Review of:

Anthropogenic Aerosol effects on Tropospheric Circulation and Sea Surface Temperature (1980-2020): Separating the role of Zonally Asymmetric Forcings

By Diao et al.

This paper utilizes the CESM large ensemble simulations and its single forcing simulations component to study aerosol effect on surface temperatures and atmospheric circulation. In addition, two new sets of ensembles of simulations with the CESM are presented. These simulations are designed to capture the shift in recent decades in aerosol forcing from the western hemisphere mid-high latitudes (USA and Europe) to the eastern hemisphere low-mid latitudes (mostly India and Chania). The new simulations are well executed set of numerical experiments, which presents a valuable contribution to the climate community. I agree with the authors' statement that: "The zonally heterogeneous changes in AA emissions since the late 20th century, …, received less attention".

Response:

Thanks for a precise summary of our study, which is mainly focused on the zonal heterogeneous forcing due to anthropogenic aerosols.

The new simulations will be released upon publication to the research community. See the updated data availability statement for the access method.

However, I fill that this paper fails to present the current knowledge in the field.

Response:

Thanks for the suggestion. We have added more references to the previous studies as suggested in the revised Introduction section. See detailed response below.

In addition, the paper is mostly descriptive and the physical explanations are lacking (please see more details below).

Response:

Thanks for the valuable comments. We have conducted further physical analyses as suggested, specifically for the linkage between the radiative imbalance and the Hadley circulation shifts. Please check our response to the major comments below.

Finally, the paper could benefit from a carful re-writing and editing as some parts are not writen well and I found numerous typos.

Response:

Thanks for the detailed suggestion in the specific comments. We carefully re-edited our manuscript and corrected many editorial issues.

Having said that, I believe that after a major revision, this paper could make important contributions to understanding aerosols' climatic impacts.

Response:

The current draft went through a major revision following valuable suggestions from the two reviewers.

General comments

- As was mentioned above currently the paper is mostly descriptive and so little physical insight is gained. Specifically, the explanation of the circulation response is lacking. I have outlined below a few examples but there are defiantly more. Hence, I would like to encourage the authors to conduct deeper thinking and to try to bring the dynamic discussion to a level suitable for publication.

Response:

Thanks for the valuable feedback. We have included more dynamical analysis to the manuscript in this round of revision:

- **The cross-equatorial atmospheric energy transport due to radiative forcing occurring at mid-to-high latitudes leads to the Hadley Cell shifting northward to balance the interhemispheric energy imbalance (Fig 7).**

- **Both atmospheric and oceanic meridional energy transport over the North Atlantic contributes to the remote warming over the North Pacific (Fig 10).**
- **Analysis of the cloud droplet concentration to show the contribution of aerosol indirect forcings (Fig 4).**
- **The additivity and sensitivity test of the two sets of regional forcings experiments (EastFF and WestFF) (Fig. 3)**

Please check the detailed responses to the specific comments below.

- The introduction is lacking many previous studies that examined the aerosol geographical distribution effect on circulation, forcing and temperature. Although I agree that this issue should get more attention, from the current manuscript it could sound almost like it is the first time anyone looked at it. This is not the case. A few examples of papers which come into my mind are Fiedler et al., 2017; Chemke and Dagan 2018; Persad and Caldeira 2018 and Fiedler and Putrasahan 2021.

Response:

Thanks for the suggestions. We added more references to the Introduction section to summarize the previous works as suggested, some of them focusing on the zonal differences of aerosol forcing. The Introduction is also restructured for clarity. Apologies for the previous oversights.

- In addition, the introduction focusses quite a bit on extremes. As this is not the focus of this paper, it is unclear to me why.

Response:

We mentioned a few previous studies related to the aerosol effect on extremes to highlight the broader implication of the inferred circulation changes here, although the paper itself here does not directly address extreme events.

We still like to keep these few (2-3) references in the Introduction but we have rearranged the Introduction for clarity, where the extremes-related discussion is now in a paragraph summarizing previous studies on regional aerosol forcing and climate responses.

Specific comments

L 13-14: this sentence sounds a bit awkward. Consider re-writing.

Response:

Thanks for the suggestion. We have modified the sentence as follow:

"The overall cooling effects of AA, which mask a portion of global warming, have been the subject of many studies but large uncertainty remains."

L 92. It defiantly also played a role in the north Atlantic. The motivation of focusing only on the north Pacific is not clear.

