Answers to Reviewer 1:

We thank the reviewer for their comments and have uploaded a revised version (with track changes) on ACPD. Below, we address each of the comments (original comment in bold):

(1), The authors can cite the newest PDRMIP data paper in the description of PDRMIP (Myhre et al., 2022). Myhre, G., Samset, B., Forster, P.M. et al. Scientific data from precipitation driver response model intercomparison project. Sci Data 9, 123 (2022). https://doi.org/10.1038/s41597-022-01194-9.

We were not aware of this newest publication and changed the reference as suggested.

(2), In line 86, the authors may cite the following new paper (Xie et al., 2020), which also obviously show the changes of the large-scale atmospheric circulations and surface precipitation associated with Asian summer monsoon induced by sulfate and black carbon aerosols using the PDRMIP data.

Xie, X., Myhre, G., Liu, X., Li, X., Shi, Z., Wang, H., Kirkevåg, A., Lamarque, J.-F., Shindell, D., Takemura, T., and Liu, Y., 2020: Distinct responses of Asian summer monsoon to black carbon aerosols and greenhouse gases, Atmospheric Chemistry and Physics, 20, 11823–11839, https://doi.org/10.5194/acp-20-11823-2020.

Thank you for pointing out this new publication and we additionally added a reference to another one by Williams et al. 2022 which investigates the dependence of the effective radiative forcing and climate response from absorbing aerosols on the geographic location of the emission source.

(3), In line 91, Previous studies (e.g., Liu et al., 2018; ?; Persad and Caldeira, 2018), which reference the symbol "?" represents? Please add the corresponding reference.

Thank you for spotting this, we added the missing reference.

(4), In the Figure 1 caption, …… the eastern China and India with regions defined in (a)-(d). The authors maybe add the detailed longitude and latitude information (such as ?-?N, ?-?E) for the defined eastern China and India to provide readers with reference, respectively.

We added the longitude/latitude values in the figure caption of the edited manuscript.

Answers to Reviewer 2:

We thank the reviewer for their insightful and helpful comments. Below, we address each of the comments (original comment in bold). We have also uploaded a revised version of the manuscript (with track changes).

This study aims to investigate seasonal atmospheric circulation and climate responses to regional aerosol emission reductions related to COVID-19 pandemic by analyzing multi-model ensembles from the CovidMIP. It's focused on January-February (JF) and March-May (MAM) in 2020 when the decrease in aerosol emissions was the largest over eastern China and India, respectively. The results show a precipitation increase over the Maritime Continent driven by regional sea-level pressure and atmospheric circulation adjustments. I find it very interesting that the anomalous climate patterns reverse polarity between JF and MAM, attributed to the shift of dominant source region of SO2 emission reduction from eastern China in JF to India in MAM. The study highlights the important global climate impact of abrupt regional emission changes. The paper is well written, and the main conclusions are mostly supported by the analyses. I have the following specific comments for the authors to consider to better put this study in the context of literature.

Thank you for the positive comments and the further questions.

(1), It's still unclear how exactly the aerosol reductions caused the atmospheric circulation adjustments. Is it mostly from the aerosol-radiation interaction or aerosol-cloud interaction? Ming et al. (2021) found that the large change in shortwave radiative fluxes in March over East Asia was due to aerosol-radiation interaction and, to a large extent, weather variability. It appears that this study attributes the circulation response merely to anomalous surface warming owing to the reduction of sulphate aerosol. How about the role of internal variability in 2020?

