We thank the constructive comments from the reviewers. We made revisions to address the concerns of reviewers and improved the presentation of our paper. A revised manuscript with all changes since its last submission highlighted is uploaded as supplements to this response.

Please see the detailed response below.

Reviewer #1:

Comments:

In this paper, you proved the changes in the SST gradient and mid-latitude eddies are instrumental in creating a similar deep vertical temperature in response to BC and SO4. It shows the importance of ocean-atmosphere interactions. This is the pioneering study about climate effects of aerosols at present. In this regard, this paper is interesting and important. The results are convincing and the simulations used are appropriate. I thereby believe this manuscript is appropriate for publication in ACP and would recommend publication subject to primarily minor revisions outlined below. Hope the comments below are of help for the authors.

Responses:

Thanks very much for the comments and suggestions. We have made revisions accordingly. Please see specific changes below.

Comments:

(1) I am confused about how to conduct the model configuration in this paper. Parameterization schemes, spatial resolution, . . .should be shown in this study. And more information about the emission inventory of BC and SO4 should be mentioned. Furthermore, the introduction of the modeling performance about simulating BC and SO4 is inadequate in this paper. BTW, BC in snow could increase the surface temperature and reduce snow pack. These impacts may result in the change of soil moisture, surface fluxes, and East Asian monsoon (Huang et al., 2011, Wang et al., 2013 and Flanner et al., 2005). Is BC in snow considered in the paper?

Responses:

We now included in the method section more details about model and experiment set-up. Some statements are copied below.

Parameterization schemes: The three-mode modal aerosol scheme (MAM3) provides internally mixed representations of aerosol number concentrations and masses (Liu et al., 2012). Aerosol indirect forcing is included for both liquid and ice phase clouds (Gettelman et al., 2010).

Model resolutions: The resolution of both atmosphere and ocean models is 1 degree by 1 degree for the coupled simulations (Experiments a and b) in this study. The resolution of atmospheric model is 2 degree by 2 degree for the uncoupled simulations (Experiments c and d) in this study.

Emission inventory: The anthropogenic forcings in CESM1 include long-lived greenhouse gases (GHGs), as well as tropospheric ozone, stratospheric ozone, sulfate

aerosols, and black and primary organic carbon aerosols. The aerosol emission inventory is from the standard Representative Concentration Pathway as described in Lamarque et al. (2010). However, the present-day emission level of BC is adjusted from the standard model emission inventory to account for the potential model underestimation of BC atmospheric heating.

Modeling performance about simulating BC: Our previous analysis (Xu et al., 2013) show that such a correction improves simulated radiative forcing compared to the direct observations. Without the observational constrains, simulated BC forcing (and associated temperature response) would be lower by about a factor of two.

BC in the snow: In addition to the atmospheric heating, deposition of BC particles onto snow surface with high albedo would reduce surface albedo and contribute to surface warming (Huang et al., 2011). The land model of CESM incorporates SNICAR (Snow and Ice Aerosol Radiation) module, which represents the effect of aerosol deposition (BC, organic carbon and dust) on surface albedo (Flanner et al., 2007).

Comments:

(2) “Reflcting and absoring aerosols” are always mentioned in this paper. However, only SO4 and BC4 were considered in the simulations. As we known, dust is one of the absorbing aerosols in the atmosphere, which can influence the climate directly by modulating the radiation budget, affect the microphysical properties of clouds, and alter the surface albedo of the ground covered by snow or glacier. Therefore, I think more aerosols species should be discussed in detail.

Response:

This is a good point. We now added that " Note that in this study we used BC, a strong absorber, to characterize absorbing aerosols that also include dust and organic aerosols. Similarly, we used SO4 to characterize reflecting aerosols although dust and organic aerosols are also partially reflecting. This approach provided a clearer contrast between these two types of aerosol forcing."

Comments:

(3) In this paper, you just showed the vertical profile of simulated results. I think the spatial distributions of the most relevant results are needed. It can help us decide whether the patterns of simulations are reasonable at global scales.