Response:

Thanks for the suggestion. We agree that the AA forcings also affect the North Atlantic. We acknowledge that many previous studies have examined the relationship and mechanisms of Atlantic changes (Booth et al., 2012; Bellomo et al., 2018; Hua et al., 2019; Watanabe and Tatebe. 2019). In contrast, the aerosol effects on the Pacific ocean are comparatively less studied in the previous work. Also, since this study focuses on the comparison and competition of East and West aerosol forcings, we are specifically interested in how the increasing Asia aerosol forcing induces warming in the North Pacific and how that might be compensated by declining aerosol forcing from North America. Therefore, in section 3.4 we specifically focused on the North Pacific and we provided further motivation at the beginning of section 3.4, copied below for references:

"Having demonstrated the tropical circulation changes and NH jet stream changes in Sect. 3.3, now we look at the SAT response to the regional aerosol forcings. Many previous studies have examined the relationship and mechanisms about Atlantic changes (Booth et al., 2012; Bellomo et al., 2018; Hua et al., 2019; Watanabe and Tatebe. 2019). In contrast, the aerosol effects on the Pacific ocean are comparatively less studied in the previous work (Allen et al., 2014; Dong et al., 2014; Hua et al., 2018), and the potential effects of aerosol redistribution need further discussion. Since this study focuses on the comparison and competition of East and West aerosol forcings, we are specifically interested in how the increasing Asia aerosol forcing affects the North Pacific and how that might be compensated by declining aerosol forcing from North America."

L 115. I wouldn’t call it “full” ACI representation. Obviously, there are many aspects that are missing. I suggest to change it to: “enables simulations of aerosol indirect effects” without the “full”.

Response:

Thanks for the suggestion. We deleted “full”. We have modified the description as suggested.

“The cloud physics scheme allows ice supersaturation and features activation of aerosols to form cloud droplets and ice crystals and thus enables simulations of aerosol indirect effects (Morris and Gettlemen, 2008), which was missing in the model’s predecessors.”

L239. If the AOD doesn’t change so much far away from the aerosol sources, how come the cloud droplet number concentration change? Have you really checked that the CDNC change?

I think that the cloud fraction changes seen here are dominated by adjustments due to changes in the SST and circulation rather than by aerosol indirect effect.

Response:

Thanks for the valuable comments.

We checked the cloud number concentrations (Fig. R1 here; now included in new Fig. 4) and see significant cloud droplet changes over the subtropical Pacific regions due to the aerosol emission over Asia. We also see some cloud droplet changes over the North Pacific region due to aerosol reduction from

North America. Therefore, we argue that the indirect aerosol effects extend beyond the emission domain and well into the ocean.

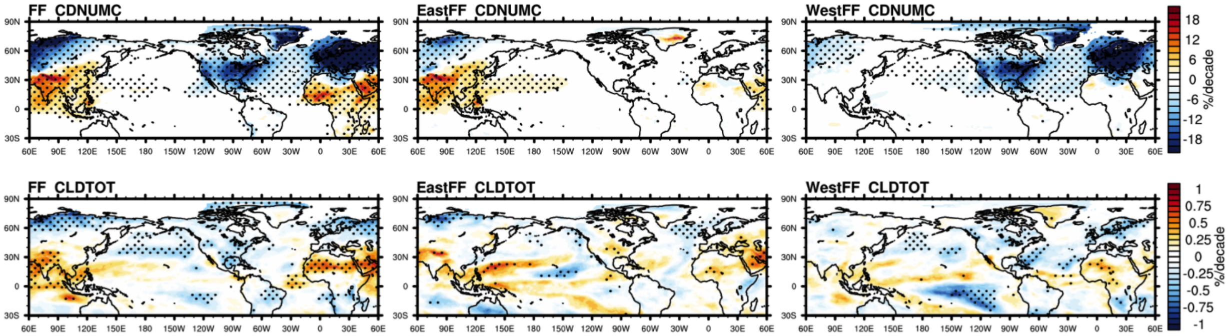

Fig R1 (also included in the new Fig. 4)

40-year trend in the percentage Vertical-integrated cloud droplet concentration (top row; CDNUMC; %/decade) and Total cloud fraction (bottom row, CLDTOT, %/decade) in response to FF (left), EastFF (mid), and WestFF (right); (2nd row).

Although the results above indicate that aerosol indirect forcing (fast response) contributes to the tropical Pacific cloud changes, we also agree with the reviewer that cloud fraction changes are partially driven by the SST and circulation responses (so-called slow response). For example, the eastern subtropical Pacific in the Southern Hemisphere shows cloud fraction changes without much CDNC change.

