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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Fast responses on pre-industrial climate from present-day aerosols in a CMIP6 multi-model study" *by* Prodromos Zanis et al.

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We would like to thank Reviewer #1 for the constructive and helpful comments. Reviewer's contribution is recognized in the acknowledgments of the revised manuscript. It follows our response point by point.

1) The Reviewer notes: "Section 1: Fast response vs. slow response discussion. I understand the use of these concepts, especially in view of intercomparing models. Imagine you have to talk to a wider audience interested in the "effective response" of climate to aerosol forcing in a naturally coupled climate system. What can the fast response analysis tell us about that ? I also understand that this concept and re-

lated time scale have more meaning on a global scale, but for regional analysis it is not that simple right ? Finally slow response is calculated only via ocean feedback, but there could be also continental reservoir (soil water) with much slower response than atmospheric processes which could induce delayed feedbacks in theory. In some region the oceanic mixed layer could also adjust to radiative perturbation on "intermediate" time scale (between fast and slow response)." A nice schematic overview of fast and slow responses concept in precipitation is presented in Fig. SB1 by Myhre et al. (2017) which breaks down the responses for three time scales. An instantaneous forcing due to perturbation of a radiative forcing agent may initially alter precipitation as a result of changes in the atmospheric radiative heating or cooling. The instantaneous change through radiation may further alter the atmospheric temperature, water vapor, and clouds, through rapid adjustments. The instantaneous radiative perturbation and rapid adjustments change precipitation on a fast time scale (from days to a few years) (fast responses). Climate feedback processes through changes in the surface temperature further alter the atmospheric absorption, which occurs on a long time scale (decades) (slow responses). In this way, the climate response to a forcing agent in the fixed SST and sea ice simulations presented in our paper is without any ocean sea ice response to climate change and therefore only weakly coupled to feedback processes, through land surface responses. The role of fast and slow drivers of precipitation changes is species dependent; for BC, fast stabilization effects due to atmospheric absorption can be important even when averaging on long time scales, while for sulfate the slow response dominates in global and zonal means (Samset et al., 2016; Shawki et al., 2018) even though at the regional level the fast response can be also important (Ganguly et al., 2012). Previous studies indicated that the fast precipitation response of BC aerosols dominates over their slow response for global precipitation changes (Andrews et al. 2010; Kvalevåg et al.; Samset et al., 2016; Liu et al., 2018). Ganguly et al. (2012) showed that the precipitation decreases over north-east India and Nepal region are due to the fast response to aerosol forcing based on aerosol emission changes from the preindustrial to present day. The following paragraphs were added in the Introduction: " A nice schematic overview of fast and slow responses concept in precipitation is presented in Fig. SB1 by Myhre et al. (2017) which breaks down the responses for three time scales; a) an instantaneous radiative perturbation may initially alter precipitation as a result of changes in the atmospheric radiative heating or cooling; b) the instantaneous change through radiation may further alter the atmospheric temperature, water vapor, and clouds, through rapid adjustments, leading to precipitation change on a time scale from days to a few years (fast responses); c) climate feedback processes through changes in the surface temperature may further alter the atmospheric absorption, which occurs on a long time scale of several decades (slow responses). Under the framework of the Precipitation Driver Response Model Intercomparison Project (PDRMIP), multiple model results indicate that the global fast precipitation response to regional aerosol forcing scales with global atmospheric absorption, and the slow precipitation response scales with global surface temperature response (Myhre et al. 2017; Liu et al., 2018)."

"The role of fast and slow drivers of precipitation changes is species dependent; for BC, fast stabilization effects due to atmospheric absorption can be important even when averaging on long time scales, while for sulfate the slow response dominates in global and zonal means (Samset et al., 2016; Shawki et al., 2018) even though at the regional level the fast response can be also important (Ganguly et al., 2012). Ganguly et al. (2012) showed that the precipitation decreases over north-east India and Nepal region are due to the fast response to aerosol forcing based on aerosol emission changes from the preindustrial era to present day. Previous studies indicated that the fast precipitation response of BC aerosols dominates over their slow response for global precipitation changes (Andrews et al. 2010; Kvalevåg et al. 2013). This “fast response” of precipitation to BC reductions tends to dominate the total response to BC, as also shown in recent PDRMIP results (Samset et al., 2016; Liu et al., 2018)."