Responses:

Thanks for the suggestions on including spatial pattern of the responses. We intend to focus on the tropospheric response in this paper, as it is a feature rarely explored before. As for spatial distribution of climate response at the surface suggested by the reviewer, we are now actively working on a complimentary paper on this issue. Nevertheless, we now included the SST response to all three forcings as Fig S1.

Comments:

(4) Some parts of supplement materials including a detailed explanation should be put in the main body.

Response: Now Fig S1 is moved to be Fig 1. Fig S3 and Fig S4 are also consolidated into main text figures.

Minor comments:

(1) Table S1: How to get these results in Table S1? Please give more details about background information.

Responses: The table caption is re-written to clarify the approach. It now reads " Table S1. (a) TOA forcing (W/m2, shortwave + longwave) due to BC (direct radiative forcing from pre-industrial to present-day; not including snow albedo effect), SO4 (direct+indirect forcing from pre-industrial to present-day, so called “adjusted forcing”) and CO2 (from pre-industrial to present-day at 400 ppm). The radiative forcing is diagnosed by contrasting two sets of five-year atmospheric-only simulations with pre-industrial and present-day emissions/concentrations, respectively. (b) Surface temperature change (℃) in response to different forcings in (a). These are calculated from the 60-year average of coupled model simulation. (c) Cumulative precipitation (cm) change in response to different forcings in (a). The relative changes in percentage are shown in parenthesis next to the absolute changes.

Comments:

(2) Section 2.1: Introduce the model configuration including the modeling domain, the BC and SO4 emission inventory.

Response: This is addressed. Please see response to major comments.

Comments:

(3) Figure 1 and Figure 3: The figures did not show the SST perturbation induced by BC. Why?

Responses:

Due to limited computational resources, we did not conducted BC-induced SST perturbation simulation. We speculate this is merely reversing the sign of the SO4-induced SST perturbation.

Comments:

(4) Figure 4 and Figure S4: These figures need to be more clearly. Please improve them.

Response: Thanks for the suggestions. We now consolidated them together to be Fig 5 and improved the presentation by showing color contour.

Reference:

134 1. Huang, J., Fu, Q., Zhang, W., Wang, X., Zhang, R., Ye, H., and Warren, S.: Dust and
135 black carbon in seasonal snow across northern China, Bull. Amer. Meteor. Soc., 92, 175–
136 181,doi:10.1175/2010BAMS3064.1, 2011.
137 2. Wang, X., S. Doherty, J. Huang, 2013: Black carbon and other light-absorbing
138 impurities in snow across Northern China, Journal of Geophysical Research:
139 Atmospheres, 118, doi:10.1029/2012JD018291.
140 3. Flanner, M. G. and Zender, C. S.: Snowpack radiative heating:Inïn˘Cuence on Tibetan
141 Plateau climate, Geophys. Res. Lett., 32, L06501, ´ doi:10.1029/2004GL022076, 2005.
142

Reviewer #2:

General comments:

This study compares the atmospheric circulation responses to absorbing black carbon (BC) and reflective sulfate (SO4) aerosols. It had been previously hypothesized that the atmospheric responses to these 2 types of aerosols differ significantly, since BC aerosols alter the atmospheric vertical heating profile whereas SO4 do not. However, this study finds similar mid-latitude responses (of opposite sign) to BC and SO4 aerosols in the CESM model, both characterized by adjustments of the Hadley cell and mid-latitude jets. The authors attribute the SO4-related changes to the interhemispheric pattern of SST changes, which perturbs the atmospheric column even though SO4 aerosols cause very little direct forcing.

This is an interesting study which contributes to the understanding of the dynamical effects of aerosols on the tropospheric circulation.

Responses:

Thanks very much for reviewing our paper.