Therefore, we modified our discussion on the aerosol-cloud interaction discussion. Now it read:

"In line with the zonal asymmetry of AOD_AA trends, simulated solar radiation flux also has significant zonal contrast due to aerosols' direct and indirect climate effects. The first row of Fig. 3 shows the Surface Downward Solar radiation (FSDS), broadly consistent with the patterns of the AOD_AA trend (third row of Fig. 2). Note the opposite colors, though, because a decline in AOD_AA leads to an increase in FSDS. The global surface radiative forcing shows an overall positive trend in response to the decrease in global sulfate emission, but with significant spatial heterogeneity due to the opposite regional emission trends. An increase in FSDS occurs over North America, Europe, and the northern part of Asia, consistent with reducing aerosol forcings over these regions. In contrast, the increasing aerosol emission over east Asia induces a substantial decrease in FSDS. The Net Solar Radiation at the Top-Of-Atmosphere (FSNTOA; the second row of Fig. 3), as the main metric for aerosol forcing, is also consistent with FSDS patterns, but shows more obvious responses over the ocean. Both FSDS and FSNTOA show significant trends over not only the emission domain but also over extended regions into the ocean surface. Due to WestFF, the north Atlantic region shows strong increases in solar radiations, which is consistent with the significant decrease in cloud droplet concentration (CDNUMC, third row of Fig. 3) in response to the WestFF aerosols. However, the cloud fractions (fourth row of Fig. 3) show very weak changes over the north Atlantic, which indicates the critical role of the aerosol first indirect effect over the north Atlantic. The reduction of aerosol emission over North America also leads to smaller cloud droplet concentrations over the North Pacific in the WestFF case, further contributing to a positive radiative forcing. In contrast, in response to EastFF, cloud droplet concentration shows a significant increase over the subtropical Pacific in the Northern Hemisphere, which is consistent with the weak increase in SO4 burden over this region. The larger cloud droplet concentration increases cloud albedo and amplifies the negative

radiative forcing. The negative radiative forcing over the subtropical Pacific is evident in the EastFF case, but weaker in the (total) FF case due to the offset by the decreasing aerosols from North America.

The North Pacific region, a focused region of this study, shows complex competition of the two emission sources, where WestFF induces a significant decrease in cloud droplet concentration (along with increasing FSNTOA) northward of 30 ºN. In contrast, EastFF leads to an opposite trend at 30 ºN and south. One may expect an increase in FF aerosol over Asia would lead to a negative forcing trend over the North Pacific, as is claimed in previous studies, but actually, the simulated negative trends are confined to lower latitude regions (30 ºN and south). The two sets of regional forcing simulations reveal clearly that the decline of FF aerosol over the WH mid-latitudes induces the positive radiative forcing trend at mid-high latitudes of the North Pacific, producing a weak positive FSNTOA trend. This demonstrated East-West competition is a focal point of our following analysis. In the subsequent sections, we will discuss the possible mechanisms in terms of temperature and circulation changes. ”

In light of the suggested mechanism of cloud fraction change due to slow response rather than aerosol microphysics, We also added a brief discussion on the possible contribution from the slow response:

“The cloud fractions over this region also show an increasing trend in the FF and EastFF, but fail to pass the significance test in the FF case. Surprisingly, the eastern subtropical Pacific in the South Hemisphere also shows significant changes in TOA solar radiation and the cloud fraction, without much aerosol changes. This may possibly be explained by the slow response of sea surface temperature (SST) to the aerosol forcing, where the cloud fraction is affected by the climate adjustment due to SST or circulation changes (Xu and Xie, 2015; Wang et al., 2016; Dong et al., 2019; Kang et al., 2021). The slow responses of cloud fraction to aerosol forcing could also occur near the emission regions where SST changes more significantly; however, as discussed above, the simulated radiation changes over and near the emission regions are highly consistent with the changes in cloud droplet concentrations, indicating a dominant role of indirect aerosol forcing through microphysics perturbation. Here we mainly focused on the overall circulation changes in response to regional aerosol forcings using a fully-coupled climate model, therefore a clear separation of the slow and fast responses of clouds and climate to aerosol forcing is beyond the scope of this study. ”

L241. I might miss something here but as far as I can tell Fig. 3 does not show any significant cloud fraction change over the North-Atlantic in response to FF.

Response:

Thanks for the correction. There is a decrease in cloud droplet numbers rather than the cloud fraction. We have re-written our analysis in this paragraph, including the discussion on cloud droplet numbers (shown in Fig. R1 and added to Fig. 3). Please see our response to the previous comment for the modified discussion.

L264. Only 2 ensembles are presented in Fig. 4a, not 3.

Response:

Thanks for the correction. We have fixed the issue.

L 303. Changes in circulation have many implications other than extreme weather.

