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 #3

General comments

By using regional aerosol forcing large ensemble simulations based on CESM1 performed earlier, this study investigates impacts of increasing fossil fuel-related aerosol emission over Asia (EastFF) and the reduction in aerosol emission over North America and Europe (WestFF) on the Pacific circulations and SST changes since the 1980s.

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.

One major concern the reviewer has is that results presented in the current version of manuscript are lack of significant test. It is not clear whether responses to different regional aerosols forcing changes described in the study are statistically significant from the internal variability. In addition, there are some other comments that need to be addressed to improve the manuscript. Therefore, the paper needs a major revision before it can be considered for publication.

Response

Thanks for pointing out this important question. We have added significance test results in Fig. 2, Fig. 4, Fig. 5, and Fig. 6. All our conclusions stay convincing. Based on the significance test, we updated the statements about the nonlinearity issues. Also, we added the statistical significance statements here and there in the manuscript. Please check the modified figures by the end of the document.

Major comments

1. It is not clear whether all results analysed are about annual changes. In data and method, there is no any information given.

Response

Thanks for pointing out this issue. All analyses are based on the annual mean results. We clarify this in the Method section as follows:

"All analyses in this study are based on the ensemble-averaged results of the monthly outputs of the five experiments mentioned above (ALL, FF, EastFF, WestFF, and BMB) to exclude the impact of randomly generated internal variability in the model. Annual means are calculated prior to analyses."

2. All results presented in the current version of manuscript are lack of significant test. It is not clear whether responses described are statistically significant from the internal variability. This aspect needs to be improved through whole manuscript.

Response

Thanks for pointing out this important question. We have added significance test results in Fig. 2, Fig. 4, Fig. 5, and Fig. 6. All our conclusions stay convincing. Based on the significance test, we updated the statements about the nonlinearity issues. Also, we added the statistical significance statements here and there in the manuscript. Please check the modified figures by the end of the document.

3. Many references cited in text are not in reference list. Please check them carefully.

Response

We really appreciate the careful review. We have updated the reference list.

4. The study is based on a set of single model simulations, some comments on this aspect would be helpful for readers.

Response

Thanks for the suggestion. We further acknowledge the recent related work and add more discussions on the caveat and limitation of the single model results 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 of 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."

Specific comments

1. Line 20. "an IPO-like SST pattern". It is helpful if authors can clarify the phase.

Response

Thanks for the suggestion. We have modified this to be " *an IPO-like SST pattern (horseshoe-like SST pattern in the North Pacific)*" in the abstract, which is more commonly described in previous studies. We also clarified this in Sect. 3.1.

2. Lines 23-25. The last sentence is very confusing. How the likely opposite responses to future aerosol emission changes are likely to introduce more profound impacts?

Response

Thanks for pointing out this issue. We completely rewrite the statements here following suggestions from another reviewer. The sentences now read as follows:

"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 changes in anthropogenic aerosol emissions are likely to introduce more profound impacts of aerosol forcing on the Pacific multi-decadal variations."

3. Lines 112-113. Are SST anomalies low frequency filtered? Please clarify.

Response

Thanks for the comment. We applied an 11-year low-pass filter before EOF to obtain the interdecadal variability. We add the description at line 113 as follows:

"An 11-year low-pass filter is applied to the SST anomalies prior to the EOF analyses in order to obtain the interdecadal variability."

4. Line 115. "global warming mode induced by the greenhouse gases (GHG)". There are also other external forcings in model simulations.

Response

Thanks for the correction. We modified the sentence as follows:

"For the model simulation results, we subtract the global averaged SST time series from the simulated SST patterns before EOF analyses in order to remove the global change modes driven by external forcings."

5. Lines 195-197. Do authors really think that the discrepancy between FF response and sum of EastFF and WestFF responses is due to aerosol forcings outside two focused regions, which are small as suggested in Figure 1d?

Response

Thanks for the valuable comments. We argue 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 central and eastern 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)."

6. Line 204. "SST anomalies". See major comment 1 and specific comment 3.

Response

Thanks for the comment. We have clarified the method of EOF analyses in the Method section.

