphysics through changes in rain formation rates (autoconversion and accretion), and hence the amount of cloud water available to freeze. However, this pathway appears to be key to aerosol effects on convective clouds (Heikenfeld et al., 2019) and the approach is conceptually able to represent the thermodynamic invigoration proposed by Rosenfeld et al. (2008), even though it does not account for the separation of processes into latent heat release from freezing followed by off-loading of the condensate mass by falling precipitation Grabowski and Morrison (2016), and it is important to recognise the limitations of the Lagrangian entraining plume for representing other proposed mechanisms. In particular, the Lagrangian perspective cannot easily describe the non-instantaneous fall of precipitation through the plume as it rises, and CCFM does not currently attempt to do so. This means that, for example, the Fan et al. (2013) mechanism cannot possibly be captured since it hinges on changes to the fall speed. Similarly, in the absence of finite fall speeds, a proper representation of the melting of falling ice is not possible.

3 Experimental set-up

3.1 Simulations

In order to quantify the role of each of these mechanisms, including rapid adjustments and feedbacks, we have run the model in a number of different aerosol-coupling configurations which differ in the inclusion or exclusion of one of these mechanisms, as shown in Table 1.

Each configuration is run with both present-day (PD, year 2000) and pre-industrial (PI, year 1850) climatological emissions of aerosols and precursors, following the AeroCom Phase II/ACCMIP recommendations (http://aerocom.met.no/emissions.html). Only aerosol emissions differ between the simulations in each pair: greenhouse gases, ozone, sea-surface temperatures (SST) etc. are fixed to present-day climatology in all cases. In the case of SST and sea-ice, these use a 1979–2008 climatology of the AMIP2 dataset (https://pcmdi.llnl.gov/mips/amip/amip2/).

The simulations have each been run for a period of 10 years (plus 15 months , of spin-up). To illustrate the aerosol perturbation that may lead to any aerosol–convection interactions, Figure 1 shows the differences between the CCN concentrations at the surface, large-scale cloud base and convective cloud base in the PD and PI simulations. The concentrations at convective cloud base look very similar to those at the surface: particles are mixed very rapidly throughout the planetary boundary layer (PBL)PBL, and if convective cloud triggers in the model it does so very close to the PBL top. (For large-scale cloud on the other hand, the cloud base can sometimes be much more decoupled from the PBL in the model.) These highlight strong increases in CCN concentrations in China and India, but only moderate increases in other regions of convective activity (e.g. over the Amazon basin).

3.2 Analysis

The set of model configurations, with aerosol coupling processes successively activated, allows the response of any given model output to each process to be quantified via the difference between two of these configurations as detailed in Table 2.

We analyse this information from three different perspectives. Firstly, we look at the precipitation fields averaged over the whole 10-year period to identify the processes which affect the climatological distribution of precipitation in the model.

Secondly, we construct histograms showing the joint distribution of the radii and tops of the individual convective plumes represented in CCFM (as introduced in Kipling et al., 2017), in order to understand the morphological responses at the convective scale in several regions with different convective regimes. The regions considered are the Amazon basin (continental deep convection), India and China (monsoon-driven, and with the largest PD−PI CCN increase) and the Caribbean (Atlantic trade cumulus).

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In order to distinguish meaningful signals indicating aerosol effects from the noise due to the limited number of years in the simulations, we have carried out statistical significance testing at the 95% level using a two-sided paired samples t-test, where the the PD and PI values for each year are treated as independent paired samples from their underlying distributions. This is visualised in the figures either by stippling over the areas of significance (for maps and 2D histograms) or by shading the corresponding confidence interval (for line plots).

4 Results

4.1 Mean precipitation response

The 10-year mean precipitation response to anthropogenic aerosol in the simulations with both Tiedtke–Nordeng and CCFM convection is shown in Figure 2. In addition to the "all effects" panel which shows the PD−PI difference with all feedbacks active, this is broken down into the separate large-scale and CCFM responses via the additional simulations as described above. (For Tiedtke–Nordeng, only large-scale response mechanisms exist.) These effects are of a similar magnitude and in many regions they can oppose one another such that the overall precipitation change is not clearly driven by one mechanism in particular. CCFM and the large-scale effects drive a decrease in precipitation in China, while there is little change in India due to compensation between large-scale and CCFM effects; partial compensation is also observed over the Amazon. Tiedtke–Nordeng, with only large-scale effects represented, shows some differences in the regional pattern of responses (e.g. in India and Australia), but also similarities in areas like China where the CCFM effect on precipitation is relatively weak. In the zonal mean, the difference remains noisy, with the only overall feature being a very small decrease in precipitation in the tropics coming from the large-scale effects – and even this has little statistical significance.

Figure 3 shows the fraction of total precipitation which comes from the convective parameterisation when using CCFM (rather than from the large-scale cloud and precipitation scheme), and also the PD−PI change due to all effects and due to the convective microphysics alone. With CCFM, a slightly larger fraction of the total precipitation is produced in the convective parameterisation compared to Tiedtke–Nordeng (not shown), although this split is largely arbitrary and often varies from one model configuration to another (relating more to the difference between resolved and unresolved scales than the difference between observable cloud types). In both cases the fraction of tropical precipitation described as convective by the model is significantly larger than that classified as such by radar observations (Labbouz et al., 2018). This is likely In addition to the above point about scale separation, this may also in part be due to the absence of mesoscale organisation with embedded stratiform precipitation in parameterised convection, one of the features highlighted by the Tropical Ocean–Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE; Houze, 1997; Halverson et al., 1999). The main pattern visible in the response of the convective precipitation fraction to PD aerosol loading is a small but statistically significant decrease over the continental northern mid-latitudes, coming from a combination on of large-scale and CCFM effects (though the latter do not show as significant in isolation), while a smaller decrease in the southern mid-latitudes results from the large-scale effects alone. This becomes clearer when looked at in the zonal mean.