2) The Reviewer notes: "Section 2: Information on the emission sectors should perhaps be a bit discussed. It is not clear for example if biomass burning emissions are

taken or not into account. Are parameterizations of natural emission also enabled." The historical CMIP6 input data were used for biomass burning emissions and anthropogenic emissions (van Marle et al., 2017; Hoesly et al., 2018). Natural emissions including dust and sea-salt are calculated interactively by all models following their own parameterizations, except CNRM-CM6-1 which used prescribed fields. The following paragraph was added: " As far as it concerns aerosol-cloud interactions all models include parameterizations for the first and second indirect effects except CNRM-CM6-1, CNRM-ESM2-1, IPSL-CM6A-LR and GISS-E2-1-G that have parameterizations only for the first indirect effect. The historical CMIP6 input data were used for the biomass burning emissions and anthropogenic emissions (van Marle et al., 2017; Hoesly et al., 2018) while natural emissions, including dust and sea-salt, were calculated interactively following their own parameterizations or used prescribed fields based on consistent offline calculations. The model simulations, assigned in Table 1 with "no interactive aerosol", use prescribed aerosol fields which are consistent with the CMIP6 emissions used in the rest of the models. " 3) The Reviewer notes: "Section 2: Table 1. There are a couple of models with “no interactive aerosol” , if they also differ from the “prescribed aerosol” category, how can they use the proposed emission scenario." Also Is the prescribed climatology consistent with the emission scenario and year used by other models (which consider year 2014 , i.e. when concentrations had already drastically decreased for some regions compared to the peak of the 70-80’s). How are the models dealing with indirect effects (some might have no indirect effects), perhaps that could be a usefull info in the table) ?" The models, with no interactive aerosol, use prescribed aerosol fields which are consistent with the CMIP6 emissions used in the rest of the models. In the case of GISS-E2-1-G model, the r1i1p1f1 experiment uses offline aerosol fields that are calculated using exactly the same model version with full chemistry and emissions turned on in the r1i1p3f1 experiment. In the IPSL-CM6A-LR simulations, tropospheric aerosol loads were prescribed as climatological data sets, produced through runs only using the atmospheric (LMDZ), land-surface (ORCHIDEE) and chemistry-aerosols (INCA) components of IPSL-CM using the CMIP6 input data

(Hoesly et al., 2018; van Marle et al., 2017) for biomass burning emissions and anthropogenic emissions. CNRM-CM6-1 used also prescribed aerosol fields which are consistent with the CMIP6 emissions. We added a paragraph in the revised manuscript as indicated in point 2 (of our response).

4) The Reviewer notes: "Section 2: L20 -24 : I was in fact a bit surprised to see such a positive ERF over the Sahara. I thought that the aerosol mixture (dominated by sulfate as mentioned by the authors, organics, and little bit of BC would be essentially diffusive enough to stand close to or over the "critical single scattering albedo" as determined by desert albedo : -Is it an effect of only BC (did not seem evident in supplement material) ? -I assume that cloud response contribution to ERF effect might be limited here (but maybe not for high clouds?). -But also could there be a positive feedback of dust aerosol (more absorbing and usually associated to a positive forcing over desert) contributing to the ERF – in response to dynamical changes ? (assuming of course that ESM account for on-line dust emissions). This "feeling" is reinforced by the result of e.g. CESM2 which clearly show a strong positive ERF signal over well known dust sub regions in Arabia and Thar desert. If such is the case, i.e. if simulated dust burden generally increase , that could be an interesting side conclusion." Similarly to our study, positive ERF values over reflective continental surfaces such as desert and polar regions were also detected in previous studies (Shindell et al., 2013; Myhre et al., 2013) and they were attributed to the fact that the very high surface albedo reduces the effect of scattering aerosols, while increasing the effect of absorbing aerosols, leading to a net positive forcing. In the case of CESM2 that shows a strong positive ERF there is an increase of both total AOD and absorbing AOD over the reflective desert regions in piClim-aer - piClim-control which is basically related to both sulfate and BC aerosols. There is however a decrease of total AOD over the sub-Saharan regions and Sahel as well as over the Taklamakan Desert and the desert regions in Australia. Furthermore, we have looked the dust optical depth changes between the two simulations. In part of Sahara desert there is a small increase in dust AOD while over sub-Saharan regions and Sahel there is a small decrease in dust AOD (in agreement with the total AOD