7. Lines 254-256. These statements about changes in Walker circulation over the equatorial Atlantic are not convincing. Figure 4b shows anomalous ascent in the tropical Atlantic, being consistent with warming in the tropical Atlantic (Fig. 2b). However, it is hard to argue whether this change is statically significant or not since no such test is shown. See major comment 2.

Response

Thanks for the comments. We have added the significance test results to all related figures. Please check the modified figure at the end of this document.

To clarify here, we wanted to mention that WestFF does not induce any noticeable Walker circulation changes over the equatorial Atlantic, although Fig. 2b shows a warming trend over the tropical Atlantic. Indeed, the ascent in the equatorial Atlantic is insignificant at the lower levels (check modified Fig. 2).

8. Lines 278-279. (Fig. 5c). Shall be (Fig. 5e)?

Response

Thanks for the correction. Yes, it should be Fig. 5e. We have corrected this in the manuscript.

9. Line 288. “convection”, use another word.

Response

Thanks for the suggestion. We have changed it to be “upper-level geopotential height pattern”.

10. Lines 298-303. These arguments about weak tropical teleconnection are not very convincing. See major comment 2 and specific comment 7.

Response

Thanks for the comment. We have added the significance test results to Fig. 5. Based on the significance test and the results of the BMB experiment and other extratropical forcing experiments as mentioned in the manuscript, we argue that our discussion about the mid-latitude pathway is the key difference between the WestFF and EastFF response.

11. Lines 305-310. It is not clear what are the aims for showing BMB experiment in Fig. 6b, d, f. What wave trains authors describe here and they are similar to what?

Response

Thanks for the great comments. 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 also mentioned some other extratropical forcing experiments from previous studies to further indicate the importance of this mechanism. We have now added a bit more descriptions and introductions of the BMB responses referring to existing studies. We now include Fig. 6 to the supplementary document so as not to divert from the main focus of this manuscript – a comparison between EastFF and WestFF.

The paragraph discussing the BMB results 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.”

Fig. 6a, c, e are not refereed in text.

Response

Thanks for pointing out this. We now added additional brief descriptions of the dynamical responses to FF in Sect. 3.4, where we cited the Fig. 6a, c, &e. It reads as follows:

“The dynamical responses in FF largely follow the mid-latitude pathway in WestFF (Fig. 6a, 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.”

12. Lines 342-344. See major comment 2, and specific comments 7 and 10.

Response

Thanks for the comments. Based on the significance test results, we argue that our discussions here are convincing. Please check our previous responses.

13. Lines 346-348. See specific comment 11.

Response

Thanks for the comment. Please check our response about the BMB results above.

14. Figure 5e, f and Figure 6e, f. Reverse colour scale for easy comparison with other panels.

Response

Thanks for the suggestion. We now reversed the color scale for Fig. 5e& f and Fig. 6e&f.