Comments:

My main suggestion is that the contrast with the GHG response should be drawn out further. In particular, the difference in the jet stream response to aerosol v. GHG forcings [e.g. Lu et al. 2008; DOI: 10.1175/2008JCLI2200.1] should be made more explicit. More broadly, how can the conclusions of this study be reconciled with [Xie et al. 2013; DOI:

166 10.1038/NGEO1931], which finds fundamental similarities between the responses to
167 aerosol and GHG forcing?
168
169 Response:
170 Thanks for the suggestions. We intended to focus on comparing absorbing and reflecting
171 aerosols, as this is less studied before. We are currently working on another paper draft
172 giving a more thorough discussion of GHGs vs aerosols response. Basically, the
173 similarity of GHG and aerosols are profound at the surface and boundary layer, and the
174 distinction is revealed in the free troposphere. Nevertheless, we moved Fig S1 to the main
175 text as Fig 1 and gave more discussions on the GHGs response in the beginning of
176 Section 3.
177
178 Specific comments / questions:
179 1: The extremely small magnitude of the SO4 fast component in Figure 2 is striking. Are
180 all of the aerosol cloud indirect interaction effects accounted for by the fast component,
181 or could some be decomposed into the slow component?
182
183 Response:
184 The aerosol cloud indirect forcing is indeed included in the fast component as we only
185 fixed SST in the experiment and clouds are allowed take fast response. If not with aerosol
186 indirect effect, the surface and atmospheric response would be even smaller.
187
188 Comments:

2. In Figure 3, it is not clear that the Hadley cell responses are similar except in magnitude. The BC Hadley cell change appears to be mainly in the northern cell, whereas the SO4 change appears to be mainly the southern cell. Please explain this difference (or alternatively, why it is not important).

Response:

This is a good observation. First, note that color for SO4 response in original Fig 3 (now Fig 4) is not reversed as in previous temperature figures, in order to depict the real direction of circulation change. The magnitude of the response in BC is weaker due to a smaller forcing (Table S1), and we selected the color scale in BC case to be 50% of SO4 case. As for the location of maximum circulation change reviewer pointed out, SO4-induced Hadley cell change is over the equator while BC-induced Hadley cell change appears slightly more on the north side. The same for the jet stream shift. The subtle difference is probably related to the geographic difference in BC and SO4 forcing (amid both are stronger in NH), which may influence Pacific and Atlantic branch of jet differently. We now include above discussions in the paper, and will further investigate in the complimentary paper.

Comments:

3. In the conclusion, the authors suggest that projected SO4 reductions may result in deep mid-latitude warming. However, would future air pollution controls also reduce BC emissions, and thus produce a mid-latitude cooling response?

Response:

That's true. We feel that the tropospheric heating from future SO4 decline is rarely recognized as a threat for mountain snow pack in the future. That's why we point it out in the conclusions and imply more stringent control on heating BC and CO2 is needed to mitigate the snow retreat.

Technical and clarification comments:

a. [Page 5539, line 2]: The singular "dust" is the more proper usage.

Responses:

Fixed.

Comments:

b. [Page 5539, lines 9-11]: It is not clear what previous studies are being referred to.

Responses:

It now reads "While previous studies (e.g. Xie et al., 2013; Ocko et al., 2014) focused on radiative forcing and climate impacts of aerosols on surface temperature and precipitation (Table S1), few looked at the tropospheric response."

Comments:

c. [Section 2.2.d]: It would be helpful to include a supplementary figure of the SST perturbation pattern, considering its importance for the mechanism.

Response:

We now included the SST response to all three forcings as Fig S1.

Comments:

d. [Figure S1]: This is a key overview of the main heating and temperature responses. Perhaps it could be included as a main figure rather than supplementary?

Response:

Thanks for the suggestion. We now move it to be Fig. 1.

Comments:

e. [Figure 3]: Would it be clearer if the sign convention for Figures 3a and 3b were reversed to match Figures 1 and 2?

Responses:

We now clarify in the text by stating that " Note that color for SO4 response in Fig. 4 is not reversed as in the temperature figures, in order to depict the real direction of circulation change." This is consistent with the following EP flux and refractive index diagnostics.

Comments:

f. [Page 5543, bottom; and Figure S5 caption]: I suggest the wording should be "the climatology."

Responses:

Fixed.

Comments:

g. [Page 5544, bottom paragraph]: The use of parenthesis to indicate opposites in this way is difficult to read. See http://climate.envsci.rutgers.edu/robock/Parentheses2010EO450004.pdf

Responses:

Thanks for the suggestion. We fixed this.