It is important however to appreciate that the constraints on total precipitation are stronger in an atmosphere-only model with fixed SST such as this than they would be in a coupled atmosphere–ocean model where the SST is able to vary in response to a perturbation, providing additional mechanisms for feedbacks including changes to global evaporation rates.

4.2 Regional cloud field response

The explicit sub-grid-scale cloud fields of CCFM allow us to look more closely at the effects on simulated cloud morphology in a way that is not possible with a bulk mass-flux scheme like Tiedtke–Nordeng. The left column of Figure 4 shows the joint distribution of the maximum radius and cloud-top pressure of the parameterised clouds in four different regions (Amazon, India, China, Caribbean) with four additional regions shown in the supplement (Congo, Indonesia, SE Atlantic, SE Pacific); The right column shows the PD−PI change in these distributions. The different regimes are clear, with the Amazon (characterised by continental deep convection) and India and China (characterised by monsoon-driven convection) showing significant greatest contribution of broad deep updraughts (upper right of the plots), and China showing the greatest proportion of very deep clouds. The SE Atlantic and Pacific (marine stratocumulus, in supplement) are confined to narrow, shallow updraughts (lower-left) as we might expect; the Caribbean (shallow convection, with occasional transition to deeper clouds) lies somewhere in between.

The change in these distributions between PI and PD aerosol conditions does not show a consistent pattern, but varies considerably between regions and regimes. Although there is some noise, many coherent features in the responses do show statistical significance. In the Amazon, we see a shift from broad deep clouds to narrower and shallower ones, either due to reduced development of the clouds or the triggering of clouds from smaller initial parcels. As there is no direct mechanism by which aerosol can retard the development of an individual cloud in CCFM, this is likely to be the result of either reduced CAPE in the environment, or reduced CIN allowing smaller clouds to trigger. India is similar, but with only a slight lowering of the deepest clouds. In China, the dominant effect is simply an overall reduction in the amount of convective cloud (with the deep clouds most affected and only a slight increase in the smallest and shallowest clouds), suggesting a reduction of the large-scale convective forcing in the region – perhaps associated with changes to the monsoon circulation (e.g. Guo et al., 2013; Li et al., 2016) – or increased atmospheric stability due to the semi-direct effect of absorbing aerosol. The Caribbean, on the other hand, exhibits both a deepening of the main shallow-cloud regime, and also an increase in the small amount of much deeper cloud, suggesting some form of convective invigoration.

In order to disentangle these different responses, we turn to look at the separate contributions of the different mechanisms. Figure 5 shows these regional cloud field responses broken down into large-scale and convective mechanisms as listed in Table 2. (A further breakdown into ACI, ARI and the convective microphysics and anvil effects, is shown in the supplement.)

In the three deep convective regions (Amazon, India and China), the total aerosol effect on the cloud field is clearly dominated by that which occurs when only the large-scale mechanisms are active, as shown in the LS row of Figure 5. The additional contribution from the microphysical effects within CCFM (and their feedbacks) tends to partially counteract the effect of the large-scale changes, but the overall aerosol response remains qualitatively similar to the large-scale response alone. In addition, even where the contribution from the CCFM effects approaches a similar magnitude to that from the large-scale effects, the former show relatively little statistical signifance. Compensation between large-scale and microphysical aerosol effects have been observed in other recent studies, for instance in CRM simulations of the impact of biomass-burning aerosols on convection by Hodzic and Duvel (2018).

In the shallow-to-deep transition environment of the Caribbean, however, the weaker large-scale forcing leaves room for further vertical development of the convective cloud, and the total effect appears to be driven by the convective microphysics (as shown in the CCFM row of Figure 5) which in this region is statistically significant. The response via large-scale mechanisms alone is quite small and indistinct in comparison, with almost no statistical significance. Coupled with the results in the other regions, this suggests that where aerosols cause a change in the large-scale convective forcing or atmospheric stability this is the dominant effect. While direct impacts of the aerosol on convective microphysics are present, on larger scales their effects are overpowered by such changes to the "first-order" parameters controlling the convective behaviour. In particular, the quasi-equilibrium hypothesis ensures that, by construction, CCFM and other Arakawa–Schubert-type schemes are constrained to balance the large-scale forcing by the nature of their closure (at least in the mean, although changes in the distributions of cloud type and precipitation rate are still possible). Furthermore, the limitations of an atmosphere-only model mean that modulation of the large-scale forcing via SST feedbacks are not possible.

The idea that aerosol effects on convective microphysics are easily obscured by changes to the large-scale forcing is consistent with idealised studies (e.g. Lee et al., 2008; Fan et al., 2009) and the review of Fan et al. (2016), but is here demonstrated in the context of a global model with a full range of feedbacks and its own limitations. The stronger impact via convective microphysics in more weakly-forced shallow convection regimes like the Caribbean is in line with the conclusions of Storer et al. (2010) in a more idealised context. In a strongly-forced deep convective environment, there may be sufficient energy input that glaciation is already occurring and any aerosol modulation of the latent heat release will have little effect; while in a more weakly-forced shallow-to-deep transition regime, such changes in latent heat release with the convective cloud may be enough to "tip" shallow clouds into transition or vice versa.