Modified Figures

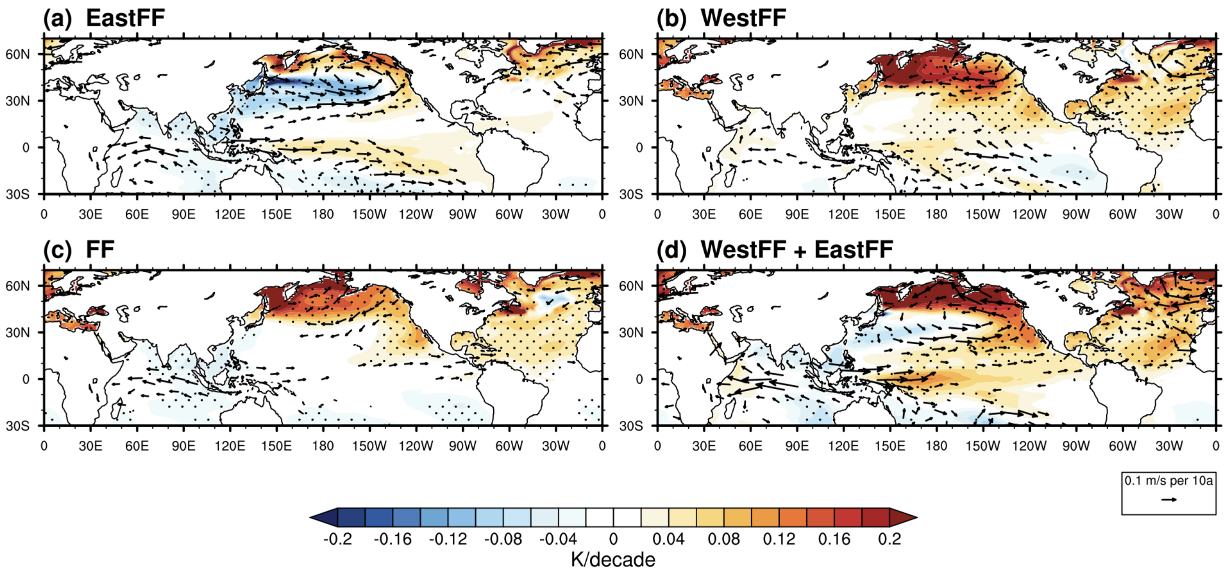

Figure 2

(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.