Ocean mediation of tropospheric response to reflecting and absorbing aerosols

Yangyang Xu[1]* and Shang-Ping Xie[2]

[1] National Center for Atmospheric Research, Boulder, CO 80303.

[2] Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093.

*Correspondence to: yangyang@ucar.edu

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Abstract

Radiative forcing by reflecting (e.g., sulfate, SO4) and absorbing (e.g., black carbon, BC) aerosols is distinct: the former cools the planet by reducing solar radiation at the top of the atmosphere and the surface, without largely affecting the atmospheric column, while the latter heats the atmosphere directly. Despite the fundamental difference in forcing, here we show that the structure of the tropospheric response is remarkably similar between the two types of aerosols, featuring a deep vertical structure of temperature change (of opposite sign) in the Northern Hemisphere (NH) mid-latitudes. The deep temperature structure is anchored by the slow response of the ocean, as large meridional sea surface temperature (SST) gradient drives an anomalous inter-hemispheric Hadley circulation in the tropics and induces atmospheric eddy adjustments in the NH mid-latitudes. The tropospheric warming in response to projected future decline in reflecting aerosols poses additional threats to the stability of mountain glaciers in NH. Additionally, robust tropospheric response is unique to aerosol forcing and absent in the CO_2 response, which can be exploited for climate change attribution.

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1. Introduction

Greenhouse gas-induced global warming is partially masked (Ramanathan and Feng, 2008) by the accompanying increase in anthropogenic aerosols (Smith et al., 2011). Relative contribution of aerosol masking effect on global temperature is hard to quantify for the following reasons: (a) some aerosols (e.g., black carbon (BC) and organics) absorb sunlight and heat the planet (Bond et al., 2013) and (b) aerosol microphysical effects on clouds are complex (Rosenfeld and Wood, 2013). Many ongoing efforts aim to reduce uncertainties in radiative forcing (Xu et al., 2013) and quantify the surface temperature response to aerosols (Levy et al., 2013). The atmospheric circulation response to reflecting aerosols has important effects on regional climate (e.g., the Indian monsoon (Bollasina et al., 2011)) and hydrological cycle (Shindell et al., 2012; Hwang et al., 2013). Much attention has been given to absorbing aerosols for the direct atmospheric heating effect, including BC (Meehl et al., 2010) and dust (Vinoj et al., 2014). It is often argued that, by heating directly the atmosphere, absorbing aerosols can greatly perturb the atmospheric temperature structure, causing changes in stability and circulation (Lau et al., 2006). The atmospheric response, especially that of clouds, is hypothesized to be sensitive to the vertical profile of atmospheric heating (Koch and Del Genio, 2010). Reflecting aerosols, however, are hinted less effective in driving large-scale circulation changes (Allen et al, 2012).

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While previous studies (e.g. Xie et al., 2013; Ocko et al., 2014) focused on radiative forcing and climate impacts of aerosols on surface temperature and precipitation (Table S1), few looked at the tropospheric response. Using climate model simulations, we show that the atmospheric responses (temperature and circulation) to reflecting and absorbing aerosols are surprisingly similar in structure (aside from a sign difference). Both responses feature a deep vertical

temperature structure in the Northern Hemisphere (NH) mid-latitudes, with a meridional shift in the westerly jet. Such a strong atmospheric temperature response to absorbing aerosols has been commonly linked to direct solar absorption in the atmosphere (Lau et al., 2006). We demonstrate, however, that changes in the sea surface temperature (SST) gradient and mid-latitude eddies are instrumental in creating a common deep vertical temperature in response to both types of aerosols, despite the fundamental difference in their forcing structure.

2. Methods

2.1 The global climate model

CESM1 (Community Earth System Model 1) is a coupled ocean–atmosphere–land–sea-ice model. CESM1 climate projections for the 21st century have been documented extensively (Meehl et al., 2013). The anthropogenic forcings in CESM1 include long-lived greenhouse gases (GHGs), as well as tropospheric ozone, stratospheric ozone, sulfate aerosols, and black and primary organic carbon aerosols. The three-mode aerosol scheme (MAM3) provides internally mixed representations of aerosol number concentrations and masses (Liu et al., 2012). Aerosol indirect forcing is included for both liquid and ice phase clouds (Gettelman et al., 2010).