Our results show that aerosol–radiation interactions are crucial to generate the local climate response to altered aerosol emissions over Asia, which is then extended downstream via atmospheric circulation adjustments instigated by regional precipitation anomalies. An interesting question is whether the aerosol-generated response (signal) is distinguishable from climate variability (noise). The latter can be estimated in several ways. One approach, used for example in Ming et al. (2021), is to compare the 2020 anomalies with those over the previous 20 years, and to ascertain whether the former falls outside the range of the latter (i.e., estimated by the standard deviation, essentially measuring interannual "weather" variability). Note that this assumes the climate to be approximately stationary over the 20-year period, which makes the isolation of the signal particularly challenging given the large aerosol emission changes and trends, and ensuing climate impact, during the recent decades (see Fig. S1 in Ming et al. (2021), showing a clear increasing trend of SO_2 emissions until 2007 and a decrease thereafter). An alternative way to estimate the magnitude of internal climate variability is to consider pre-industrial (PI) experiments, which allows to ascertain whether the 2020 anomalies would potentially be outside the range of unforced climate variability. We adopted this approach and, similarly to Ming et al. (2021), we compared the top of the atmosphere (TOA) net anomalies in all-sky and clear-sky shortwave (SW) radiation in 2020 with the standard deviation of those from the corresponding PI simulations. The PI standard deviation here is the mean of the individual models' standard deviations, each calculated using the last 150-year segments of the PI experiments. While the 2020 anomalies in all-sky TOA SW radiation are generally well below one standard deviation of the PI anomalies (Figure not shown), the signal emerges more clearly in clear-sky radiation (Fig. 1). These findings are consistent with Ming et al. (2021). This suggests that the impact of COVID-19 aerosol emission changes on clear-sky radiation is detectable outside the bounds of internal climate variability, which further underscore the importance of aerosol-radiation interactions in generating the impact. We have included a short discussion of this aspect in the conclusion section of the manuscript.

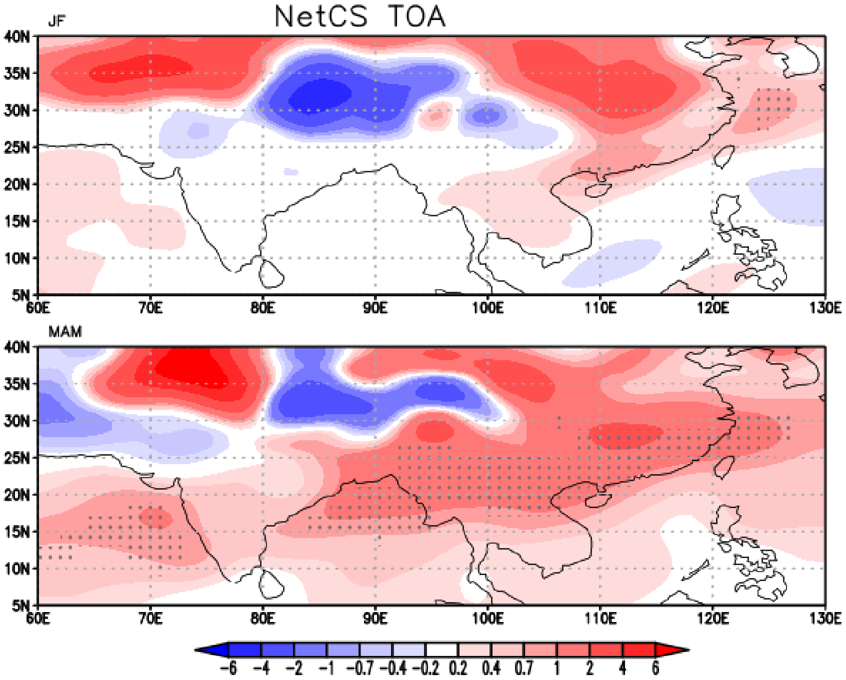


Figure 1: Net clear sky shortwave radiation anomalies (W m^{-2}) at the top of the atmosphere for (top) JF and (bottom) MAM during 2020 for the CovidMIP multi-model ensemble mean (10 models). Stippling marks the grid points where the ratio of the CovidMIP anomalies to the standard deviation in the PI simulations exceeds the value of one.