decrease). In these regions (Sahara and sub-Sahara) it seems that dust changes can contribute to the positive ERF. This is not the case for the Saudi Arabia and Thar deserts where dust AOD seems either to decrease (over Thar) or not changing (over Arabia) which would rather cause a negative (or no change) in ERF at the TOA. Thus the positive ERF values cannot be attributed to dust changes in these regions. Over the Taklamakan Desert and the desert regions in Australia there is a decrease in dust AOD which spatially coincide with the total AOD decreases which could contribute to small negative ERF at the TOA. We added that " Differences in natural aerosols like dust could potentially also contribute to the positive ERF (e.g. in the case of the strong positive ERF in CESM2)."

Figure I: Differences between piClim-aer and piClim-control at annual basis in CESM2 for a) total aerosol optical thickness (550 nm), b) absorbing aerosol optical thickness, c) dust aerosol optical thickness, and d) BC aerosol optical thickness.

5) The Reviewer notes: "Section 2: An other feature of interest to me was the rather strong negatve ERF change over south-eastern pacific (along southern America-coast) . How to explain this signal ? Is it a signature of aerosol interaction with low clouds amplifying the aerosol forcing ?" This magnitude of the negative ERF signal over south-eastern pacific (along southern America-coast) is not a robust feature among the models although there is a tendency for negative ERF values in most of the models. It is more clearly depicted in CESM2 model and then MRI-ESM2. Aerosol-cloud interactions is a plausible explanation. However a full analysis to decompose the aerosol ERF into components (following Ghan et al. 2013) is beyond the scope of this manuscript but certainly deserves a deeper investigation. It should be noted that for most of the models, all the necessary diagnostics for such a decomposition analysis are not yet available in ESGF. 6) The Reviewer notes: "Section 3.2: The results confirm previous studies. A question perhaps relevant is : has CMIP6 model climate sensitivity also changed with regards to aerosol radiative forcing / emissions compared to CMIP5 models, as is the case for GHG forcing (considering for example possible different cloud

responses) ? The climate sensitivity cannot be fully assessed in the fixed SST runs, but requires fully coupled ocean simulations. Recent work shows that CMIP6 models tend to have a higher range in climate sensitivity than the CMIP5 models (Zelinka et al, 2020). As far as it concerns the comparison of aerosol ERF between CMIP5 and CMIP6 models, we have compared our results (shown in Table 2) with those presented in Allen (2015) and those in Shindell et la. (2013).

We have added the following paragraphs:

"The global annual average of all aerosols ERF (-1$\pm$0.24 W m-2) is similar to the multi-model mean ERF value of -0.97$\pm$0.43 W m-2 based on 13 CMIP5 models (see Table 1 in Allen, 2015) and the ERF value -1.17$\pm$0.29 W m-2 based on 8 ACCMIP models in IPCC AR5 with the patterns being also similar (Shindell et al., 2013)."

"Recent work shows that effective climate sensitivity has increased in CMIP6 models which is primarily due to stronger positive cloud feedbacks from decreasing extratropical low cloud coverage and albedo (Zelinka et al, 2020)."

7) The Reviewer notes: "Section 3.3: Precipitation response: If we look closely we can notice that over tropical region (take west Africa for example) there is a sharp inversion of the signal from land to sea. The precipitation shift due to the large scale differential hemispheric cooling should produce a precip signal more continuous from land to ocean. I think there is in addition also an influence of local surface forcing and response here. Continental surface reacts to aerosol dimming (less surface flux, enhanced stabilization) whereas only atmospheric absorption is effective over the ocean when SST is kept constant and the precipitation signal becomes positive over the ocean. If you take into account a slight effect of aerosol dimming on SST (e.g. using slab ocean and without considering necessarily a long time scale) you might end up with a negative precipitation signal consistent with land counterpart. This remark perhaps illustrate my earlier concern about the interpretation of “fast response”. This is an interesting point set by the reviewer which also troubled us for the precipitation increase over the ocean