The changes to the vertical profile of rain and ice production (and associated latent heat release) within the CCFM-parameterised convective clouds (Figures 6 and 7) show that the response in the Amazon and China is again dominated by changes to the large-scale forcing, while in the Caribbean both are dominated by the response of the convective microphysics. Over India, their overall effect appears to be a more complex combination of the two mechanisms, even though the impact on the spectrum of cloud-top pressure is largely that of the large-scale forcing. The delaying of rain production to higher levels seen in the Caribbean, and greater ice production above, is exactly the signature of convective invigoration as described by Rosenfeld et al. (2008), suggesting that this can be a regionally important effect within a full global model, but only in a limited range of conditions. India is an interesting case, in that the overall effect on precipitation production is dominated by a reduction from the convective microphysics (not the anvil effects, as confirmed by Figures S5 and S6 in the supplement), even though the impact on the spectrum of cloud-top pressure is largely that of the large-scale forcing. This can be understood in terms of aerosol-suppressed autoconversion reducing warm rain production; however unlike in the Caribbean much of the cloud in this region is already glaciating, and the effect of additional rain suppression on the cloud field dynamics is much smaller in this case.

4.3 Implications for radiative forcing

The direct and indirect responses of parameterised convective clouds to aerosol have the potential to contribute positively or negatively to the overall effective radiative forcing due to aerosol–cloud interactions (ERFaci). These cannot in general be captured by the bulk mass-flux parameterisations commonly used in global climate models, and thus CCFM provides a novel and potentially useful tool for investigating their role from a modelling perspective at the global scale.

With Tiedtke–Nordeng, there is only a single class of aerosol–cloud interactions represented in the large-scale cloud and precipitation; using CCFM this contribution (ERFaci_ls) is joined by that due to interactions between aerosol and convection scheme itself (ERFaci_cv) if these are activated. These two combine to produce the total ERFaci. The extra ERFaci_cv seen in CCFM when these effects are activated is small and of marginal statistical significance from 10 years of simulation (95% confidence interval $-0.15 \pm 0.17\,\mathrm{W\,m^{-2}}$).

5 Conclusions

By explicitly considering convective microphysics and the sub-grid-scale heterogeneity of convective cloud, the Convective Cloud Field Model (CCFM) allows a physically-based parameterisation of aerosol–convection interactions to be included in a global atmospheric model. This extends the more usual state of the art, where only aerosol interactions with large-scale liquid clouds are explicitly represented in global models.

Using 10-year ECHAM–HAM–CCFM simulations with each of the interaction mechanisms (de-)activated in turn, we have shown how the different processes and feedbacks typically interact to produce an overall response. The global mean precipitation response is not dominated by one process, but results from a combination of convective and large-scale microphysics, and feedback from aerosol–radiation interactions. To a large extent, these tend to counter one another, as expected based on the energetic control of global mean precipitation especially in an atmosphere-only mode with fixed SST. Investigation of how aerosol affects the distribution of precipitation intensity in the model, even if the total remains fixed, may be worth further study, as would the future extension to a coupled atmosphere–ocean model.

The impacts on cloud field morphology are also a combination of large-scale and convective mechanisms, with considerable regional variation. In the deep convective regions, the overall response is dominated by the combination of large-scale radiative and cloud effects (including their feedbacks on circulation), with a smaller countering contribution from convective microphysics (which is often not statistically significant) via changes in the vertical profiles of process rates within the CCFM cloud model. In the Caribbean shallow convection region, however, the response of the convective parameterisation itself to the aerosol dominates and is statistically significant, with rain suppression, enhanced glaciation and deeper clouds indicative of convective invigoration.

These results are consistent with previous more idealised studies which have suggested that shallower regimes with weaker forcing may be more susceptible to aerosol-induced invigoration than strongly-forced deep convection, and that aerosol microphysical effects become apparent only when they are not overpowered by the greater effect of changes to the large-scale forcing (e.g. Lee et al., 2008; Fan et al., 2009; Storer et al., 2010). These conclusions have in general been based on idealised or limited-area models; this study shows evidence that they also hold in the context of the global atmosphere with all its feedbacks. However, the assumption of convective quasi-equilibrium in CCFM and many other convective parameterisations implicitly requires the large-scale forcing to be the dominant control on convection; at least a relaxation of this assumption may be required to investigate any cases where aerosol might have a dominant effect *despite* changes to the large-scale forcing.

However, the results also show that, allowing for feedbacks on convective forcingvia energetic and water-budget constraints, the traditional invigoration hypothesis does not apply globally. This has implications in particular for nested convection-resolving simulations in which the large-scale forcing remains fixed, suppressing these feedbacks which may be key to the total response of the system to increased aerosol.

From an effective radiative forcing perspective, a small additional effective forcing is seen from the aerosol–convective interactions captured in CCFM, but with 10 years of data this is of marginal statistical significance.

CCFM currently only represents a subset of the possible aerosol–convection interactions, especially in the context of mixed-phase microphysics; however these interactions appear to be of particular importance for the overall aerosol efffect on convection (Heikenfeld et al., 2019). Revision of the cloud model beyond the limitations of the Lagrangian entraining plume approach (which cannot include a proper treatment of hydrometeor sedimentation and accretion by rain or falling ice) to allow the incorporation of more sophisticated microphysics may open the way to capturing additional ice- and mixed-phase aerosol effects. We have demonstrated, however, that CCFM is already able to identify a (modelled) susceptibility of one convective regime in particular (trade cumulus as found in the Caribbean) to aerosol-induced invigoration that is not damped or obscured by larger-scale dynamics. It is our hope that this hypothesis can be tested further by a comparison with detailed observations and cloud-resolving modelling on domains sufficiently large to capture these larger-scale feedbacks.

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Code and data availability. The relevant model source code can be accessed via the HAMMOZ SVN repository (https://svn.iac.ethz.ch/external/echam-hammoz/echam6-hammoz/branches/uni_oxford_climate_processes/ccfm_diag_paper) under the revision number 4416 (see the HAMMOZ Redmine for access and licensing conditions: https://redmine.hammoz.ethz.ch/projects/hammoz/wiki). The simulation output used in this paper can be obtained by contacting the corresponding author.