(2), Yang et al. (2022) found that the atmospheric convection over eastern China was enhanced by COVID emission reductions and there was a positive feedback of moisture convergence from a sea-level pressure anomaly over northwestern Pacific, which together contributed largely to the record summer rainfall in eastern China. They identified a key role of the intensified western Pacific subtropical high (WPSH). In the section 3.2 of this study (starting from Line 235), the weakening and eastward shift of WPSH are also mentioned. Are the mechanisms consistent with each other? Please provide a discussion on this.

A thorough comparison between Yang et al. (2022) and our study is not entirely possible given that the former analysed the June-July (JJ) 2020 climate response, while the latter focused on JF and MAM 2020. Climatologically, the WPSH is characterised by a strong seasonality with a marked northwestward migration of its centre and expansion from late spring to the summer, which ultimately determines its imprint on East Asian climate. While Yang et al. (2022) includes an analysis of the CovidMIP multi-model ensemble, the detailed mechanistic analysis of low-tropospheric atmospheric circulation and sea level pressure anomalies (their Fig. 3) focuses only on one model (E3SM1.1). Furthermore, their comparison between individual model responses shows substantial inter-model differences, especially in the dynamical fields (see their Fig. S9). In contrast, our study focused on the multi-ensemble mean across 10 CovidMIP models. The need for this multi-model comparison is further highlighted in Fig. 2 below which compares the 850-hPa wind response between E3SM and CovidMIP during MAM and JJ. Note in particular that the JJ flow across eastern China is southwesterly in E3SM, consistent with Yang et al. (2022), but northerly in the CovidMIP ensemble. Correspondingly, the sea level pressure pattern features an anomalous anticyclone over the western tropical Pacific in E3SM, again consistently with Yang et al. (2022), while a cyclone, displaced further northward over the subtropical Pacific, appears in CovidMIP.

When focusing on MAM, the E3SM and CovidMIP ensemble circulation responses display more consistency (with the CovidMIP response also showing several features common to the JJ pattern, notably an anomalous anticyclone over the northwestern Pacific). Note also that 850-hPa wind anomalies are relatively modest over the tropical Pacific. As described in the main text and also further highlighted in Figure 3 below, the CovidMIP response in MAM features a weakening of the WPSH, with low sea level pressure anomalies over the western subtropical Pacific and, of even larger magnitude, over East Asia, associated with warmer surface conditions compared to the baseline. As a result, southwesterly winds blow over eastern Asia, carrying moisture and leading to enhanced precipitation along the entire coast (Fig. 3 below). While this anomalous flow bears resemblance to that described in Yang et al. (2022) over East Asia for JJ, including the associated land warming, the large-scale pattern is fundamentally different: Our results show a widespread cyclonic flow over Asia with enhanced moisture advection from the eastern Indian Ocean and negligible anomalies over the Pacific, compared to a marked strengthening of the WPSH and moisture advection from the western Pacific in Yang et al. (2022). The latter also lead to enhanced precipitation, but the increase is more confined to southern and eastern China. Thus, while the mechanism identified in this study is not inconsistent with that proposed in Yang et al. (2022), there also some important differences with regards, for example, to the moisture pathways and the large-scale dynamical anomalies. This is not surprising given, in general, the large inter-model differences in representing atmospheric circulation changes and the marked uncertainties associated with them.

