We would like to thank all three reviewers for their valuable comments and suggestions. We have responded to each referee's comment and revised the manuscript based on the suggestions. We also attached the modified figure at the end of this response for reference.

Referee #1

Summary

The authors use a set of CESM1 simulations (1980-2020 transient runs; 10 members for each experiment) to isolate the impacts of fossil fuel/industrial aerosol emissions from China+India (EastFF; where emissions have increased) and North America+Europe (WestFF; where emissions have decreased) on the tropical Pacific and Pacific Decadal Variations (PDV). There are interesting differences between the two experiments, e.g., different North Pacific SST responses; EastFF drives a more El Nino-like SST pattern whereas WestFF drives a more CP-type El Nino SST pattern, etc. The authors continue onwards and discuss the dynamical mechanisms.

Overall, the paper is interesting and adds to our understanding of the potential climate impacts associated with regional changes in aerosol emissions.

Response

Thanks for the precise summary of the manuscript, which is mainly focused on the comparison of industrial aerosol forcings between West and East (WestFF vs. EastFF). We have revised the manuscript accordingly following the reviewer's comments and suggestions. Please check our detailed response below.

Comments

L23. "The competing effects of the heterogeneously distributed regional aerosol forcings are expected to be changed in the near future, which is likely to introduce opposite and more profound impacts of aerosol forcing on the Pacific multi-decadal changes." This is unclear. If emissions decrease, this will reinforce the WestFF pattern showed here, but potentially flip the EastFF pattern showed here? EastFF changes are likely complex, as emissions from China are likely to decrease (and have been decreasing, see below) whereas emissions from India may not, i.e., the east Asian dipole AOD pattern in Samset et al. 2019 (already referenced). Moreover, the components of EastFF and WestFF aerosol is different, as EastFF has a larger aerosol absorption component that has unique impacts on circulation, precipitation, etc. (e.g., https://www.nature.com/articles/nature11097).

Response

Thanks for pointing out this. We totally agree with the reviewer's comments on the complicated future changes in regional aerosol forcings. We also want to thank the reviewer for pointing out the difference in aerosol species, which was not covered in the previous manuscript.

We further clarified our statement starting at Line 23 (abstract) to be: "*The competing effects of the heterogeneously distributed regional aerosol forcings are expected to exhibit different patterns in the near future, especially the redistribution of aerosol emissions within the domain of EastFF (i.e., from East Asia to South Asia) and changes in aerosol composition. The complex future change in anthropogenic aerosol emissions is likely to introduce more profound impacts of aerosol forcing on the Pacific multi-decadal variations.*"

We also modified the related discussions about the aerosol composition in the last paragraph of the conclusion section:

"In this study, we focus on the period of 1980–2020, when aerosol emissions over Asia show an overall increasing trend. However, studies have shown that the emission from East Asia reached a peak around the 2010s and started to decline recently while South Asia emission continues to increase (Samset et al., 2019; Ramachandran et al., 2020; Wang et al., 2021). The sensitivity of aerosol forcing's latitudinal placement within Asia is also highlighted by recent studies on dipole patterns emerging in Asia (Wang et al., 2022; Xiang et al., 2023). Also, the current offsetting effects between EastFF and WestFF can flip to a joint effect over specific regions of the North Pacific in the coming few decades. Such decline and/or redistribution of aerosol emissions can lead to distinct climate responses locally and remotely, which demands further continuous investigation in the future."

Linearity. The authors show WestFF+EastFF relative to FF. The FF AOD changes are well captured by WestFF+EastFF (Figure 1). However, this is less true for the responses (e.g., Figure 2). In particular, Figure 2 shows a much larger tropical Pacific response (the focus of this paper) under WestFF+EastFF as compared to FF. Why might this be? Is it related to aerosol outside these two regions? I suppose this is unlikely given Figure 1. Or is it related to differences between WestFF+EastFF versus West+EastFF (i.e., the latter is the signal from both perturbations simultaneously, which may be a better estimate for FF?). I understand the authors have not performed the West+EastFF simulation, but some discussion on this matter is warranted.

Response

Thanks for the valuable comments. We agree with the reviewer that the nonlinearity is likely the primary reason for the difference between WestFF+EastFF and FF in the tropics. We add the significance test to the linear summation of WestFF+EastFF. Overall, most of the differences between FF and WestFF+EastFF in the tropical Pacific show statistically insignificant results, with some regional exceptions (e.g., Western Tropical Pacific). We now add more detailed discussions about the nonlinearity in the paragraph starting at line 194.

However, we still think the impact of aerosol forcings outside the two regions (i.e., in Africa and the Arabian Peninsula, see Fig. 1d) cannot be entirely ruled out, which could still partially contribute to the Walker circulation remotely, particularly by driving cooling over the tropical Indian Ocean region (Fig. 2d). Nevertheless, as mentioned by the reviewer, this impact is likely to be smaller than the nonlinearity, given the small magnitude of aerosol forcings.

We modified the paragraph starting at line 194 as follows:

"The linear summation of WestFF and EastFF results presented in Fig. 2d shows greater SST responses in the tropical Pacific and tropical Indian Ocean compared with actual FF results (Fig. 2c). However, most of the differences between FF and the linear summation (warming signals) in the central and eastern tropical Pacific are statistically insignificant, with some regional exceptions. Notably, The equatorial West Pacific (160ºE–180º) exhibits a significant warming signal in WestFF+EastFF, which is likely due to the nonlinear interactions between the impacts of EastFF and WestFF. Similarly, in the

extratropical North Pacific, the linear summation closely resembled the EastFF signature while the actual FF results are dominated by WestFF. The Atlantic response appears to be largely consistent, with warming from both EastFF and WestFF. Note that the aerosol forcings outside the two focused regions (i.e., aerosols in Africa and the Arabian Peninsula; see Fig. 1d) could also partially contribute to the differences between FF and WestFF+EastFF, especially, particularly by driving cooling over the western tropical Indian Ocean and weakening the wind anomalies (Fig. 2c&d). Additionally, the aerosols outside the focused region could also impose a remote impact on the tropical Pacific region (Huang et al., 2021; Shi et al., 2022), but such impacts are likely to be smaller compared to the nonlinear interactions between EastFF and WestFF impacts, given the small magnitude of the forcing (Fig. 1d).”