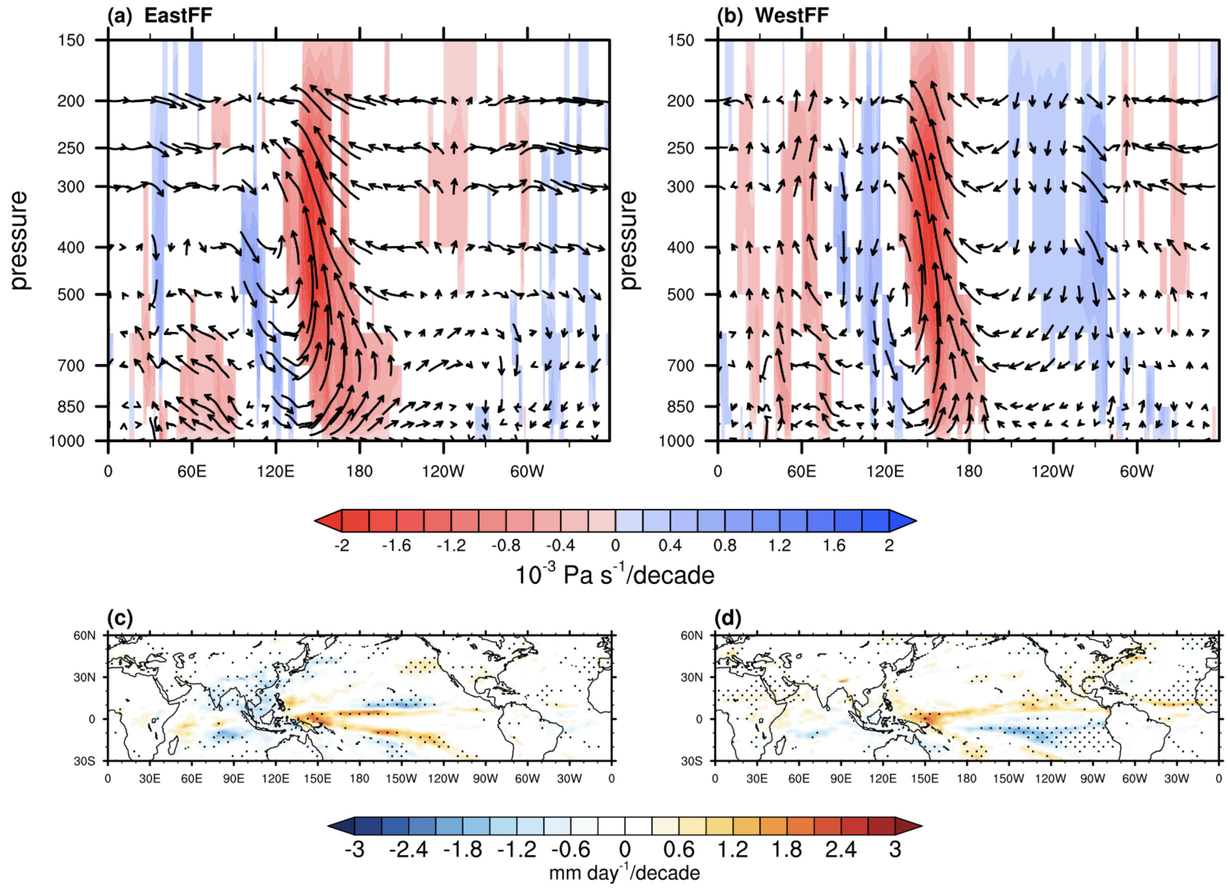

Figure 4 Changes in the tropical circulation.

(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.

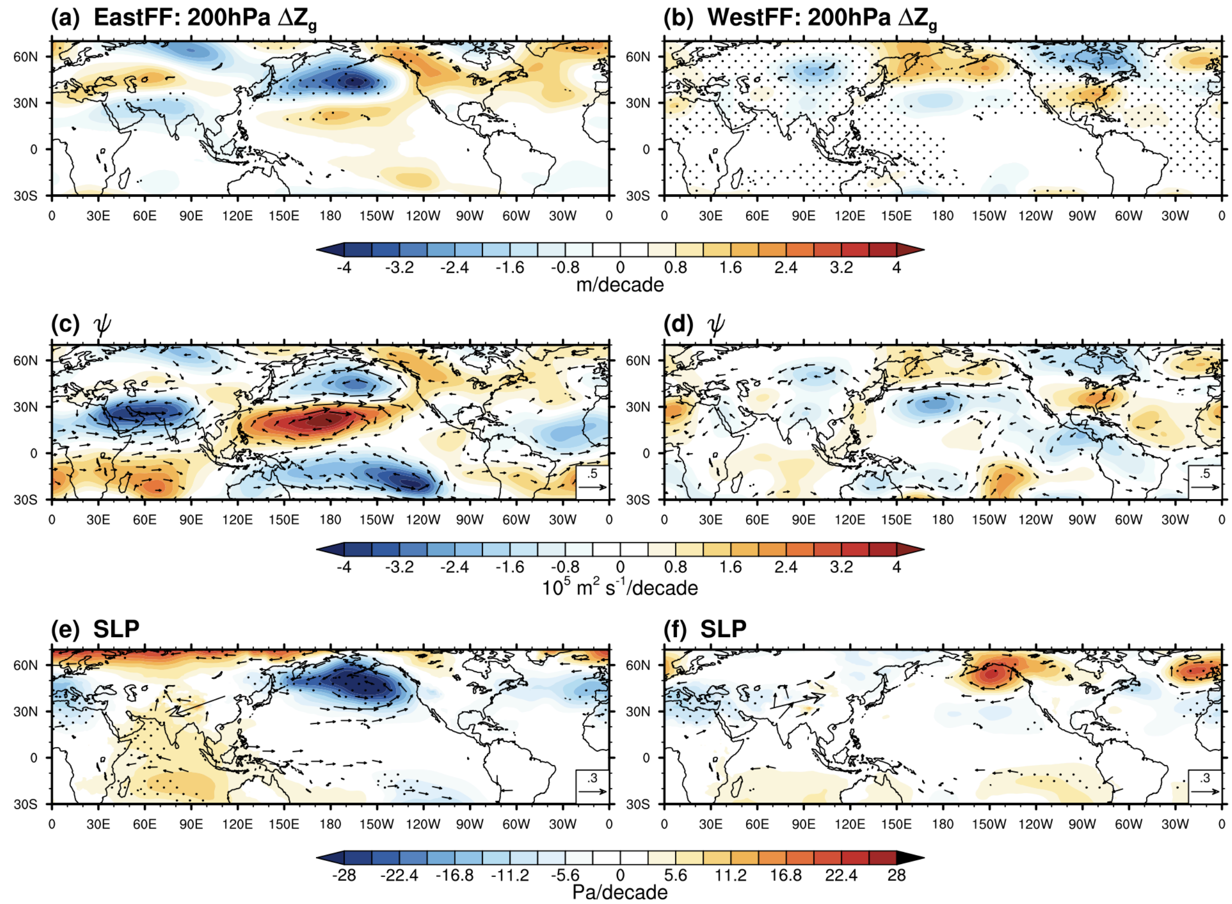

Figure 5

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 reviewer's suggestion.