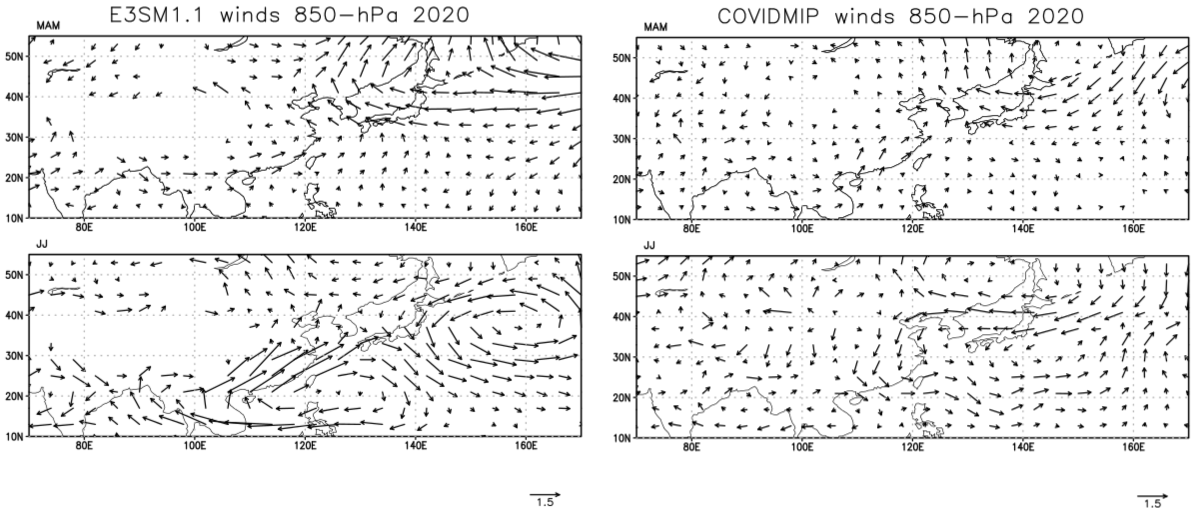
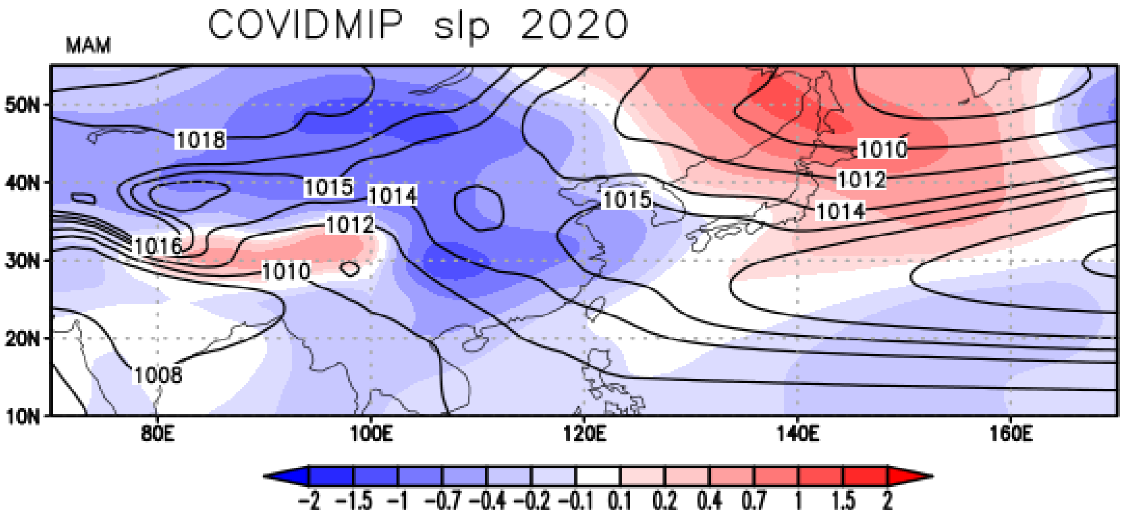


Figure 2: Anomalies in 850-hPa winds (m s^{-1}) in (left) E3SM and (right) the CovidMIP ensemble (10 models) for (top) MAM and (bottom) JJ 2020.