The aerosol emission inventory is from the standard Representative Concentration Pathway as described in Lamarque et al. (2010). However, the present-day emission level of BC is adjusted from the standard model emission inventory to account for the potential model underestimation of BC atmospheric heating. Our previous analysis (Xu et al., 2013) show that such a correction improves simulated radiative forcing compared to the direct observations. Without the observational constrains, simulated BC forcing (and associated temperature response) would be

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lower by about a factor of two. In addition to the atmospheric heating, deposition of BC particles onto snow surface with high albedo would reduce surface albedo and contribute to surface warming (Huang et al., 2011). The land model of CESM incorporates SNICAR (Snow and Ice Aerosol Radiation) module, which represents the effect of aerosol deposition (BC, organic carbon and dust) on surface albedo (Flanner et al., 2007).

Note that in this study we used BC, a strong absorber, to characterize absorbing aerosols that also include dust and organic aerosols. Similarly, we used SO4 to characterize reflecting aerosols although dust and organic aerosols are also partially reflecting. This approach provided a clearer contrast between these two types of aerosol forcing.

2.2 Model experiments

(a) Fully coupled model simulations with instantaneous forcing. We used a 394-year, pre-industrial simulation as the control case. Starting from the end of the 319th year, we ran the simulations for 75 years, with the last 60 years of output analyzed. This allows the first 15 years for model spin-up to establish a quasi-equilibration with changes in radiative forcing (Long et al. 2014). The forcing is imposed by increasing BC emissions (as a proxy for absorbing aerosols) and SO2 emissions (a precursor of SO4, as a proxy for reflecting aerosols) instantaneously from pre-industrial levels to the present-day level. This methodology is similar to the classical CO2 doubling experiment (Manabe and Wetherald, 1975). The long averaging time (60 years in the perturbed simulation versus 394 years for the pre-industrial control simulations) enabled us to dampen the influence of decadal natural variability and to obtain a clear effect due to aerosol perturbation. To increase the signal-to-noise ratio in the BC case (due to a smaller BC forcing), five ensembles of perturbed simulations were conducted.

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(b) The 20th century transient simulations using fully coupled model, with time-evolving sulfate forcing. The details of the simulations can be found in Meehl et al, (2013). The resolution of both atmosphere and ocean models is 1 degree by 1 degree for the coupled simulations (Experiments a and b) in this study.

(c) The atmospheric-only simulations with instantaneous forcing. The model setting and imposed forcing are identical to (a), but SST is fixed at a pre-industrial level, with only seasonal variability. The model was also run for 75 years.

(d) The SST perturbation experiment. The SST was perturbed according to the zonal mean of the CESM SO4 Experiment a (Fig S1). This corresponds to with a temperature profile that varies from 0 °C at 90°S to -0.5 °C at the equator, and then to -1.2 °C at 90°N. The SST perturbation did not include any longitudinally varying pattern, as our focus here was to understand the zonal averaged temperature response. The perturbed model was run for 25 years (with 10 years of daily output for eddy flux analysis). The resolution of atmospheric model is 2 degree by 2 degree for the uncoupled simulations (Experiments c and d) in this study.

3. Tropospheric response linked to SST gradient

BC atmospheric radiative forcing is concentrated at 30°N and extends well above the boundary layer to the free atmosphere (Fig. 1), a structure determined by atmospheric concentration, and indirectly by emission sources. Intuitively, solar absorption by BC results in atmospheric warming. Indeed, BC (Fig. 1 upper panels) induces a warming maximum in the NH mid-latitude troposphere (350 mb, 30 to 40°N) in the coupled ocean-atmosphere model, which dwarfs the upper tropical and Arctic warming. This simple thermodynamic mechanism seems consistent

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with the fact that the magnitude of BC warming is much larger in the boreal summer (JJA) than in the boreal winter (DJF) (Fig. 2 upper panels) due to solar insolation.