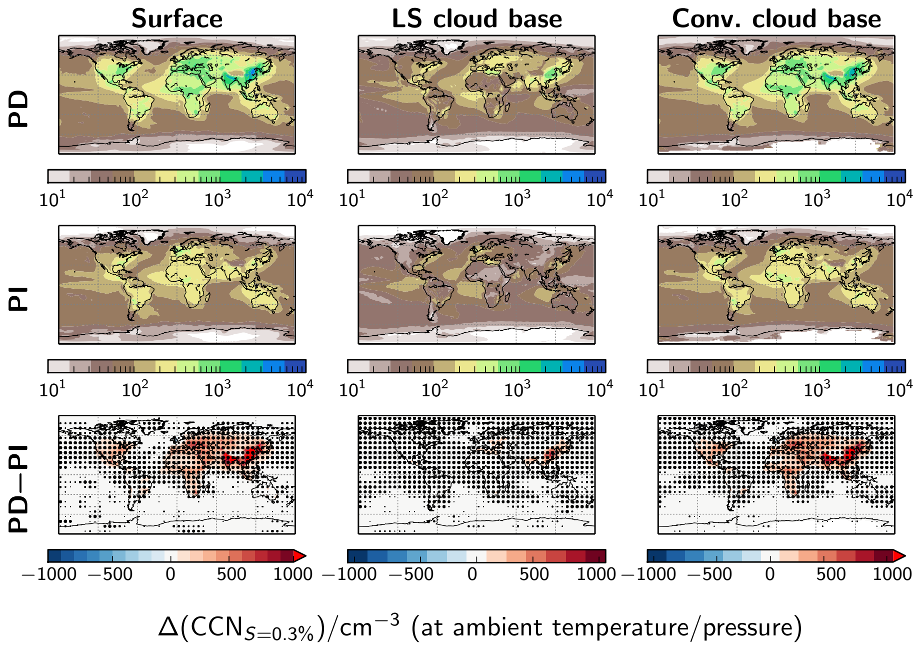

Figure 1. Annual mean CCN concentrations at the surface (left), large-scale cloud base (centre) and convective cloud base (PD−PI) from simulations using CCFM convection under PD (top row) and PI (middle row) aerosol emission scenarios, and the difference (bottom row). Specifically, these come from the CCFMall_ari simulations (see Table 1); however the difference in the others is small. (PD=present-day aerosol; PI=pre-industrial aerosol; stippling indicates areas where the PD−PI difference is statistically significant at the 95% level.)