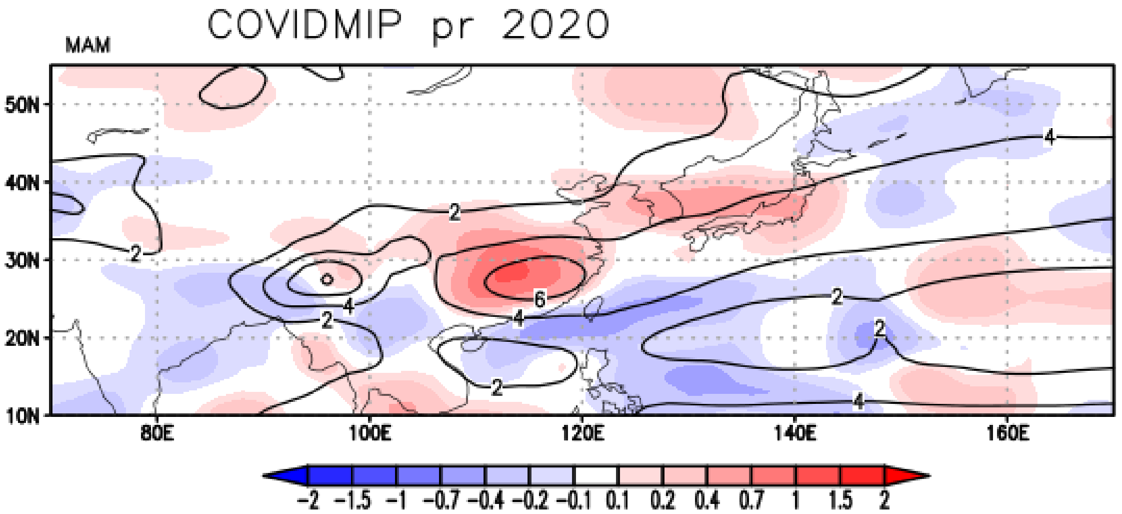
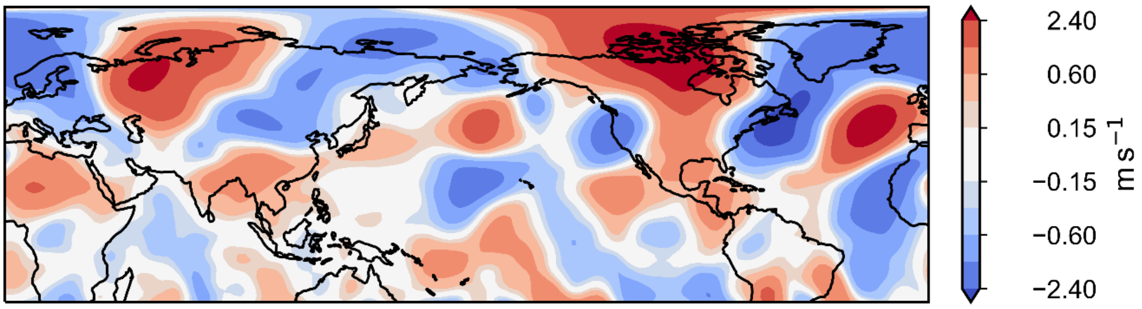


Figure 3: Anomalies in (top) sea-level pressure (hPa) and (bottom) precipitation (mm day^{-1}) in the CovidMIP ensemble for MAM 2020. Also shown are the corresponding baseline patterns (black contours).

(3), Two low-resolution CovidMIP models were excluded from the analysis. Jones et al. (2021) didn't mention potential issues associated with model resolution. I am curious whether the resolution was key to resolving the atmospheric circulation adjustments in response to the abrupt aerosol changes. Is there evidence supporting this?

The initial analysis described in Jones et al. (2021) did not show atmospheric circulation changes and focused primarily on regional Asian or global mean responses. Nonetheless, we do not think that the large-scale circulation adjustments discussed in our study are dependent on the model resolution. Indeed, the following Figures 4 and 5 compare the spatial patterns of the JF and MAM 2020 anomalies in meridional wind speed with and without the two coarse resolution models. As expected, the main features of the upper-tropospheric circulation are common to both ensembles, which further strengthens our findings and indicates that the underlying physical mechanism is consistent. However, we do expect differences to appear in near-surface fields, including in the precipitation distribution around Asia, which could smooth out some important sub-regional details. Thus, we decided to focus on the multi-model response across the 10 finer resolution models as we aimed to analyse regional as well as large-scale adjustments.