close to West Africa. If we look the fields of anomalies in vertical velocities (see Figure II below) we note that the areas of precipitation increase are associated with consistent upward motion anomalies (see the figure below). We also note downward motions over land near the coast. This may imply a local circulation anomaly with upward motion anomaly over the sea, a downward motion anomaly over the land, a low level outward motion anomaly from the land towards the sea and inward motion anomaly from the sea towards the land higher up. If we assume the influence of local surface forcing with more cooling over land than over the ocean (fixed SSTs) (see Figure 6) due to the total aerosol forcing, this may induce a slight local circulation anomaly with more outflow from land towards the ocean consistently with the implied local circulation anomaly. The Sea Level Pressure anomalies (not illustrated in the manuscript) show a small decreasing pressure gradient from land towards the ocean (see Figure III below). Furthermore, the large-scale horizontal wind anomalies at 850 hPa (Figure 9) indicate a westerly anomaly (inward motion from the sea towards the land) which weakens the climatological easterly flow and the outflow of the relatively drier air masses from land towards the ocean.

Figure II: Differences between piClim-aer and piClim-control in vertical velocity (mPa/s) at 850 hPa for the ensemble of 10 models on an annual basis (a). for DJF (b) and for JJA (c). The dot shading indicates areas in which the differences are statistically significant at the 95% confidence level.

Figure III: Differences between piClim-aer and piClim-control in SLP (hPa) for the ensemble of 10 models on an annual basis (a). for DJF (b) and for JJA (c). The dot shading indicates areas in which the differences are statistically significant at the 95% confidence level.

8) The Reviewer notes: "Section 3.3: There is a robust increase of Indian and SEA monsoon in terms precipitation (in term of wind anomaly it is difficult to see on the figure, but it seems that there is a cyclonic anomaly). However the text is stating a weakening of the monsoon (line 25) linked to southward ITCZ shift. This is a bit confusing.

The precip signal obtained is in fact opposite to several studies relating a weakening of Indian monsoon precip due to regional anthropogenic aerosol, in model and observation analyses (as noted by the author a bit later p10 L1-5). Given the importance of this hot spot region, perhaps the author should develop a bit more the analysis of their results here (an interesting paper could be the one of Bollasina et al., 2014, GRL) ? Could these results be also linked to the forced SST set up as air sea coupling might be particularly important in this region?

The reviewer is absolutely right. Over East Asia there is an anticyclonic anomaly (Figure 9c) which deteriorates the climatological southerly and southwesterly winds, thus weakening the East Asian monsoon and leading to lower precipitation (Figure 8c). The anticyclonic anomaly indicated by the geopotential height anomaly at 850 hPa over East Asia is also confirmed by a positive sea level pressure anomaly over the region (see Figure III of our repsonse). The importance of this precipitation decrease in East Asia due to the fast response is justified by similar results in the two PDRMIP studies by Samset et al. (2016) and Liu et al. (2018) comparing fast and slow precipitation responses. Both PDRMIP studies show that the fast precipitation response to sulfate aerosols dominates the decrease in south and east Asian precipitation over land while they also reveal an increase over the adjacent oceans. The decrease in land precipitation is consistent with aerosol weakening the land-sea warming contrast leading to anomalous high sea level pressure over land and weakening of the influx of moisture (Monsoon weakening). This is presumably stronger in fixed SST than in ocean coupled simulations because the SSTs cannot also cool in response to the aerosols. With fully coupled runs, both the land and sea cool. And the cooling of the sea mutes some of the impact on the land-sea contrast. So interestingly, the fast response dominates when it comes to the Asian/Indian monsoons. Over India, there is a cyclonic flow anomaly extending from the Arabian Sea towards the Bay of Bengal (Figure 9c) associated with a positive anomaly in precipitation constrained to a latitude lower than 22 deg N (Figure 8c). This cyclonic anomaly reinforces the climatological westerly - southwesterly winds over south India, thus strengthening the Indian monsoon and leading to more