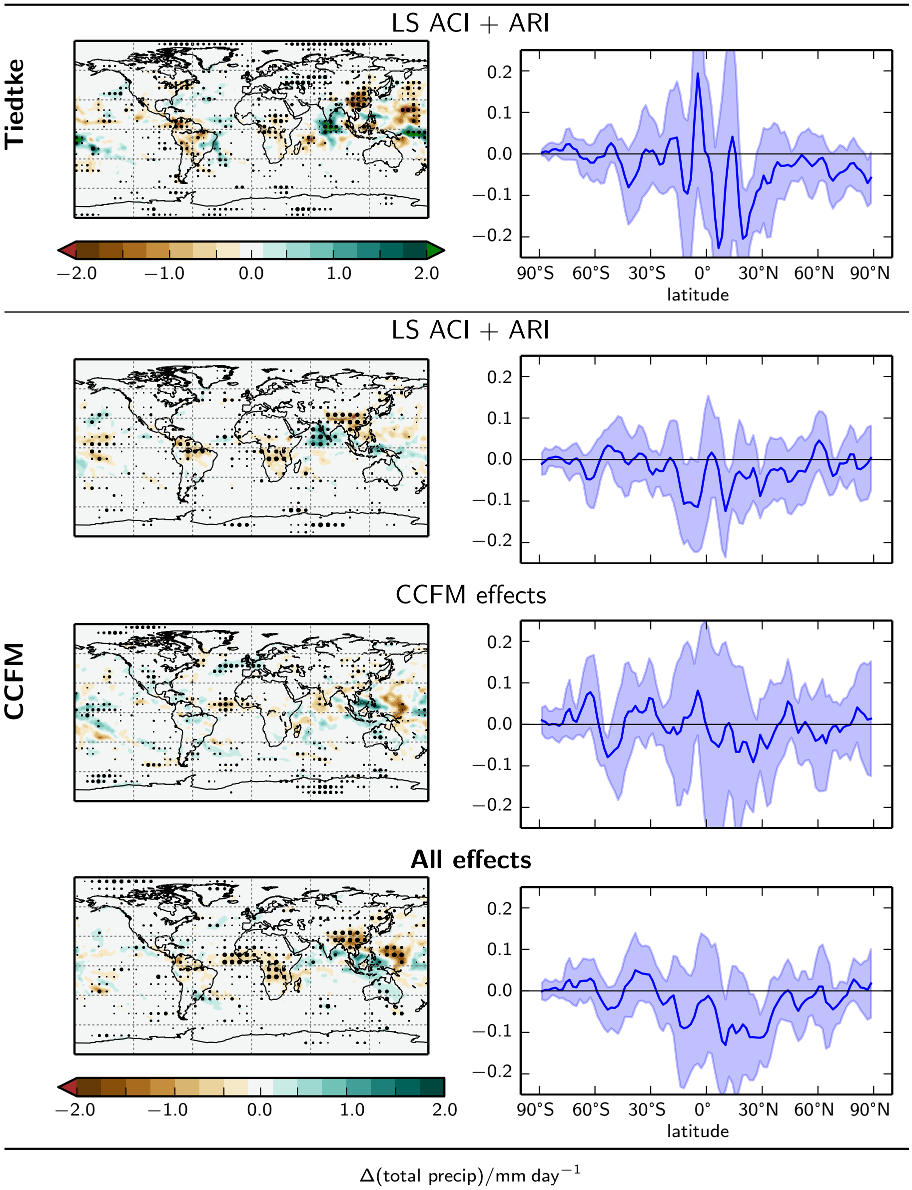

Figure 2. Annual mean precipitation response (PD−PI) in ECHAM–HAM with Tiedtke (top) and CCFM (below) convection, with the latter decomposed into large-scale and convective mechanisms as listed in Table 2. The plots on the right-hand side show the zonal mean of the maps on the left. A further breakdown into individual process effects is included in the supplement. (PD=present-day aerosol; PI=pre-industrial aerosol; stippling indicates areas where the PD−PI difference is statistically significant at the 95% level, while the corresponding confidence interval is shaded on the zonal mean plots.)

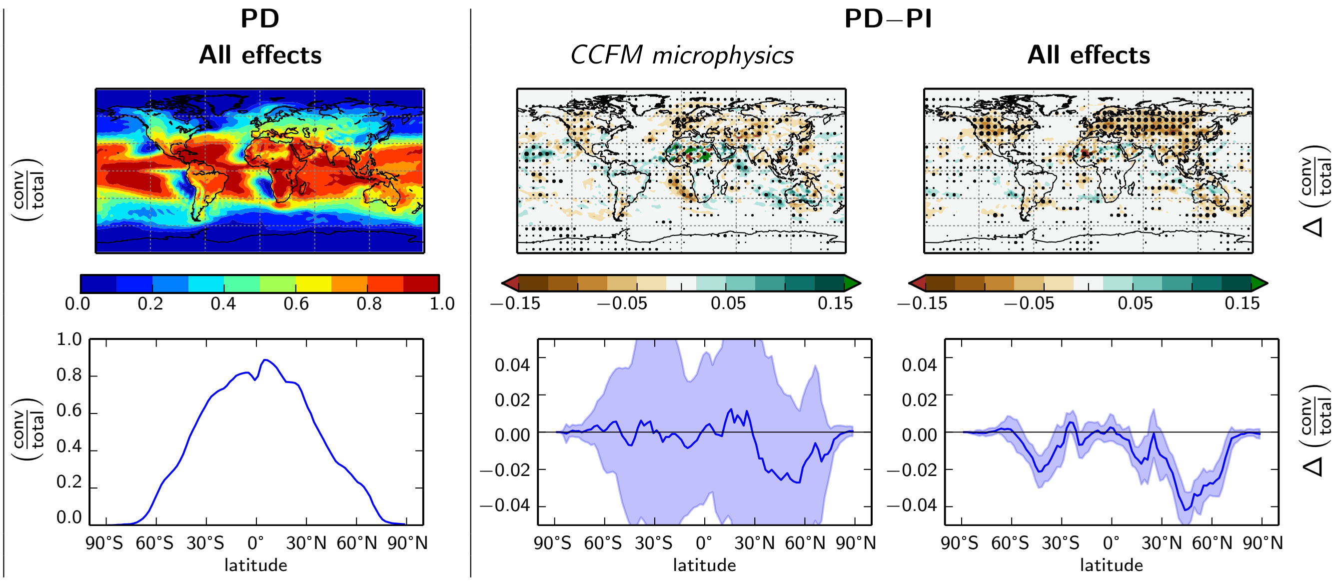

Figure 3. 10-year mean PD (left) and PD−PI change in (centre/right) fraction of precipitation which comes from CCFM (rather than resolved large-scale/stratiform cloud). The right-hand plot shows the total response, while the middle plot shows the component due to CCFM microphysics alone. The plots on the bottom row show the zonal mean of the maps above. (PD=present-day aerosol; PI=pre-industrial aerosol; stippling indicates areas where the PD−PI difference is statistically significant at the 95% level, while the corresponding confidence interval is shaded on the zonal mean plots.)