Response:

Thanks for the suggestion. We modified it to cover more general climate changes:

"In this subsection, we discuss the global and regional tropospheric circulation responses due to the evolving anthropogenic aerosol emission, which have a major implication on mid-latitude climate (Xu and Xie, 2015; Mann et al., 2017; Wang et al., 2020). "

L 306. As was mentioned above, previous studies have also looked at the west-east contrast effect of aerosol on the circulation

Response:

Thanks for the suggestion. We now add related references to the paragraph, copied below:

“Previous studies have explored the tropospheric circulation responses to inter-hemispheric (meridional) forcing gradient due to anthropogenic aerosols – more reflecting aerosols over NH compared to SH will lead to an equatorward shift of NH Hadley circulation and NH westerly wind (e.g., Hwang et al., 2013; Hilgenbrink et al., 2018). Meanwhile, recent studies also put effort into how the west-east contrast effects of aerosol induce the circulation changes (Wang et al., 2015; Kang et al., 2021).”

The paragraph starting at L344. The “rule-of-thumb” explanation presented here is circular and the causality here is not clear. Changes in circulations due to any forcing will derive changes in clouds and humidity, which will derive changes in radiation, which will feed back on the changes in the circulation. Hence, suggesting that the apparent end-result radiation changes (which are also driven by changes in circulation, not just directly by the external forcing) leads to the changes in the circulation is misleading.

The literature is full with explanations and theories about what determines the location of the jet stream. I suggest to change the discussion here to follow the previous knowledge in the field.

Response:

Thanks for the valuable comments. We agree with the reviewer’s point that the circulation changes will induce the radiation changes. However, by introducing the “rule-of-thumb” indicator, we argue that the latitudinal gradient of FSNTOA, a measurable quantity, can be considered as an indicator of the circulation shifts in NH. We do not intend to claim that the circulation changes are simply driven by the FSNTOA gradient. In this revision, we further clarify our point in the manuscript to avoid misleading.

As suggested by the reviewer, here we introduce a new analysis on the meridional heat transport (MHT) to provide a deeper causality discussion on the circulation change, specifically for the Hadley Cell shift. Due to the length of the manuscript, we did not include further diagnostics on the NH jet streams. More detailed analyses on jet streams will be presented in a future study.

The heavily modified Section 3.3 portion related to MHT now reads:

"Previous studies have explored the tropospheric circulation responses to inter-hemispheric (meridional) forcing gradient due to anthropogenic aerosols – more reflecting aerosols over NH compared to SH will lead to an equatorward shift of NH Hadley circulation and NH westerly wind (e.g., Hwang et al., 2013; Hilgenbrink et al., 2018). Meanwhile, recent studies also put effort into how the west-east contrast effects of aerosol induce circulation changes (Wang et al., 2015; Kang et al., 2021). However, from 1980 to 2020, NH anthropogenic aerosol forcing (Sect. 3.1) is highly heterogeneous, with both strong zonal contrasts and subtle latitudinal differences (Fig. 4), further compounding the forcing-response relationship (Shindell and Faluvegi, 2009; Persad and Caldeira, 2018). Next, we analyze the aerosol-induced tropospheric responses in terms of zonal average, both globally and regionally for the EH and WH portions (marked as red boxes in Fig. 4a).

Figure 6a–c shows the decadal trend of global Zonal Mean Meridional overturning Stream Function (ZMMSF) in response to FF, EastFF, and WestFF during 1980–2020. The ZMMSF, in response to FF, features a counter-clockwise Hadley Cell anomaly (shown in blue) over the tropics, which indicates a northward shift of the Hadley Cell into NH. The northward shift of Hadley Cell also clearly occurs in response to WestFF, but not to EastFF, indicating that the shift of Hadley Cell is mainly due to the WestFF. The global mean ZMMSF shifts in our results are consistent with previous studies (Xu et al., *2015; Allen and. Ajoku, 2016; Amaya et al., 2018;* Shen *et al., 2018) focusing on the inter-hemispheric forcing gradient. That is, the tropical circulation always tends to move towards a warmer hemisphere with larger positive forcing.*

To further diagnose why EastFF and WestFF induce distinct changes of the Hadley Cell, we calculated the zonal, column integrated meridional energy transport in response to aerosol forcings, shown in Fig. 7b-d. The Atmospheric Energy Transport (AET) is calculated based on the:

$$\frac{\partial}{\partial \Phi} F_a = R_{TOA} - Q, \qquad (2)$$

Where Φ*is latitude,* F_a *(a function of latitude and longitude) is the meridional energy flux,* R_{TOA} *is the net radiative flux at the top-of-atmosphere (downward positive), and Q is the net downward energy flux at the surface. Q includes shortwave radiation, longwave radiation, sensible heat flux, and latent heat flux. AET is then obtained by integrating the energy flux from south to north:*

$$AET(\Phi) = 2\pi a^2 \int_{-\pi/2}^{\Phi} \cos \Phi' \, (R_{TOA} - Q) \, d\Phi' \qquad (3)$$