Related to the comments above is L93. “One note here is that the climate changes in response to FF do not necessarily equal the simple combination of that in response to EastFF and WestFF because the FF results also contain anthropogenic aerosol forcings originated from other regions not covered by EastFF and WestFF (e.g., Africa and Arabian Peninsula, Fig. 1d). More details of the regional AA single forcing large ensemble simulations are described in Diao et al. (2021).” This seems to suggest the differences in Figure 2c and Figure 2d are due to the very small differences in AOD from Figure 1d. Could there not be nonlinearities? Again, there are some sizable differences between Figure 2c and Figure 2d.

Response

Thanks for the great comment. We further clarify our statements here. Again, as mentioned above, we still want to keep a brief description of the aerosol outside focused regions, even though it might be small. The sentence now reads as follows:

“One note here is that the climate changes in response to FF do not necessarily equal the simple sum of that in response to EastFF and WestFF (denoted as EastFF+WestFF) because FF can contain potential nonlinear interactions between EastFF and WestFF impacts. additionally, the FF results also contain aerosol forcings originating from other regions not covered by EastFF and WestFF (e.g., Africa and Arabian Peninsula, Fig. 1d), even though their magnitude is considerably smaller compared to the aerosol forcings in EastFF and WestFF.”

Biomass burning aerosols (BMB). Are they not important, i.e., in driving tropical Pacific SST variations? There is a very small discussion (e.g., Figure 6). A recent paper (https://www.nature.com/articles/s41612-024-00602-8) focused on the AMOC, using the same CESM1 Large Ensemble, and showed that BMB aerosols drove significant changes in the AMOC (that were largely out of phase relative to AMOC variations under FF aerosols).

Response

Thanks for the great comments. Yes, BMB also makes significant contributions to the Pacific decadal variations, particularly in the North Pacific based on the CESM1 single forcing large ensemble (see Fig. S1 below). However, in this study, we mainly focus on the climate impact of industrial aerosol forcings (FF), so we did not include detailed discussions on the BMB responses. The reason why we included BMB results in Fig. 6 is to highlight the importance of mid-latitude pathways driven by aerosol forcings located at high latitudes. We have now added a bit more descriptions and introductions of the BMB responses referring to existing studies and put a few related figures here in the response so as not to divert from the main focus of this manuscript.

The paragraph discussing Fig. 6 now reads as follows:

"This sensitivity to the latitudinal displacement of forcing is supported by our secondary analysis of the biomass burning-related aerosol experiment (BMB), in which one major aerosol forcings are located in northeastern Asia in this particular model experiment (Fig. 2 in Diao et al., 2021), and we find similar wave trains propagating in the mid-latitudes (Fig. 6b). Similarly, in some other model experiments, the Atlantic heating, when placed in the extratropical, regardless of internal variability (Yao et al., 2021) or external forcings (Ruprich-Robert et al., 2017), does not excite the tropical teleconnection pathway. This further highlights the sensitive role of the latitudinal location of forcings. The BMB forcing excites a wave train propagating in the mid-latitudes, which later impacts the lower latitudes remotely. In fact, studies show that BMB, in addition to FF, also plays important roles in driving long-term climate variations (e.g., Fasullo et al., 2022; Tian et al., 2023; Yamaguchi et al., 2023; Allen et al., 2024), and more detailed analyses on the climate impacts of BMB on Pacific variations are warranted. However, since the focus of this study is the fossil fuel-related aerosol emissions, we leave such explorations to future work."

A caveat/limitation of this study is the use of a single model, which should be acknowledged and discussed. The results presented here are no doubt model dependent. The recently established Regional Aerosol Model Intercomparison Project (RAMIP) is one community effort designed to understand similar questions as addressed here (climate impacts of regional aerosol emissions changes) in a multi-model framework (https://gmd.copernicus.org/articles/16/4451/2023/gmd-16-4451-2023.html).

Response

Thanks for the suggestion. We agree with the reviewer's comments here. We further acknowledge the recent related work and add more discussions on the limitations of this work at the end the conclusion section. The new paragraph reads as follows:

"Based on the single model large ensemble method, the simulations applied in this study effectively separate the externally forced climate responses from the model generated internal variations (Kay et al., 2015; Deser, et al., 2020; Diao et al., 2021). However, one limitation of this study is that all results shown in this study are purely based on a single climate model (i.e., CESM1), which inevitably includes model biases. Although CESM1 is proven to have good performance in aerosol simulations, it has a relatively larger aerosol effective radiative forcing among climate models (-1.37 W m^{-2} based on Deser et al., 2020). However, the recently established Regional Aerosol Model Intercomparison Project (RAMIP; Wilcox et al., 2023) introduces a new multi-model framework to explore the climate impacts of regional aerosols. Further analyses, similar to those covered in this study, based on the multi-model simulations in RAMIP are worth conducting to test the robustness of the conclusions presented here."

Statistical significance and robustness of the ensemble mean signal. This information is not provided in any figure. We do not know what changes are significant, nor do we know the spread across individual realizations. For example, maybe the multi-model mean response is driven by 1 or 2 ensemble members. How robust are the responses shown here?

Response

Thanks for the constructive comments, we now added significance tests in Fig. 2, Fig. 4, Fig. 5, and Fig. 6. All our conclusions stay the same. Based on the significance test, we updated the statements about the nonlinearity issues (see previous response). Also, we added the statistical significance statements here and there in the manuscript. Please check the modified figures by the end of the document.