precipitation. However, the cyclonic anomaly weakens the climatological westerly flow at about 22 deg N, thus constraining the positive precipitation anomaly up to this latitude. This is presumably linked with a southward shift of the ITCZ as can be implied by the pattern of positive geopotential height anomaly north of 22 deg N and negative geopotential height anomaly south of 22 deg N (Figure 9c). The circulation changes due to fast responses in Figure 9c shows similarities with the ones presented by Ganguly et al. (2012) (see their Figure 2a) where it is also noted a cyclonic flow anomaly in the Arabian Sea associated with a positive anomaly in precipitation as well as a positive precipitation anomaly over Bay of Bengal. Nevertheless, the JJA fast precipitation response over India is model dependent with a few showing opposite response (Figure S8). We revised our text explaining in more detail our results over this area. Furthermore, we discussed our results in relation to other similar studies pointing also their large sensitivity to the forced SSTs. The following paragraphs were added: "Over East Asia there is an anticyclonic anomaly (Figure 9c) which deteriorates the climatological southerly and southwesterly winds, thus weakening the East Asian monsoon and leading to lower precipitation (Figure 8c). The anticyclonic anomaly indicated by the geopotential height anomaly at 850 hPa over East Asia is also confirmed by a positive sea level pressure anomaly over the region (not shown here). However, the effect of aerosols on the monsoon is only partly realized in these simulations because the ocean temperatures are kept fixed. The importance of this precipitation decrease in East Asia due to the fast response is justified by similar results in two PDRMIP studies by Samset et al. (2016) and Liu et al. (2018) comparing fast and slow precipitation responses. Both PDRMIP studies indicate that the fast precipitation response to sulfate aerosols dominates the decrease in south and east Asian precipitation over land while they also reveal an increase over the adjacent oceans. The decrease in land precipitation is consistent with aerosol weakening the land-sea warming contrast leading to anomalous high sea level pressure over land and weakening of the influx of moisture (Monsoon weakening). This is presumably stronger in fixed SST than in ocean coupled simulations because the SSTs cannot also cool in response to the aerosols while the cooling of the sea in the ocean coupled simulations mutes some of the impact on the land-sea contrast. So interestingly, the fast response plays a dominating role for the Asian/Indian monsoons. Over India, there is a cyclonic flow anomaly extending from the Arabian Sea towards the Bay of Bengal (Figure 9c) associated with a positive anomaly in precipitation constrained to a latitude lower than 22 deg N (Figure 8c). This cyclonic anomaly reinforces the climatological westerly - southwesterly winds over south India, thus strengthening the Indian monsoon and leading to more precipitation. However, the cyclonic anomaly weakens the climatological westerly flow at about 22 deg N, thus constraining the positive precipitation anomaly up to this latitude. This is presumably linked with a southward shift of the ITCZ as can be implied by the pattern of positive geopotential height anomaly north of 22 deg N and negative geopotential height anomaly south of 22 deg N (Figure 9c). The circulation changes due to fast responses in Figure 9c shows similarities with the ones presented by Ganguly et al. (2012) (see their Figure 2a) where it is also noted a cyclonic flow anomaly in the Arabian Sea associated with a positive anomaly in precipitation as well as a positive precipitation anomaly over Bay of Bengal. It was shown, however, that the location of the emission region plays an important for shaping the detailed features and magnitude of the response. Decomposition of the total response into fast and slow components indicate that almost all of the precipitation reductions over India (south of 25 oN), Arabian Sea, and Bay of Bengal are a result of the slow response to aerosol forcing, whereas increases in precipitation over the north-western part of the subcontinent as well as decreases over north-east India and Nepal region are due to the fast response to aerosol forcing (Ganguly et al., 2012)."

9) The Reviewer notes: "Section 3.3: Summer precipitation and dynamics over Europe. In term of radiative forcing summer and winter show similar patterns over europe. Intuitively we understand the anticyclonic anomaly generated via regional forcing over Europe for winter, but we would also expect the same for summer (i.e. regional strengthening of stable conditions by mostly diffusive aerosol). Instead the Icelandic cyclonic anomaly extends over the euro-mediterranean domain associated with increased pre-