Where a is the Earth radius. The oceanic energy transport (OET) is calculated based on the:The oceanic energy transport (OET) is calculated based on the:

$$\frac{\partial}{\partial \Phi} F_o = Q \qquad (4)$$

The positive radiative forcing in NH extratropics from WestFF induces a strong negative AET at the equator (Fig. 7d), which leads to the northward shifts of Hadley Cell and ITCZ to balance the interhemispheric difference in radiative forcing. Previous studies demonstrated that cooling NH leads to a southward shift of ITCZ (Broccoli et al., 2006, Kang et al., 2021), and the mechanism is consistent with what we find here. On the other hand, the EastFF introduces a strong negative radiative forcing close to the NH tropics and a weak positive forcing in NH extratropics; as a result, *the AET has much smaller trends at all latitudes compared to WestFF (Fig. 7c vs. Fig. 7d). Therefore, the Hadley Cell does not shift significantly in response to EastFF. The AET changes in response to the total FF (Fig. 7b) closely resemble that in response to WestFF, again confirming the dominant role of WestFF in driving the Hadley Cell. OET at the equator in response to all three cases shows a near-zero trend, so it does not contribute much to the shift of Hadley Cell. "*

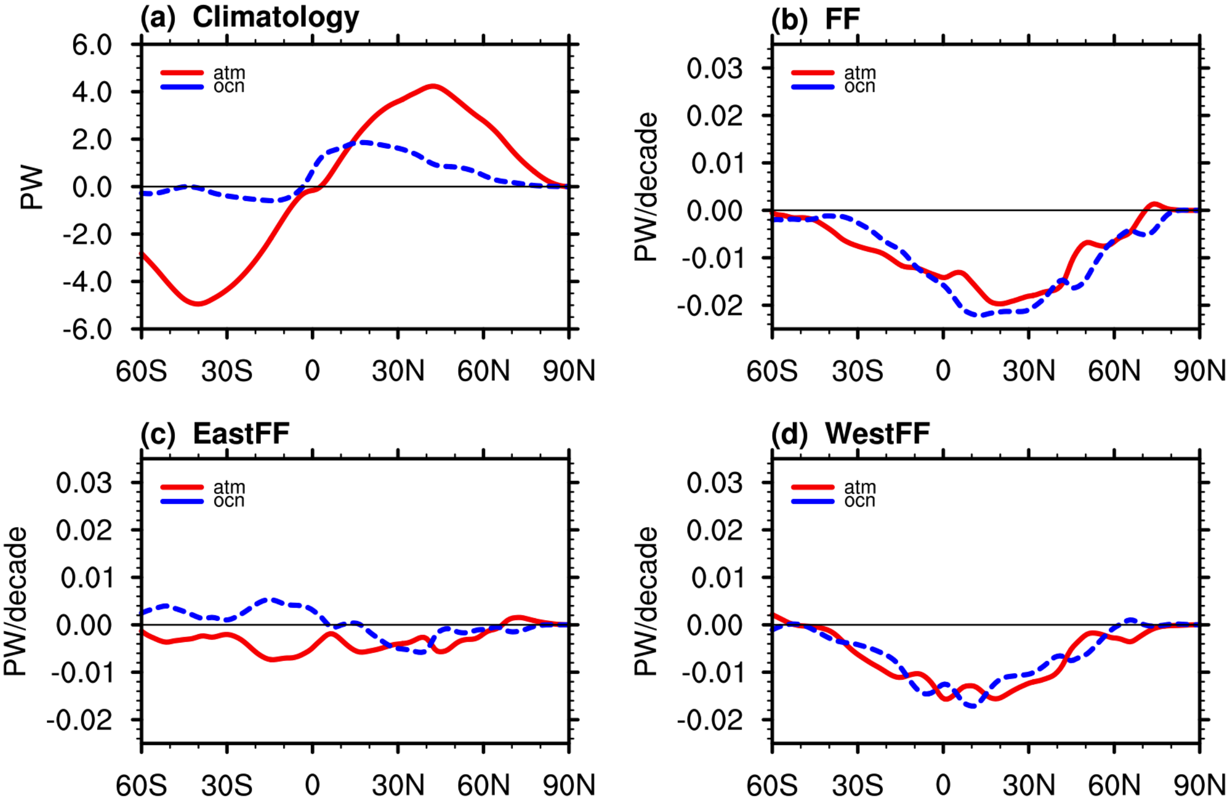

Fig R2 (added as the new Figure 7)

(a) The 40-year climatology of Northward energy transport (Pwatt) is calculated based on ALL experiments ensemble average. (b–d) The decadal trend of northward energy transport in response to FF, EastFF, and WestFF (Pwatt/decade), which are obtained by subtracting the fixed single forcing experiments from the ALL experiment.

The dashed blue lines represent the oceanic energy transport; the solid red lines represent the atmospheric energy transport.

In addition, it is not clear here if the focus is on the sub-tropical jet or the eddy-driven jet.