Emissions. I assume CMIP5 emissions are used here? And they are extended to 2020 using RCP4.5? I just wonder about the similarities (or dissimilarities) between real-world changes in aerosol emissions and what is used to drive the model, particularly in the context of East Asia (largely China) emissions, where there are known disagreements. For example, it is noted in a few places that EastFF is associated with “continuous cooling” (e.g., L140), which presumably means progressively more negative ERF and/or decreasing near-surface air temperatures regionally and/or globally? Is this the case, or is there an inflection point where cooling transitions to warming (or perhaps the cooling levels off)? If so, the EastFF forcing may be more complicated than is currently expressed. Maybe this is not true in the modeling realm, but it might be true in the real-world, which certainly has impacts on one’s ability to make/attempt attribution (e.g., Figure 3).

Response

Thanks for the comments. Yes, the experiments use the CMIP5 historical emission up to 2005 and then the RCP8.5 emission scenario thereafter (2005–2020). We followed this scenario setup to ensure our regional model experiments were comparable to the CESM1 single forcing large ensemble experiments.

Based on the observational studies (e.g., Wang et al., 2021; Xiang et al., 2023), aerosol emission in East Asia reached a peak and started to decrease slightly Since the early 2010s, while South Asia emissions continued to increase. Generally speaking, the RCP8.5 scenario overestimates the aerosol forcing in the EastFF domain from 2010 to 2020, which definitely introduces bias to the attribution in Fig. 3, as mentioned by the reviewer. Nevertheless, we want to mention that we only performed a *qualitative* comparison between the aerosol-driven multi-decadal responses and the observed variation. Also, although the aerosol forcing is overestimated in the simulations, the EastFF emission level remains at high levels from 2010 to 2020. Therefore, we believe that our comparison between model results and the observed variations still indicates possible relationships between aerosol forcings and the observed results.

Following the reviewer's concern, we add caveat statements about the emission scenario issue at the end of Sect. 3.2 and also in the last paragraph of the conclusion section.

We add the following statement in Sect. 3.2:

"One caveat to be noted is that the aerosol forcing scenario (RCP8.5) used in the Fix_EastFF1920 experiments has been proven to overestimate the aerosol emission level in East Asia since the early 2010s although it remains at a high level (Wang et al., 2021; Xiang et al., 2023). This leads to the overestimate of the EastFF forcing in the experiments. Therefore, the comparison above can only be treated as a qualitative comparison but not a quantitative attribution. In addition, the South Asia emission largely follows the emission scenario, which leads to a dipole of aerosol forcings changes within the EH. The forcing dipole might introduce complex circulation responses and new simulations with accurate emission forcings are necessary to further explore more realistic climate responses."

We modified the last paragraph in the conclusion section:

"In this study, we focus on the period of 1980–2020, when aerosol emissions over Asia show an overall increasing trend. However, studies have shown that the emission from East Asia reached a peak around the 2010s and have started to decline recently while South Asia emissions continue to increase (Samset et al., 2019; Ramachandran et al., 2020; Wang et al., 2021). The discrepancy between observed forcing and the forcing scenarios applied in the experiments in East Asia introduces additional biases to the results in EastFF, and new simulations with more accurate forcing scenarios are necessary to further test the climate response to regional aerosol forcings. In fact, the sensitivity of aerosol forcing's latitudinal placement within Asia is also highlighted by recent studies on dipole patterns emerging in Asia (Wang et al., 2022; Xiang et al., 2023). Moreover, the current offsetting effects between EastFF and WestFF can flip to a joint effect over specific regions of the North Pacific in the coming few decades. Such declines and/or redistribution of aerosol emissions can lead to distinctly complex climate responses locally and remotely, which demands further continuous investigation in the future."

In a similar vein, additional details on the CESM1 model (specifically details relevant to this study) should probably be included. For example, CESM1 contains a relatively large aerosol ERF (this ties into the comment above on the fact this study uses one model).

Response

Thanks for the suggestion. We have included related caveat statements in the conclusion section. Please refer to our response above.

After Figure 2, plots generally only include EastFF and WestFF results (although Figure 6 throws in some BMB panels). What about FF? Do we not also want to compare EastFF and WestFF (or the linear sum of the two) to FF? One is left wondering if these two aerosol signals (or their sum) resemble the total FF signal. And more generally, what about the ALL forcing signal? Some discussion is perhaps warranted, e.g., does the ALL signal in any way look like FF and/or EastFF+WestFF? In other words, how important is the EastFF+WestFF signal relative to ALL/FF forcings. For example, Figure 5 and 6 attempt to do this, and it seems clear the FF dynamical response is quite different than BMB, as well as EastFF and WestFF (Fig. 5).

Response

Thanks for the comments. We only keep the results from EastFF and WestFF in order to focus on the different dynamical responses between EastFF and WestFF. Given that the FF and ALL responses have been widely discussed in previous studies (e.g., Smith et al., 2016; Deser et al., 2020), we are keen on highlighting the new results from the two regional forcing simulations.

Following the reviewer's suggestion, we now include a figure about the walker circulation response in FF in the supplementary document for comparison and add brief discussions in Sect. 3.3 as follows:

"Similar to the SST changes, a strong nonlinear interaction between the impacts of EastFF and WestFF in the equatorial Pacific also occurs in FF results, where no significant PWC responses are exhibited in the Pacific (Fig. S1). Instead, FF induces a slight weakening of Walker circulations over the Indian Ocean and the Atlantic, which is consistent with the low-level wind anomalies shown in Fig. 2c."