cipitations. Would that imply that summer aerosol impact over Europe is not driven by regional emissions but rather responds to global scale adjustment to global emissions? Do the authors have some indications that the signal is robust when considering ocean coupling and slow response (from PDRMIP for example). Looking at model to model variability , it would be good perhaps to have information on effective optical properties (e.g. total and absorption AOD, effective singe scattering albedo) for perhaps understanding the sensitivity of response pattern to aerosol parameters." In JJA we have a stronger negative regional ERF over Europe (than in DJF) with the pattern of ERF changes being similar with the pattern of near surface cooling. This points the radiative causes for the near surface cooling. Possibly the level of static stability in JJA is a factor that could play a role for the development of the anticyclonic anomaly. In central and south Europe the lower stability may hinder an anticyclonic anomaly while in north Europe with the higher stability regional forcing promotes the anticyclonic anomaly. However the large scale cyclonic anomaly over the N. Atlantic in JJA that extends towards Europe is presumably linked to global scale circulation adjustment to the global forcing. In DJF we note a negative ERF over Europe which is weaker than in JJA. The negative ERF in DJF does not cause a radiative cooling at near surface. In contrast, we note a slight warming which is dynamically driven from the induced circulation changes, an anticyclonic anomaly over Europe and the cyclonic anomaly over the N. Atlantic. This synoptic pattern anomaly causes warmer air advection and subsidence over Europe. Even though the regional forcing is rather weak in DJF over Europe it could potentially contribute to the development of the anticyclonic anomaly over Europe in DJF. Presumably even in DJF there is contribution from global scale circulation adjustment to the global forcing. The following paragraph was added in the revised manuscript: " In JJA over Europe, the pattern of negative regional ERF anomalies (Figure 3c) is similar to the pattern of near surface temperature anomalies (Figure 6c) pointing to radiative causes for the near surface cooling. At north Europe there is anticyclonic anomaly (Figure 9c) which could be linked to the negative regional radiative forcing and high stability. The large scale cyclonic anomaly over the N. Atlantic in JJA that extends towards Europe is presumably linked to global scale circulation adjustment to the global scale radiative forcing.

Following the suggestion of the reviewer we added one Figure with information about the ensemble mean difference between piClim-aer and piClim-control simulation for the total AOD and the absorbing AOD. The ensemble mean annual difference between piClim-aer and piClim-control simulations is 0.027±0.012 for the globe, 0.046±0.020 for the NH and 0.011±0.003 for the SH. The following paragraph was also added: "Based on the ensemble of the 10 models on an annual basis, Figure 2 shows, in turn, the differences between piClim-aer and piClim-control for total aerosol optical depth (AOD) and absorbing aerosol optical depth (AAOD) at 550 nm. Their spatial distribution reflects the key emission regions of the anthropogenic scattering and absorbing aerosols. The mean annual difference between piClim-aer and piClim-control simulations for the 10-models ensemble is 0.027±0.012 for the globe, 0.046±0.020 for the NH and 0.011±0.003 for the SH."

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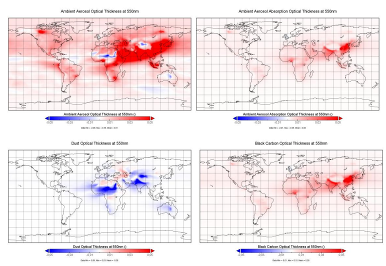

Figure I: Differences between piClim-aer and piClim-control at annual basis in CESM2 for a) total aerosol optical thickness (550 nm), b) absorbing aerosol optical thickness, c) dust aerosol optical thickness, and d) BC aerosol optical thickness.

Fig. 1. Figure I:Differences between piClim-aer and piClim-control at annual basis in CESM2 for a) total aerosol optical thickness (550 nm), b) absorbing aerosol optical thickness, c) dust aerosol optical thi

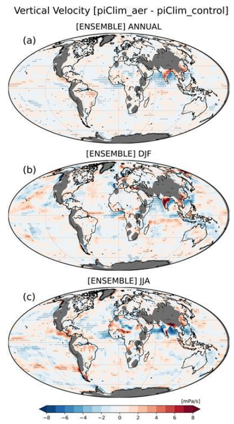

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Fig. 2. Figure II:Differences between piClim-aer and piClim-control in vertical velocity (mPa/s) at 850 hPa for the ensemble of 10 models on an annual basis (a). for DJF (b) and for JJA (c).

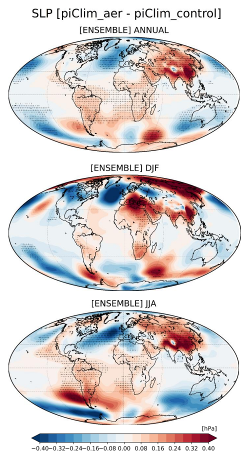

Figure III: Differences between piClim-aer and piClim-control in SLP (hPa) for the ensemble of 10 models on an annual basis (a). for DJF (b) and for JJA (c). The dot shading indicates areas in which the differences are statistically significant at the 95% confidence level.

Fig. 3. Figure 3:Differences between piClim-aer and piClim-control in SLP (hPa) for the ensemble of 10 models on an annual basis (a). for DJF (b) and for JJA (c).