Response:

Thanks for the question. We look at the NH jet that occurs at the subtropical region of around 30 ºN. But in this study we do not intend to separate the subtropical or eddy-driven jet, which are mostly entangled for NH. We further clarify this in the text.

L371. Obviously, the sub-tropical jet is largely linked to the geostrophic winds. This isn't a surprise.

Response:

Yes, we agree. The subtropical jet largely follows geostrophic winds. By showing the diagnostic geostrophic winds in Figure 7 (now Figure 8), we just want to explain that the shifts of the jet stream are consistent with the simulated SAT gradient.

Therefore, we removed the sentence in question:

"The sign of SAT gradient supports our previous argument that the jet stream changes are largely linked with Ug. ".

L446. In the North Atlantic there is a clear signal of the North-Atlantic warming hole (Dagan et al., 2020; Fiedler and Putrasahan 2021;). Worth mentioning here, I think.

Response:

Thanks for the suggestion. We have added more discussion on the Atlantic ocean and set it to be a separate paragraph.

"The North Atlantic warming, as many other studies (e.g., Navarro et al., 2017; Qin et al. 2020) pointed out, can be attributed to the reduction of aerosol emission over North America and Europe since the 1980s, which is clearly seen in TOA net energy flux (blue circle in the 2nd row of Fig. 10). A North Atlantic warming hole is also significant in the FF response (Dagan et al., 2020; Fiedler and Putrasahan 2021). Notably, the simulated warming hole is less significant in response to WestFF forcing alone. In response to the EastFF forcing, the high latitudes of the North Atlantic show a warming trend despite insignificant local changes of TOA net energy flux (2nd row of Fig. 10)."

L430. By "warming forcing" do you mean positive forcing? Similarly, in L 435 "cooling forcing" should be negative forcing.

Response:

Thanks for the suggestion. We have changed all "warming/cooling forcings" to "positive/negative" forcings.

The explanation around L 435. This is a very descriptive explanation. It is still unclear to me why the differences in the aerosol latitudinal distribution between WH and EH impact the North-Pacific response.

Response:

Thanks for the question. We further discussed the differences between low and high latitude forcings based on the cloud droplet concentrations in Fig. 4 and clarified our descriptions. It now reads:

"Let's compare the three sets of responses. The weak cooling over the Pacific warm pool region in response to FF can be explained by the offsetting effects between EastFF and WestFF, where the WestFF-induced warming weakens the strong cooling due to EastFF. Similarly, at the North Pacific region southward of 40 ºN, the extended aerosol cooling effect from East Asia is largely offset by the warming effect due to WestFF in the total FF response. A notable finding is that, at least based on the simulation here, the North Pacific warming northward of 40 ºN is dominated by the positive forcing from WH mid-to-high latitudes, overwhelming the cooling from EH low-to-mid latitudes. The subtle difference in the latitudinal displacement of EH and WH forcings is playing a role here. Indeed, Fig. 4 shows that the EastFF-induced CDNUMC changes are concentrated over low-to-mid latitudes (close to the emission sources and western subtropical Pacific). In contrast, the WestFF-induced CDNUMC changes expand to a larger domain over North Pacific and North Atlantic. The simulation here indicates that mid-to-high latitude SAT is more sensitive to extratropical forcing than forcings originating from a lower latitude. This finding is consistent with previous findings that emission at higher latitudes generates stronger temperature responses (Shindell and Faluvagi, 2009; Persad and Caldeira, 2018). We also examine the BB case (not shown), which has a strong negative forcing over northeastern Asia over 50 ºN, and we find that BB-induced cooling occurs over the entire North Pacific similar to WestFF-induced response. Therefore, we highlight that the latitudinal distribution of aerosol forcing is essential to the North Pacific climate responses. "

Explanation around L 460. It is not clear to me how you calculated ZMMHT but I assume that it includes only the atmosphere heat transport and not the ocean transport. The surface temperature is strongly controlled also by the ocean heat transport and aerosol forcing could modulate it (Cai et al., 2006; Delworth and Dixon, 2006; Dagan et al., 2020; Menary et al., 2020; Fiedler and Putrasahan 2021; Hassan et al., 2021). This is something that can’t be ignored, definitely for the North-Atlantic. This comment about the role of the ocean circulation changes in shaping the SST (or SAT) is true also for many other parts of this paper. It can’t be simply ignored.

Response:

Thanks for the valuable comments. We now included oceanic transport into the discussion in section 3.4 and as the bottom row of Fig. 10 (shown as Fig. R3 below). It now reads:

“In addition to the atmospheric ZMMHT, we also show the zonal, column integrated AET response in EH versus WH (bottom row of Fig. 10). The AET results show a strong northward energy transport trend in the WH, while the equatorward energy transport trend in the EH, both of which resemble the ZMMHT trends. Moreover, it is clear that the strong WestFF positive radiative forcing induces the strong poleward energy transport trend in the WH and the AET in response to EastFF is much weaker.