We also add brief discussions about the dynamcial responses from FF in Sect. 3.4 as follows:

" The dynamical responses in FF largely follow the mid-latitude pathway in WestFF (Fig. 5a, e, &e), whereas the tropical Pacific shows no significant changes in Z200e. This is consistent with the surface patterns where WestFF dominates the North Pacific warming and tropical Pacific exhibits insignificant temperature changes (Fig. 2c). In addition, the North Atlantic in FF exhibits a significant decrease in sea level pressure, which is absent in either WestFF or EastFF. "

Dynamical responses/teleconnections. The focus here is on annual means, but atmospheric teleconnections tend to have strong seasonal variations. Are these results (e.g., Fig. 5) largely boreal wintertime responses? A related paper that also addresses aerosol changes and their impacts on atmospheric circulation/teleconnections (but focused on Pacific Coast precipitation), which should probably be cited, is here: https://iopscience.iop.org/article/10.1088/2752-5295/ac7d68/meta

Response

Thanks for the thoughtful question. We are not trying to touch the seasonality responses, but inspired by the reviewer, We conducted a simple analysis on the seasonality of wave teleconnections and found that the annual-mean dynamical responses are, as mentioned by the reviewer, largely consistent with the wintertime (DJF) wave teleconnections, but with a magnitude around one-third of that magnitude in wintertime. Because our study focuses only on the annual mean results throughout the manuscript and we do not want to include detailed analyses on the seasonal analyses, we would like to keep the annual mean results in the main text. However, we have included a brief discussion on the seasonality in Sect. 3.4. The discussion reads as follows:

"Evidence also suggests that the teleconnection pathways induced by both EastFF and WestFF are predominantly associated with wintertime wave responses. Recent studies demonstrated that the impacts of anthropogenic aerosol forcings on regional precipitation are heterogeneous and seasonal dependent (e.g., Allen and Zhao 2022; Samset 2022). The distinct pathways of EastFF and WestFF are

likely to introduce complex regional precipitation patterns that vary seasonally, which warrants further investigation in future studies."

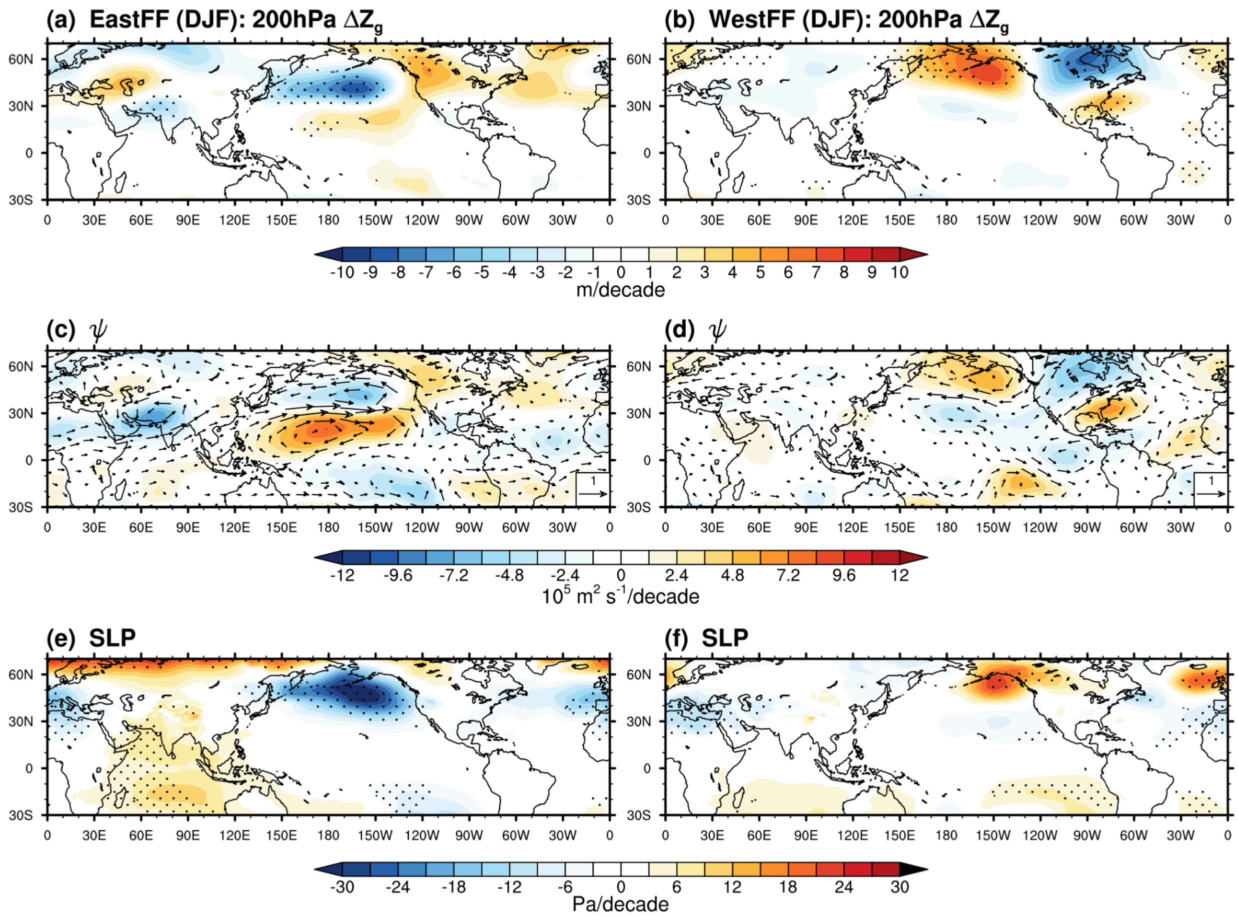

Fig. R1

Left panels: wintertime (DJF) dynamical response induced by EastFF (a) 200 hPa eddy geopotential height (m per decade), (c) 250 hPa stream function (shading; m2 s-1 per decade), and wind (vectors; m s-1 per decade), and (e) sea level pressure (shading; Pa per decade) and 850 hPa low-level wind (vectors; m s-1 per decade). Right panels: same as Left panels, but induced by WestFF. Stippled regions indicate insignificant values at the 90% confidence level based on a two-sided t-test.