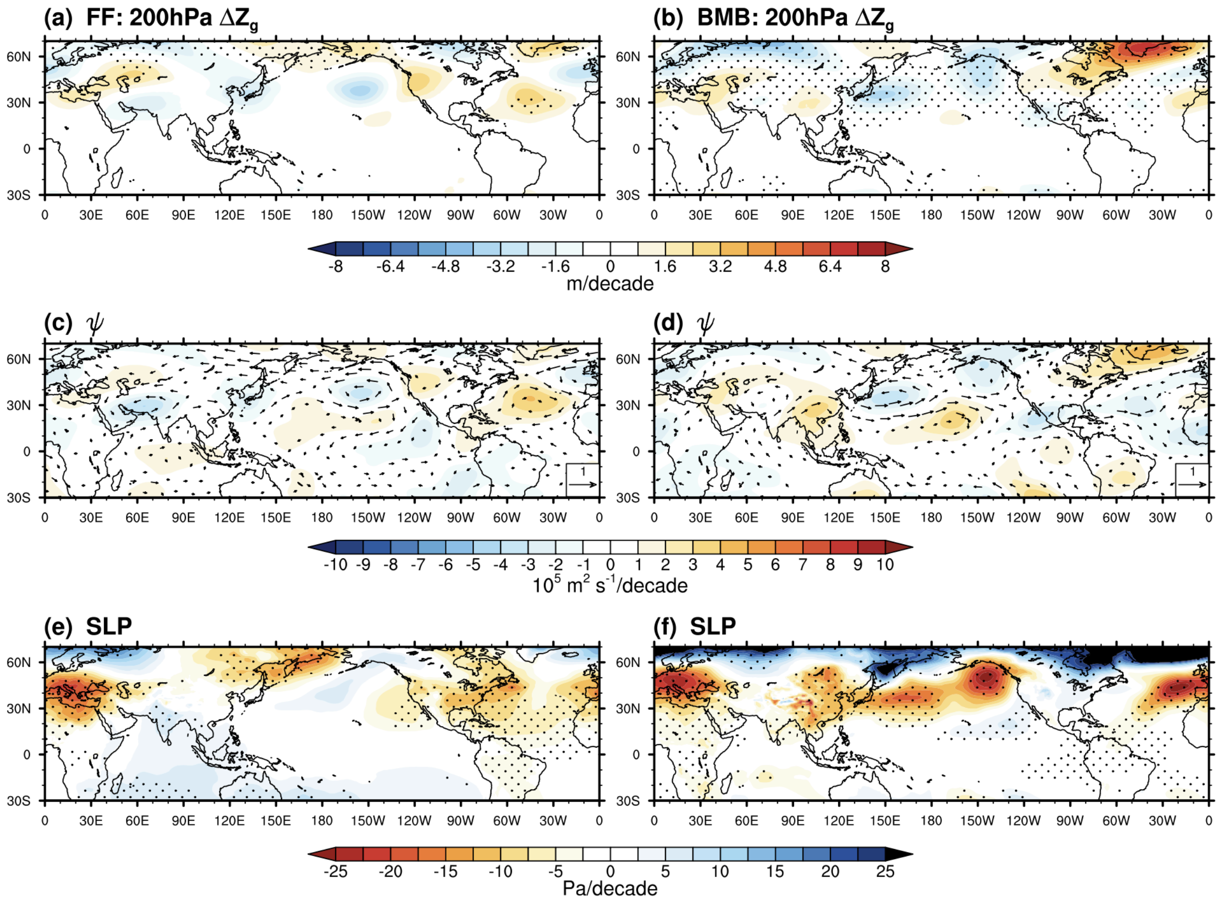

Figure 6

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 reviewer's suggestion.