Previous studies have also shown that the surface temperature response to aerosol forcing is also strongly modulated by the oceanic energy transport (OET; Cai et al., 2006; Delworth and Dixon, 2006; Dagan et al., 2020; Menary et al., 2020; Fiedler and Putrasahan 2021; Hassan et al., 2021). Here we show that OET (blue lines in Figure 10 bottom row) can have different trends from AET or

ZMMHT. In response to the WestFF (positive) forcing, OET increases in WH high latitude and decreases in EH, indicating that poleward heat transport via the ocean is strengthened over the North Atlantic, but is weakened over the North Pacific. The stronger poleward OET in WH, in addition to poleward AET in a larger magnitude, explains why the North Pacific shows a stronger warming trend without local forcing. The EastFF also induces increasing OET in WH and decreasing OET in EH, but with small magnitudes compared with WestFF-induced OET responses, which is similar to AET responses. This further suggests that the WestFF forcing at mid-to-high latitude is the dominant driver of atmospheric and oceanic poleward energy transport in NH."

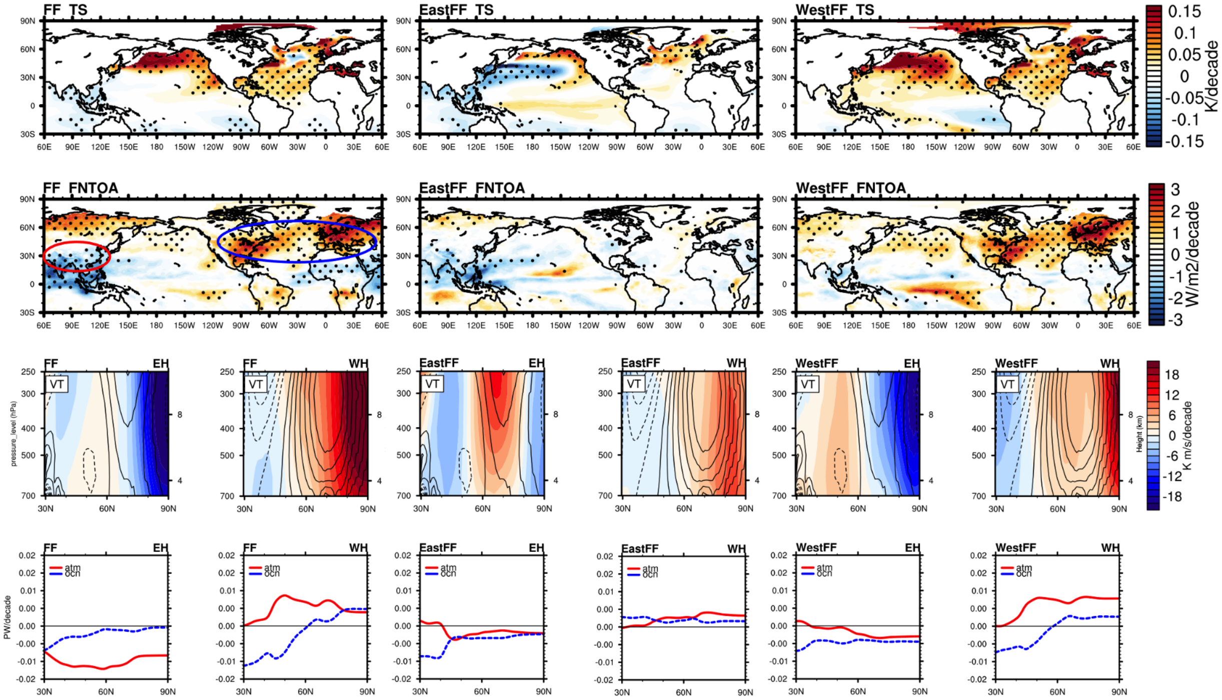

Fig R3 (new Figure 10):

1st & 2nd rows: 40-year sea surface air temperature trend (SAT) and net energy flux at TOA (Rtoa). Arctic regions with significant sea ice changes are masked.

The blue (red) circles in the 2nd row indicate the major regions with a decline (increase) of aerosol emission.

3rd row: 40-year trends of zonal mean meridional heat transport (ZMMHT) in EH and WH. The positive values (solid lines for climatology and red shading for long-term trend) indicate poleward transfer. The arrows indicate the energy transfer responses relative to the climatology.

4th row: Similar to Fig. 7 but showing the regional northward energy transport (Pwatt/decade; northward positive) in EH and WH. The dashed blue lines indicate oceanic northward energy transport (OET), while the solid red lines indicate atmospheric northward energy transport (AET).