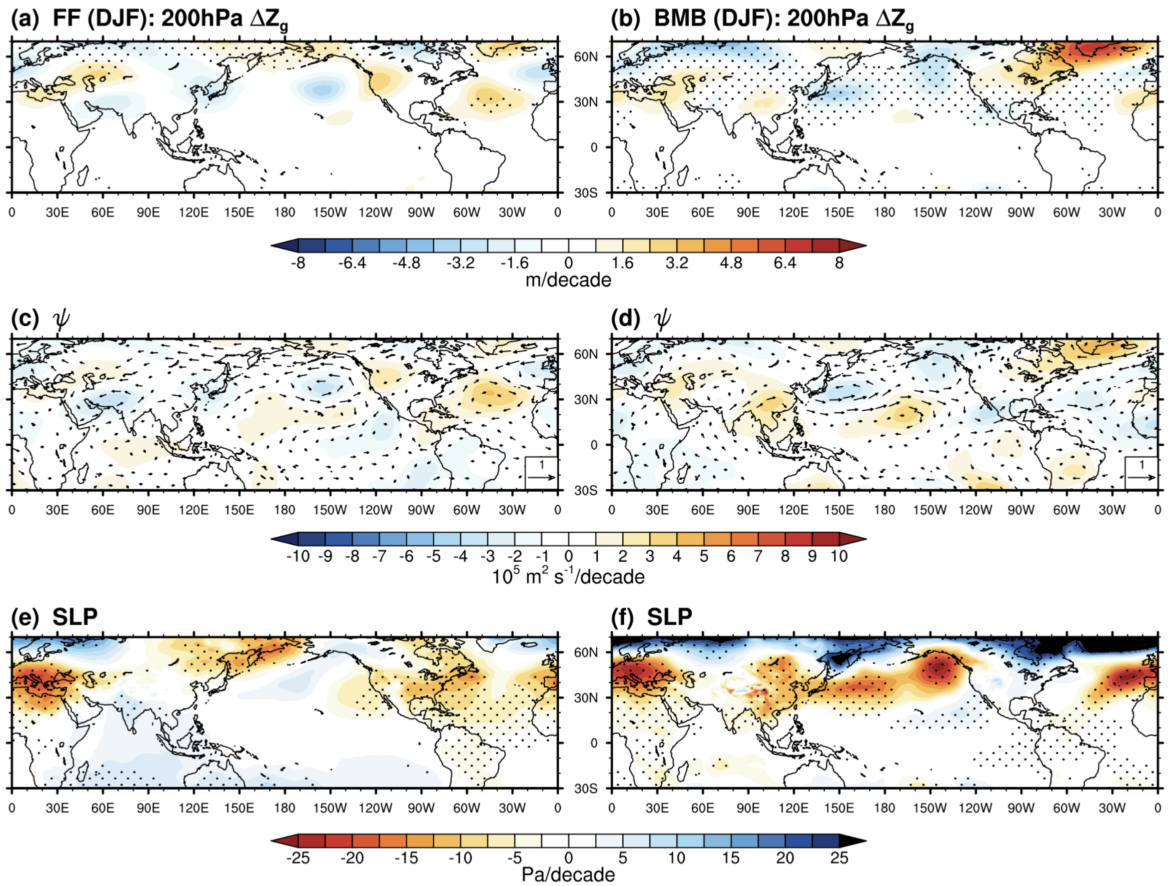

Fig. R2

Left panels: wintertime (DJF) dynamical response induced by FF (a) 200 hPa eddy geopotential height (m per decade), (c) 250 hPa stream function (shading; m2 s-1 per decade), and wind (vectors; m s-1 per decade), and (e) sea level pressure (shading; Pa per decade) and 850 hPa low-level wind (vectors; m s-1 per decade). Right panels: same as Left panels, but induced by BMB. Stippled regions indicate insignificant values at the 90% confidence level based on a two-sided t-test.

Modified Figures

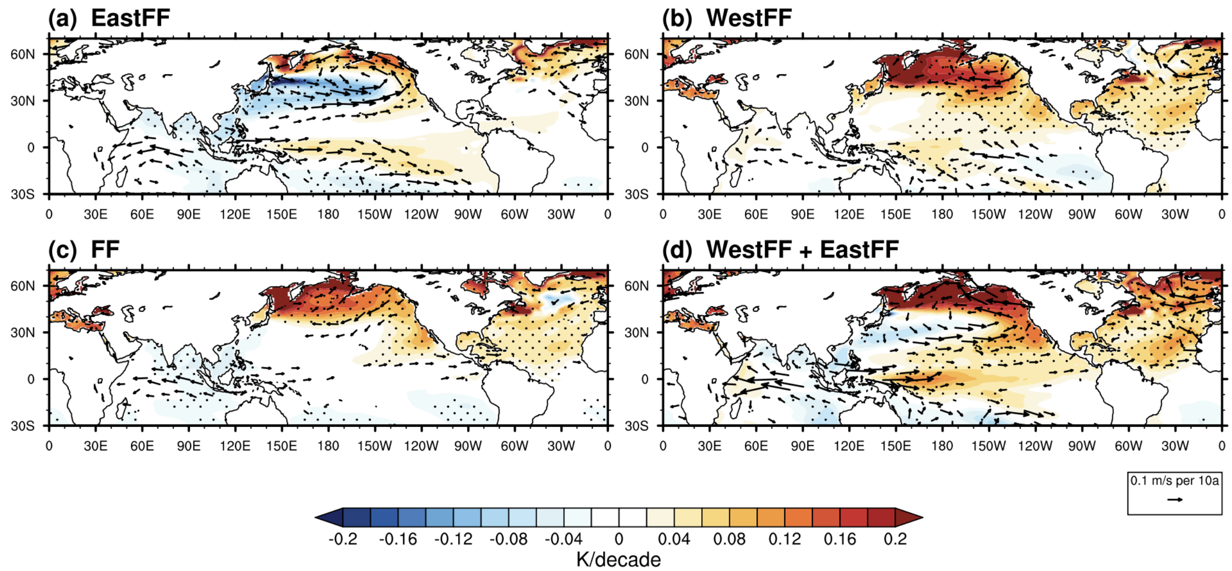

Figure 2

(a) Decadal changes in sea surface temperature (shading; K per decade) and 850 hPa horizontal wind (vectors; m s^{-1} per decade) during 1980–2020 calculated in response to EastFF. (b) and (c): As in (a), but showing results for WestFF and FF, respectively. (d) Linear addition of panels (a) and (b). Stippled regions indicate insignificant values at the 90% confidence level based on a two-sided t-test.