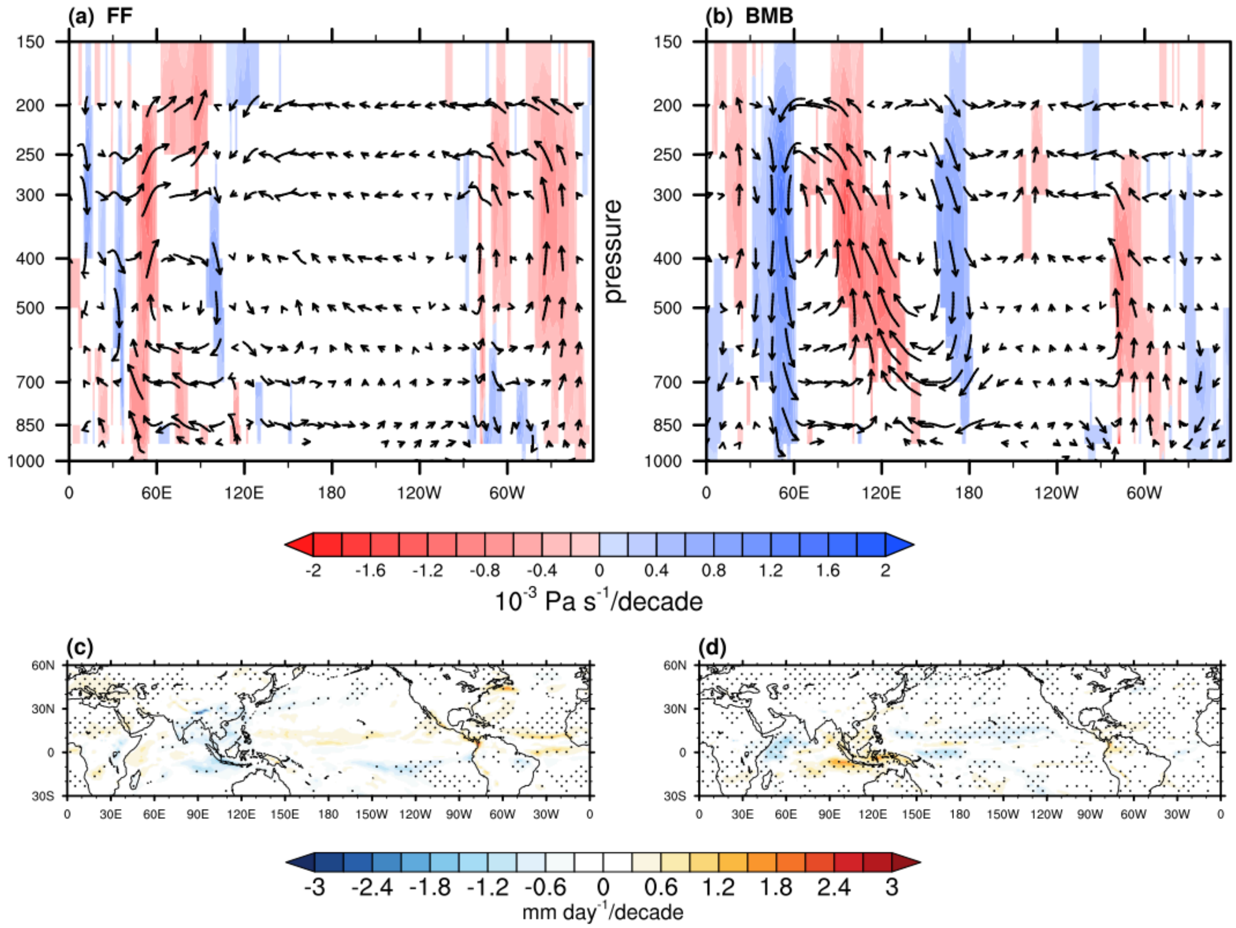

Figure S1 (new figure)

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