L 481-489. This is not a main finding of this paper. The trend of a shift in aerosol forcing from the WH to the EH in recent decades is well known and was discussed in many previous studies.

Response:

Thanks for the suggestion. We have removed well-explained conclusions here, only keeping our major point: the zonal and latitudinal distribution.

"(1) The significant zonal contrast in aerosol emission redistribution, and to a lesser extent the latitudinal difference, leads to opposite local radiative forcing that has competing effects on regional climate."

Technical comments

Response:

Thanks for the corrections. We have carefully re-edited our manuscript and fixed all the issues listed below.

L69: “et al., 2014”. Please correct.

Changed to “Allen et al., 2014”.

L 90. “Northern Hemisphere, We”. Please correct.

Changed to “Northern Hemisphere. We ”.

L 95. “radiation(Sect. 3.1)”

Changed to “radiation (Sect. 3.1)”.

L 217. “(1)1”

Changed to “Eq. (1)”.

L239. “the. U”

Changed to “the zonal wind speed”.

Fig. 5 some of the y-axis are cut out.

We replot Fig. 5.

L 429. “50 North North”

Changed to “the east coast region northward of 50 ºN. The North Atlantic”.

L430. “induce es strong”. This all sentence is not written well.

Changed to: *“On the other hand, the WestFF, with positive forcing at WH mid-to-high latitudes (30 ºN–60 ºN; blue oval in Fig. 10), induces a strong warming pattern not only locally at North Atlantic but more so over the North Pacific. ”.*

L 468. “othe ver”

Changed to “over the”.

L527. “More specifically, The”

Changed to “More specifically, the”.

L 557. You jump from point 3 to 5.

Changed the order.

Line 775. “(d–f) Similar to Fig. 6 (d–f)” ? it is also not clear to me if you are presenting here the EH only or also the WH? (all titles say EH).

Response:

Thanks for pointing out the confusion. We show the vertical patterns of EH from the three sets of experiments (FF, EastFF, and WestFF). And we mentioned in the text that the result of global mean and WH are all consistent, thus not shown.

We changed the description to:

“(d–f) Similar to the bottom row of Fig. 6 but for the U trend in Eastern Hemisphere (EH) from the three sets of experiments. ”

References

Cai, W., Bi, D., Church, J., Cowan, T., Dix, M., & Rotstayn, L. (2006). Pan-oceanic response to increasing anthropogenic aerosols: Impacts on the Southern Hemisphere oceanic circulation. Geophysical Research Letters, 33(21). https://doi.org/10.1029/2006gl027513

Chemke, R., & Dagan, G. (2018). The effects of the spatial distribution of direct anthropogenic aerosols radiative forcing on atmospheric circulation. Journal of Climate, 31(17), 7129– 7145.

Dagan, G., Stier, P., & Watson-Parris, D. (2020). Aerosol forcing masks and delays the formation of the North Atlantic warming hole by three decades. Geophysical Research Letters, 47(22), e2020GL090778. https://doi.org/10.1029/2020gl090778

Delworth, T. L., & Dixon, K. W. (2006). Have anthropogenic aerosols delayed a greenhouse gas-induced weakening of the North Atlantic thermohaline circulation? Geophysical Research Letters, 33(2). https://doi.org/10.1029/2005gl024980

Fiedler, S., Stevens, B., & Mauritsen, T. (2017). On the sensitivity of anthropogenic aerosol forcing to model-internal variability and parameterizing a Twomey effect. Journal of Advances in Modeling Earth Systems, 9(9), 1325.

https://doi.org/10.1002/2017MS000932

Fiedler, S., & Putrasahan D. (2021). How Does the North Atlantic SST Pattern Respond to Anthropogenic Aerosols in the 1970s and 2000s? Geophysical Research Letters, https://doi.org/10.1029/2020GL092142

Hassan, T., Allen, R. J., Liu, W., and Randles, C. A. (2021). Anthropogenic aerosol forcing of the Atlantic meridional overturning circulation and the associated mechanisms in CMIP6 models, Atmos. Chem. Phys., 21, 5821–5846, https://doi.org/10.5194/acp-21-5821-2021

Menary, M. B., Robson, J., Allan, R. P., Booth, B. B., Cassou, C., Gastineau, G., et al. (2020). Aerosol-forced AMOC changes in CMIP6 historical simulations. Geophysical Research Letters, 47, e2020GL088166.

Persad, G.G., & Caldeira, K. (2018). Divergent global-scale temperature effects from identical aerosols emitted in different regions. Nat Commun 9, 3289 https://doi.org/10.1038/s41467-018-05838-6

Response:

Thanks for the references list below, we have cited all references in the revised manuscript.