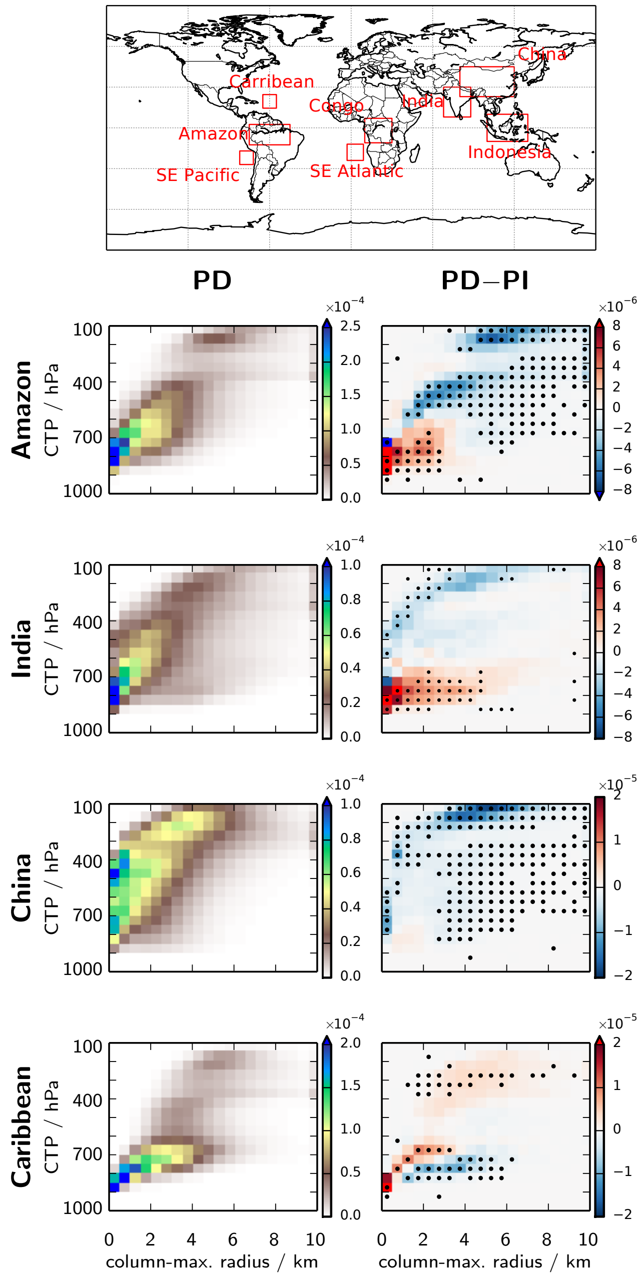

Figure 4. Response of the CCFM cloud top–radius distribution in four different regions, as shown in the map (top, along with four additional regions included in the supplement). Note that the "India" region used for analysis is restricted to the land points in the box. The left column shows the distribution under PD aerosol emissions; the right column shows the difference from PI aerosol emissions (with all effects included). The radius on the x-axis indicates the broadest part of a given entraining plume in the CCFM 10-member cloud-type ensemble over its whole height. (PD=present-day aerosol; PI=pre-industrial aerosol; black dots indicate histogram bins where the PD−PI difference is statistically significant at the 95% level.)

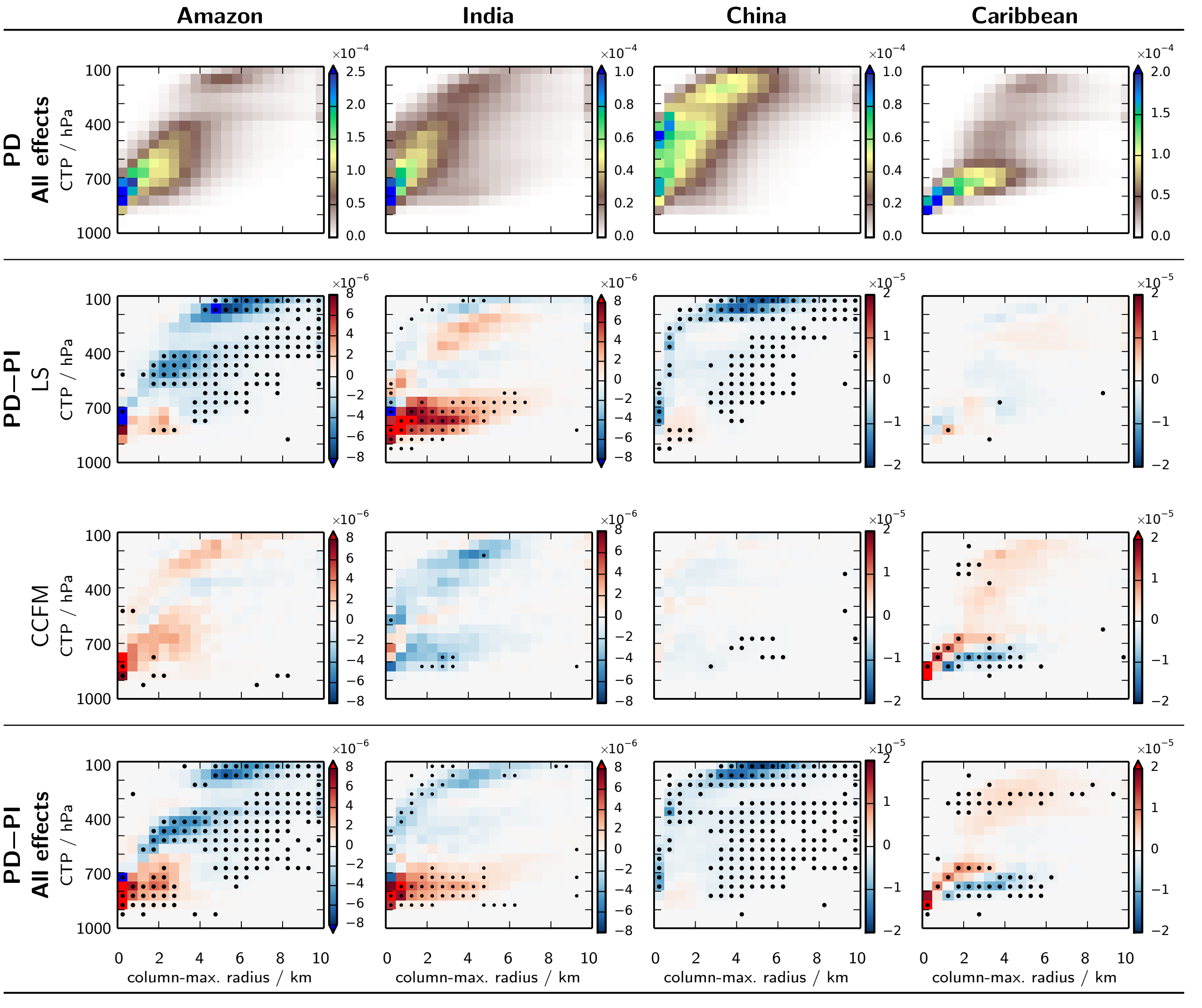

Figure 5. Regional cloud field response decomposed into its different mechanisms as listed in Table 2. The top row shows the PD distributions, while the bottom row shows the PD−PI difference (both with all effects included as in Figure 4); the middle rows show the contributions from large-scale and CCFM (convective) mechanisms. Note that the colour scales are identical between mechanisms to allow comparison of their magnitude, but not between the different regions. A further breakdown into individual process effects, along with additional regions, is included in the supplement. The radius on the x-axis indicates the broadest part of a given entraining plume in the CCFM 10-member cloud-type ensemble over its whole height. (PD=present-day aerosol; PI=pre-industrial aerosol; black dots indicate histogram bins where the PD−PI difference is statistically significant at the 95% level.)