Changes

We add the significance test in all panels.

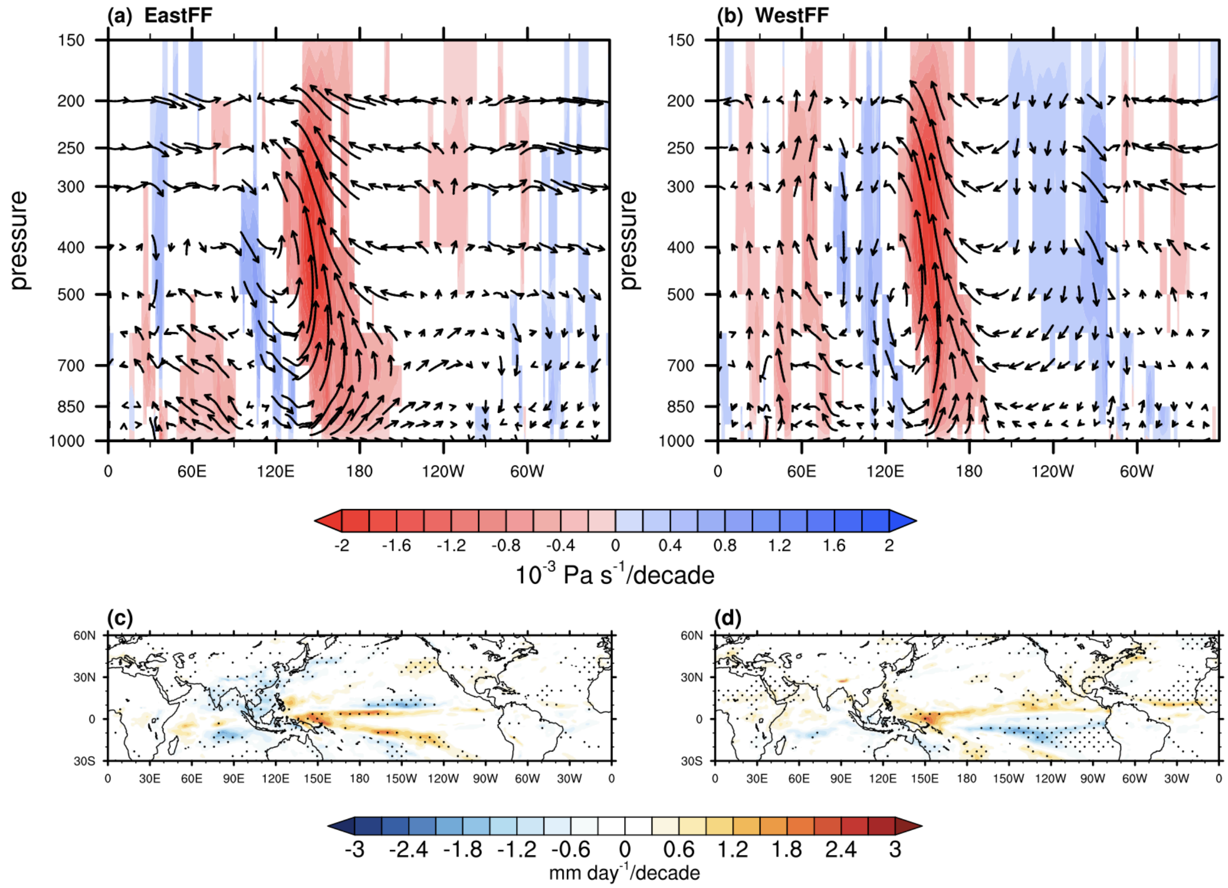

Figure 4 Changes in the tropical circulation.

(a) Decadal changes in cross-section of winds averaged from 5° S–5° N (vectors; The vertical component of the velocity vectors is scaled by a factor of 300) and vertical motion (shading; Pa s-1 in response to EastFF. Blue shading indicates downward motions; red shading indicates upward motions). Regions that fail to pass the significance test (90% confidence level based on a two-sided t-test) are masked in white. (b) As in panel (a) but for WestFF. (c) Changes in tropical Precipitation (mm day-1 per decade) in response to EastFF. (d) As in (c), but for WestFF. Stippled regions in (c) and (d) indicate insignificant values at the 90% confidence level based on a two-sided t-test.

Changes

We add the significance test.