Interestingly, SO4 also induces a similar enhanced tropospheric cooling in the mid-latitudes (Fig. 1 and Fig. 2). For easy comparison, the response is reversed in sign to be positive. The deep atmospheric response is unexpected from the weak, direct atmospheric forcing of reflecting aerosols (Fig. 1 middle left). Also contradictory to the above thermodynamic argument for BC, the temperature response to SO4 is of a similar magnitude in DJF and JJA (Fig. 2). The CO2 response features a structure of amplified upper tropical troposphere warming (maximum at around 300 mb), which is a robust feature due to thermodynamical adjustment of the tropical atmosphere to maintain a moist adiabatic lapse rate there. The lower tropospheric atmospheric temperature over the Arctic also has a larger response, mostly due to stronger snow albedo feedback.

The climate response may be decomposed into fast and slow components, defined as the atmospheric response without and due to SST change, respectively (Ganguly et al., 2012). The BC temperature response results predominately from the fast component in the summer due to direct atmospheric heating (Fig. 3), but the slow response dominates in the winter. The SO4 fast response, due to the lack of atmospheric forcing, is strikingly small (except in summer polar regions where air temperature above sea ice is free to change), despite aerosol indirect forcing through fast adjustment of clouds are allowed. The SO4 slow response in winter features a narrow maximum around 30°N, and the summer mid-latitude response is weaker and extends into the upper tropics. Therefore, the slow component of the response due to SST change is

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entirely responsible for the SO4 deep atmospheric response and partially responsible for the BC response.

The dominant role of SST in causing the deep atmospheric response is further confirmed by a set of perturbed-SST experiments, in which the zonal mean SST change in the full SO4 simulation (Fig. S1) is applied to the atmospheric-only model, but with no radiative forcing. The model response to the perturbed SST (3rd row of Fig. 2) is remarkably similar to the SO4 slow response (Fig. 3), explaining a large fraction of the total response (2nd row of Fig. 2). The boundary layer air temperature (below 850 mb) is closely tied to the underlying SST because of turbulent mixing, while in the mid-latitudes, the free atmospheric temperature is not tied to the SST because the atmosphere is stably stratified. However, changes in the SST may affect the free troposphere through the changes of tropical circulations and mid-latitude eddy, which we explore next.

4. Understanding zonal mean circulation changes

Fig. 4 shows the circulation responses to aerosols in terms of meridional overturning stream function (positive values indicate clockwise circulation) and zonal averaged zonal wind (positive values indicate westerly winds). Note that the responses of SO4 and BC are similar in space but of opposite signs. SO4 cooling in the NH induces an anomalous Hadley cell that rises in the SH and sinks in the NH (also shown in Ocko et al., (2014)). The atmospheric model forced by SO4-induced SST change largely reproduces the Hadley cell response (Fig. 4, bottom left), highlighting the importance of the inter-hemispheric SST gradient. Consistent with the Hadley cell response, the NH jet stream shifts equatorward in response to SO4, and vice versa to BC. Following the thermal wind relationship (the maximum temperature gradient sets the maximum

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zonal wind), the equatorward shift of westerly winds must be accompanied by a deep cooling structure (Fig. 1 and Fig. 2).

The color scale for the SO4 response in Fig. 4 is not reversed as in previous temperature figures, in order to depict the real direction of circulation change. The magnitude of changes in response to BC is weaker due to a smaller forcing magnitude (Table S1). In addition, the SO4-induced Hadley cell change is interhemispheric across the equator while the BC-induced Hadley cell change appears more confined to the NH. The same for the jet stream shift. This is probably because of the geographic difference in BC and SO4 forcing (amid both are stronger in NH than SH), which may influence the Pacific and Atlantic branches of jets differently.

Eddy fluxes that transport heat and momentum in meridional directions are instrumental in maintaining the climatological mid-latitude jets. Here we use the Eliassen-Palm (EP) flux to diagnose how eddy flux adjustment in response to aerosols leads to changes of zonal winds. The EP flux vector, with its vertical component depicting the meridional heat flux and its meridional component depicting the equatorward meridional momentum flux, is calculated using 10-year daily data from the control and the perturbed SO4_SST simulations following Holton (2004).