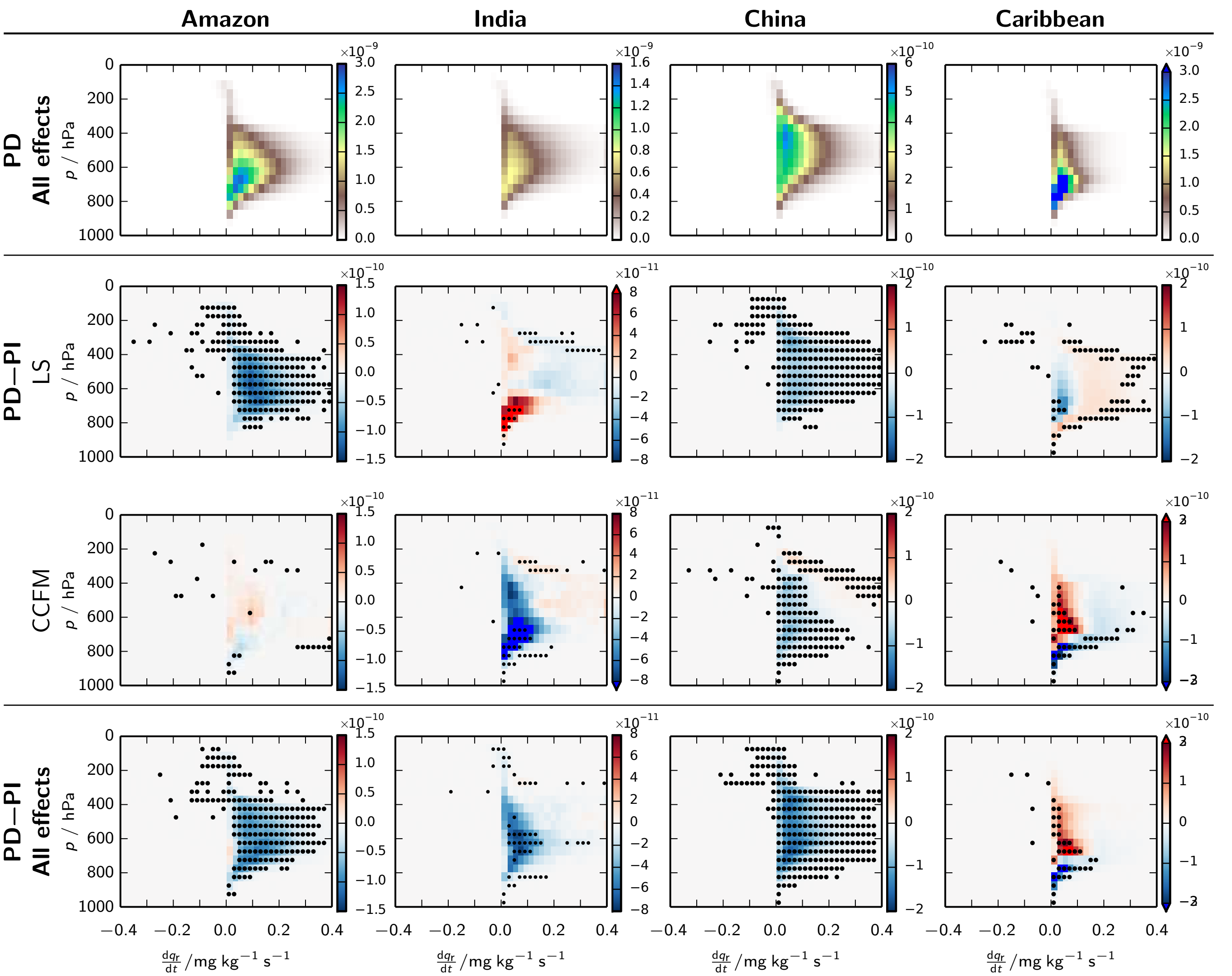

Figure 6. Regional change in the vertical profile of rain production within CCFM clouds, weighted by mass. The top row shows the PD distributions, while the bottom row shows the PD−PI difference (both with all effects included); the middle rows show the contributions from large-scale and CCFM (convective) mechanism. Note that the colour scales are identical between mechanisms to allow comparison of their magnitude, but not between the different regions. A further breakdown into individual process effects, along with additional regions, is included in the supplement. (PD=present-day aerosol; PI=pre-industrial aerosol; black dots indicate histogram bins where the PD−PI difference is statistically significant at the 95% level.)