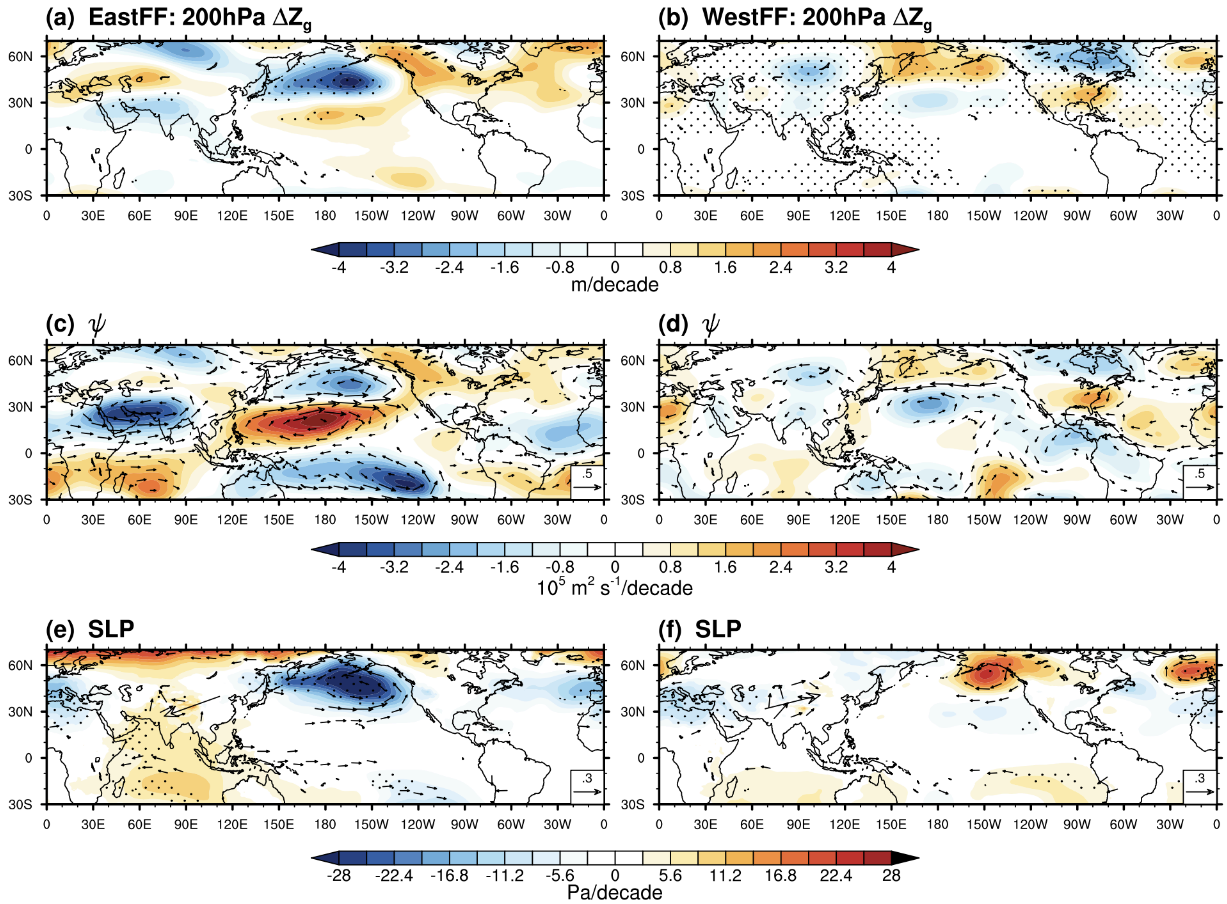

Figure 5

Left panels: EastFF-induced decadal changes of (a) 200 hPa eddy geopotential height (m per decade), (c) 250 hPa stream function (shading; m2 s-1 per decade), and wind (vectors; m s-1 per decade), and (e) sea level pressure (shading; Pa per decade) and 850 hPa low-level wind (vectors; m s-1 per decade). Right panels: same as Left panels, but due to WestFF. Stippled regions indicate insignificant values at the 90% confidence level based on a two-sided t-test.

Changes

We add the significance test.

The colormap in panels e and f is reversed for better comparison, as suggested by the reviewer's suggestion.