(a) 10 model MEM



(b) 12 model MEM

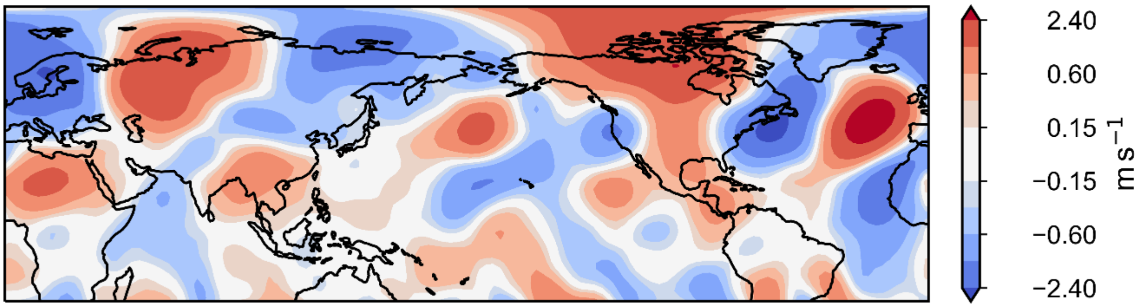
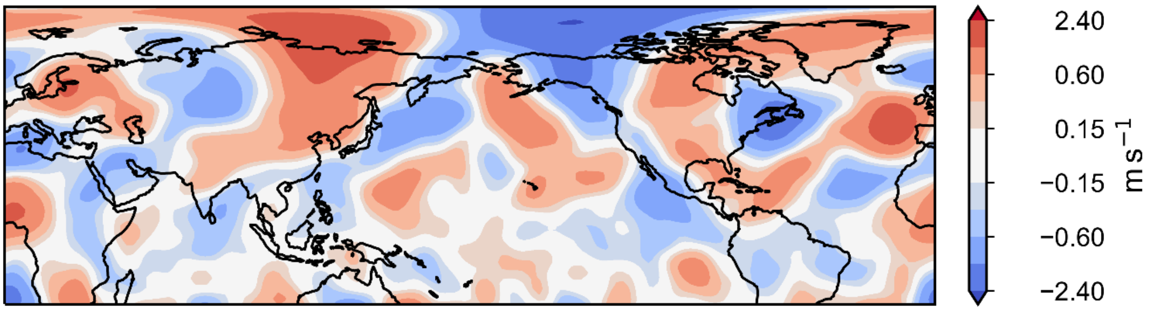


Figure 4: Spatial patterns of JF 2020 anomalies in meridional wind speed at 250 hPa (m s^{-1}) for the MEM calculated across (a) the ten models used in our manuscript (at a resolution of 2°x2°) and (b) across all 12 models including the two low-resolution CovidMIP models (at a resolution of 2.8°x2.8°).

(a) 10 model MEM



(b) 12 model MEM

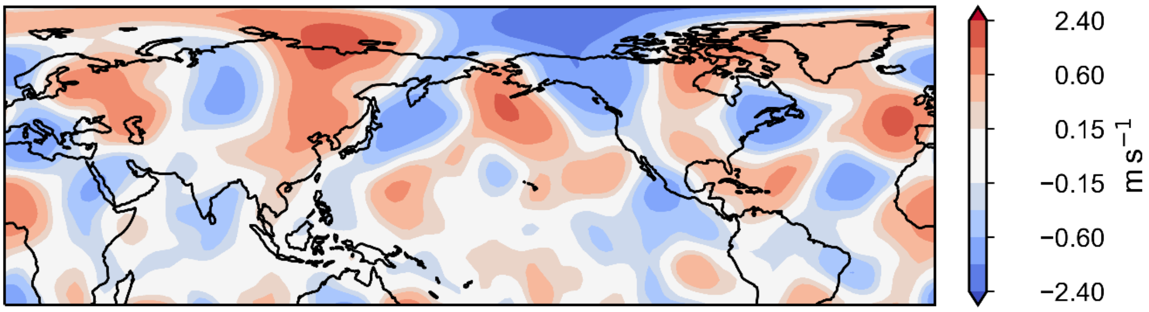


Figure 5: As in Figure 4 but for MAM 2020.