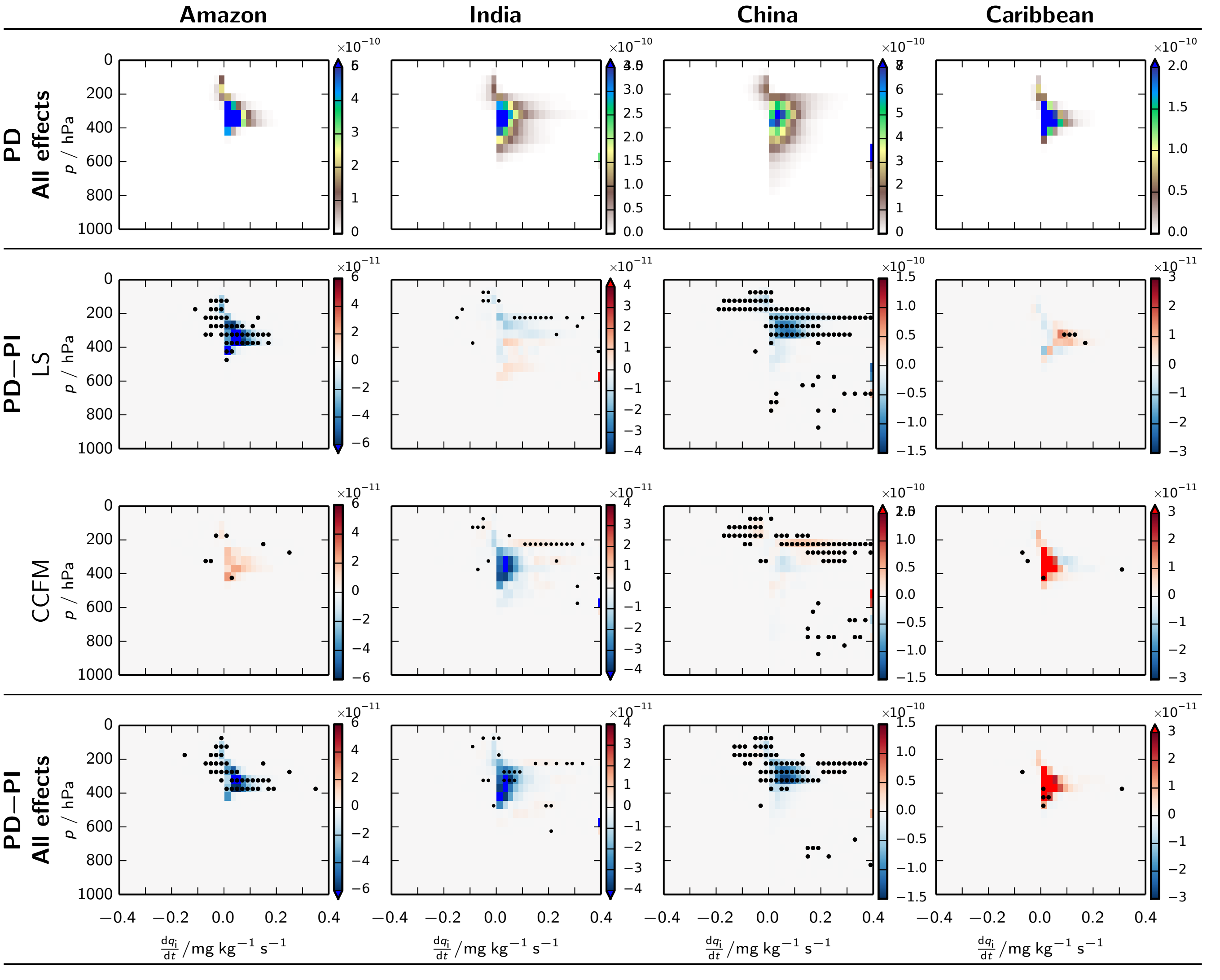

Figure 7. Regional change in the vertical profile of ice production (and consequent latent heat release) within CCFM clouds, weighted by mass. The top row shows the PD distributions, while the bottom row shows the PD−PI difference (both with all effects included); the middle rows show the contributions from large-scale and CCFM (convective) mechanism. Note that the colour scales are identical between mechanisms to allow comparison of their magnitude, but not between the different regions. A further breakdown into individual process effects, along with additional regions, is included in the supplement. (PD=present-day aerosol; PI=pre-industrial aerosol; black dots indicate histogram bins where the PD−PI difference is statistically significant at the 95% level.)

Table 1. Configurations used for aerosol effects in the ECHAM–HAM simulations. "Convective microphysics effects" refers to changes in microphysical process rates (autoconversion, accretion, freezing etc.) within the convective cloud as aerosol effects on droplet number propagate through the convective microphysics. "Convective anvil effects" refers to changes in the size distribution of droplets and/or ice particles detrained to the large-scale cloud scheme. (See Section 2.3 for further detail.)

Label	Includes
Tiedtke_noari	large-scale cloud coupling only
Tiedtke_ari	as above + direct radiative effects
CCFMfix_noari	large-scale cloud coupling only
CCFMμphy_noari CCFMfix_ari	as above + convective microphysics direct radiative effects
CCFMall_noari CCFMμphy_ari	as above + convective anvil microphysics effects
CCFMall_ari	as above + direct radiative convective anvil effects

Table 2. How the separate contributions of each mechanism to the total aerosol effect is extracted by taking the difference between pairs of simulations. (**ARI**: aerosol–radiation interactions; **LS ACI**: large-scale aerosol–cloud interactions; **CCFM microphysics**: changes to autoconversion etc. in convective cloud; **CCFM anvil**: changes to size distribution of detrained condensate. See Section 2.3 for more detail.

Tiedtke	LS ACI	= Tiedtke_noari
	ARI	= Tiedtke_ari − Tiedtke_noari
	All effects	= Tiedtke_ari
CCFM	*LS ACI*	= CCFMfix_noari
	ARI	= CCFMfix_ari − CCFMfix_noari
	LS ACI + ARI	= CCFMfix_ari
	CCFM microphysics	= CCFMμphy_ari − CCFMfix_ari
	CCFM anvil	= CCFMall_ari − CCFMμphy_ari
	CCFM effects	= CCFMall_ari − CCFMfix_ari
	All effects	= CCFMall_ari