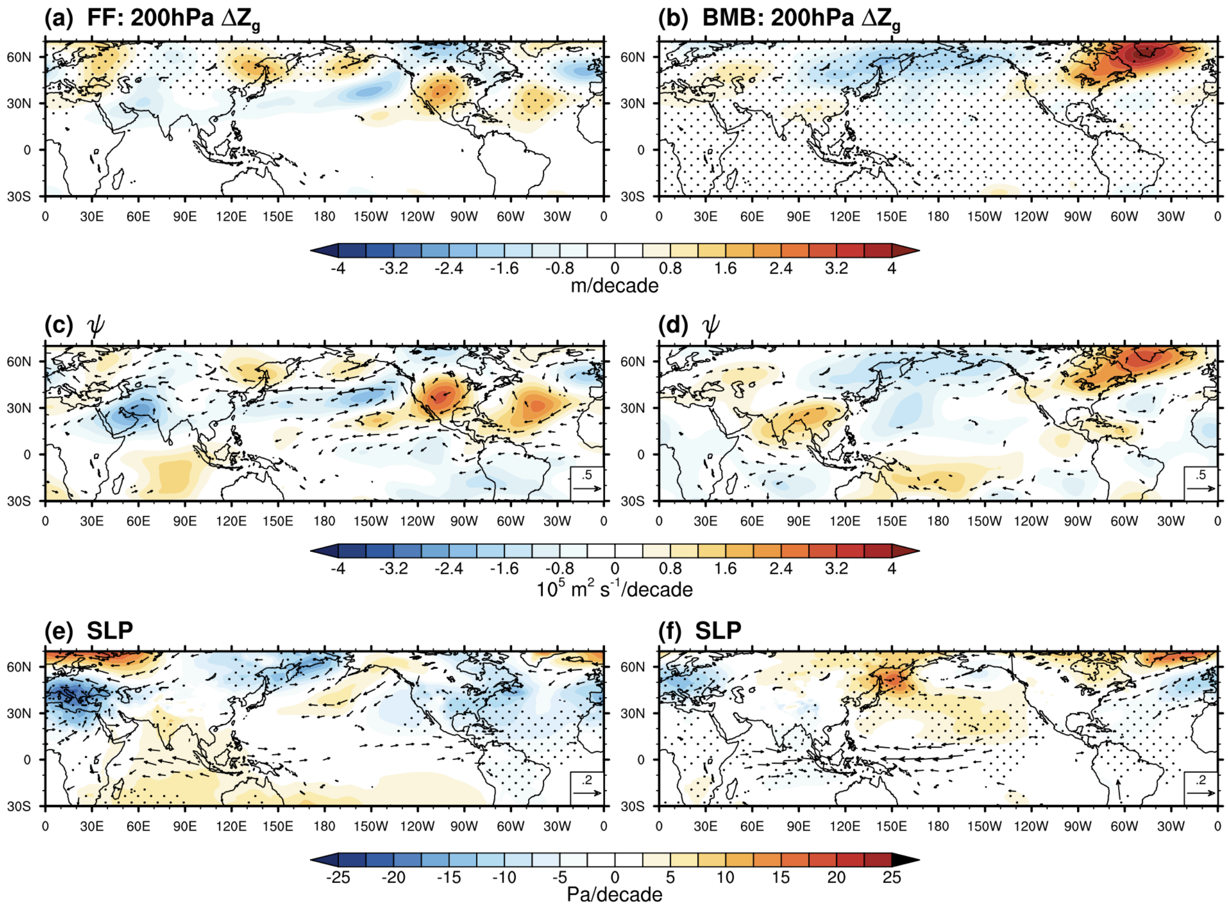

Figure 6

Left panels: FF-induced decadal changes (1980–2020) of (a) 200 hPa eddy geopotential height (m per decade), (c) 250 hPa stream function (shading; m^2 s^{-1} per decade), and wind (vectors; m s^{-1} per decade), and (e) sea level pressure (shading; Pa per decade) and 850 hPa low-level wind (vectors; m s^{-1} per decade). Right panels: same as Left panels, but due to Biomass burning (BMB) simulations. Stippled regions indicate insignificant values at the 90% confidence level based on a two-sided t test.

Changes

We add the significance test.

The colormap in panels e and f is reversed for better comparison, as suggested by the reviewer's suggestion.

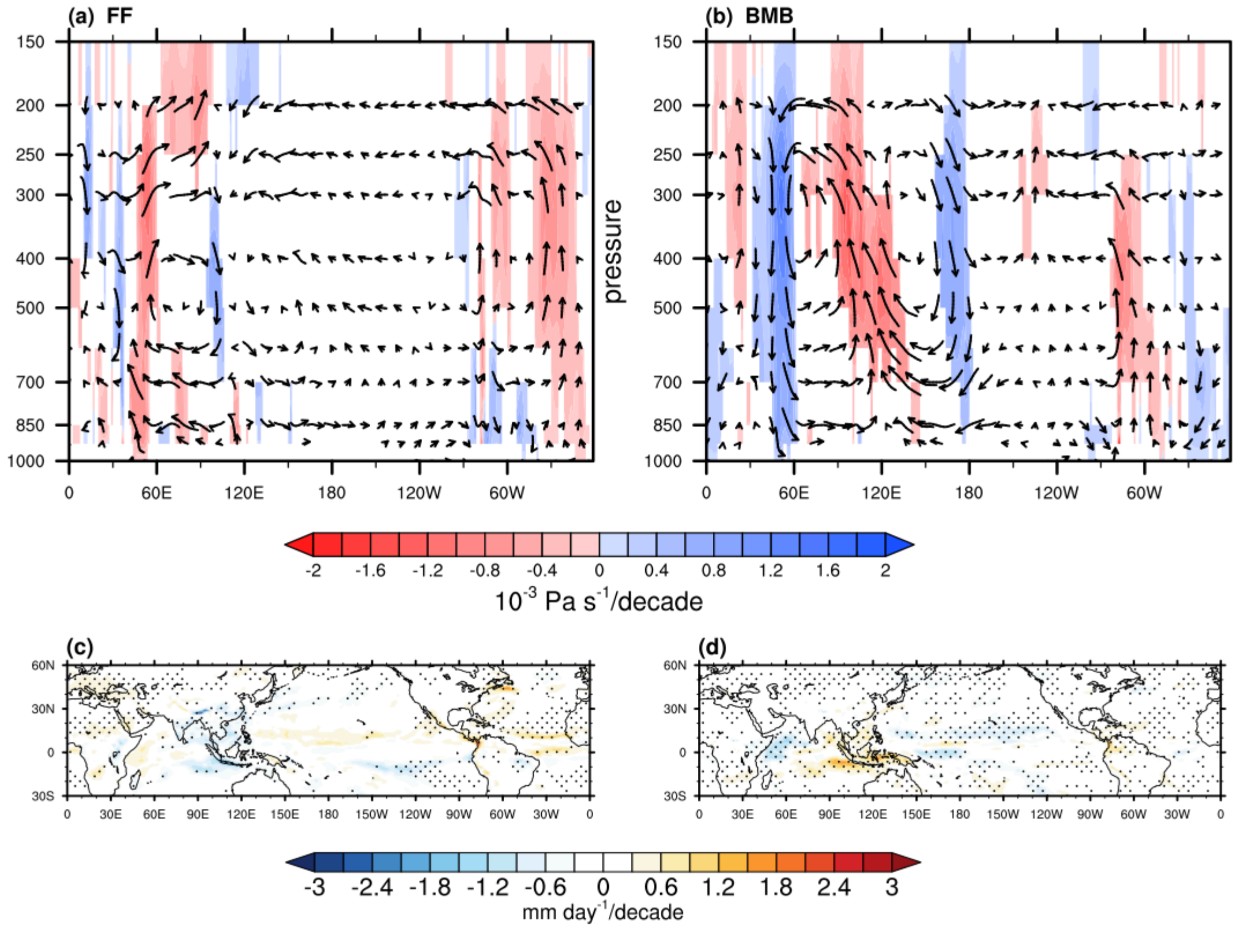

Figure S1 (new figure)

So as Fig. 4 but for (left) FF, and (right) BMB responses.