(4), I understand that this study focuses on the fast atmospheric responses at the monthly timescale. However, the CovidMIP short simulations were conducted with coupled atmosphere-ocean models. I wonder whether the authors assessed any oceanic responses that cause SST changes and sea-level pressure anomalies.

The simulations analysed in this study were conducted with fully coupled atmosphere-ocean models, thus including the oceanic response and air-atmosphere interactions. The term "superfast" response used here refers to the climate response to emission changes including feedbacks from sea surface temperature (SST) changes (see manuscript around line 100). This is different from the traditional fast response which refers to atmospheric-only changes (i.e., keeping SSTs fixed). However, as we focus on the first months of the simulations, it is reasonable to assume the climate response to be predominantly driven by atmospheric adjustments, with a negligible contribution of the oceanic circulation.

Overall, the response features distinctive SST anomalies, especially across the Pacific Ocean (See Fig. 3 in the manuscript). As mentioned for example around line 230, the SST anomalies are consistent with the overlying pattern of sea-level pressure and near-surface wind anomalies, in turn largely consistent with, and driven by, the adjustment of the large-scale upper-tropospheric atmospheric circulation to aerosol forcing over Asia via, for example, wave propagation (as for example discussed around line 285). To examine the relationship between near surface atmospheric circulation and SSTs in more detail, we enclose here the Figure 6 below. During JF 2020, the anomalous anticyclone over the north-eastern Pacific, associated with mid-tropospheric subsidence on the eastern flank of the upper-tropospheric anomalous high and related northerlies via Sverdrup balance (see Figs. 4a and c in the manuscript), induces an anomalous near-surface wind convergence over the tropical central Pacific and strong southerlies to the North of it. The former leads to Ekman downwelling, while the latter reduces the magnitude of the baseline wind, thus decreasing the evaporation cooling, and induces warm advection anomalies compared to the baseline meridional temperature field. As a result of these processes, a warm SST anomaly appears in the central Pacific. Similarly, Ekman divergence-induced upwelling as well as coastal upwelling off the north-western coast of the US lead to SST cooling. Note that the circulation and SST anomaly patterns are similar, and of opposite sign (thus indicating a consistent response), to those described in Boo et al. (2015) associated with increased East Asian aerosols. Along the equatorial Pacific, both stronger easterlies (over the western part of the basin) and, even more importantly, near surface anomalous equatorial divergent flow, lead to larger evaporation and upwelling, resulting in cold SST anomalies.

Similar reasoning can explain the anomalous SST pattern during MAM 2020 and, in particular, its incremental changes with respect to JF. For example, near-surface wind convergence is found over the eastern sub-tropical Pacific, leading to anomalous downwelling and thus surface warming. Anomalous northerlies blow over the northern Pacific west of the dateline associated with an anomalous cyclone (and mid-tropospheric ascent). This wind anomalies reinforce the baseline flow: Increased evaporation, together with cold water advection and wind-driven upwelling, lead to the reduction, if not reversal, of the warm JF SST anomalies over the central north Pacific. Weaker trade winds are noticeable along the western and central equatorial Pacific, leading to reduced evaporation and eastward advection of warm water, and thus to the disappearance of the cold JF SST anomalies. We have slightly rephrased the main text to further highlight the wind-driven formation of the SST patterns.

Boo, K.-O., Booth, B. B. B., Byun, Y.-H., Lee, J., Cho, C., Shim, S., and Kim, K.-T.: Influence of aerosols in multidecadal SST variability simulations over the North Pacific, J. Geophys. Res.-Atmos., 120, https://doi.org/10.1002/2014JD021933, 2015.

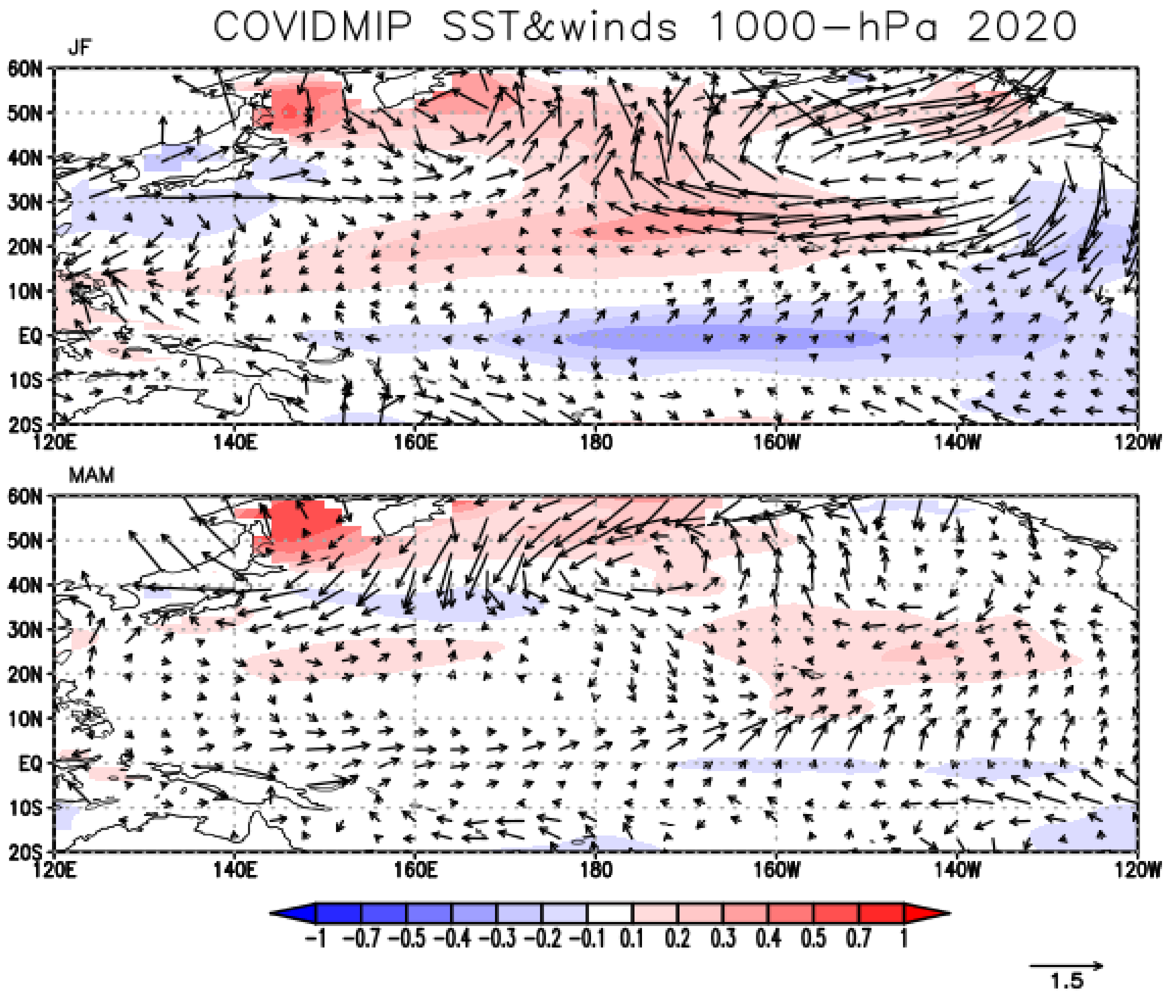


Figure 6: Spatial patterns of SST anomalies (K) and 1000hPa-meridional winds (arrows; m s^{-1}) for the MEM across 10 CovidMIP models for (top) JF and (bottom) MAM 2020.