The NH annual mean EP flux and its divergence (in contour) are shown in Fig. 5a. Over extratropical atmosphere, EP flux convergence (negative value) suggests that meridional heat eddy flux (the vertical component of EP flux) acts to slow the westerly wind aloft (Holton, 2004). However, the strong equatorward wave propagation in the mid-latitude troposphere (meridional component of EP flux) is acting to extract momentum from the tropics to the mid-latitude, therefore maintaining the westerly wind at 40-60°N.

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Under the SO4-induced SST perturbation, the EP flux change is found strongest in the NH mid-latitudes 30-40°N, equatorward side of its climatology (Fig. 5b). Poleward EP flux anomalies reduce the climatological equatorward wave propagation. In the middle troposphere (400-800 mb), EP flux convergence (blue) decelerates the vertically average westerly wind at 50-60°N, while EP flux divergence (red) tends to accelerate the westerly wind at 30-40°N. Therefore, westerly winds shift equatorward in response to SO4 (Fig. 4). Of the total eddy flux, stationary eddies contribute about 60% (Fig. 5c) with the rest coming from transient eddies. The EP flux change occurs predominately during the NH winter, because the background mid-latitude wave activity is stronger. This is shown by the larger vectors in Fig. 5d and stronger EP flux divergence (red) at 30-40°N.

The change in EP flux is consistent with that in the stationary wave refractive index as wave propagation is mainly from a high refractive index region to a low refractive index region (Held and Hou, 1980; Fig. S2). The quasi-geostrophic refractive index and its change under SST perturbation were calculated following Limpasuvan and Hartmann (2000). In the climatology (Fig. S2a), the high refractive index is located in the mid and high latitudes, and the tropics are mainly occupied by a smaller refractive index, facilitating the equatorward propagation of mid-latitude wave activities (Fig. 5a, also seen in Sun et al., 2013). The refractive index negative anomaly due to perturbed SO4 SST is mainly found in the NH mid-latitude regions (Fig. S2b), which causes the reduction of wave propagation to the equator (Fig. 5b).

The above diagnosis explains the SO4 induced deep tropospheric cooling and associated equatorward shift of westerly jet in the NH mid-latitudes. Firstly, the intensified NH Hadley cell accelerates the upper tropospheric westerly jets in the subtropics. Secondly, the EP flux

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divergence accelerates the westerly jet on the equatorward flank of the mean Hadley cell, while the jet is decelerated on the poleward flank due to EP flux convergence. Both the Hadley and eddy adjustments are anchored by the SST change with strong meridional gradients. Aqua-planet model experiments exploring the response to an idealized mid-latitude heating (Ceppi et al., 2013) supported our arguments here about the coupled adjustments of the Hadley circulation and mid-latitude jets to realistic aerosol forcing.

5. Conclusions

Our results show that despite the fundamental difference in forcing structure, BC and SO4 share common atmospheric response patterns. The common response is mediated by the ocean through sea-surface temperature gradient, and insensitive to microphysical representations of aerosols. This highlights the importance of ocean-atmosphere interactions in shaping large-scale patterns of climate response (Xie et al. 2010), a process overlooked so far in aerosol-climate connection.

The deep mid-latitude warming in response to BC contributes to the retreat of mountain glaciers in the NH near anthropogenic BC emissions, including the Alps (Painter et al, 2013) and the Himalayas. Although the cooling effect on the free troposphere is rarely discussed, SO4 aerosols may have mitigated glacier retreats elsewhere in the past. Into the future, declining SO4 aerosols may lead to an elevated atmospheric warming and pose a threat to mountain snow packs. This implies that more stringent controls on BC and GHGs are needed to mitigate the snow pack retreat.

The tropospheric temperature and circulation response to SO4 is also found in the 20th century transient simulation (Fig. S3) and the 21st century multi-model projections (Rotstayn et al.,

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2014). This suggests that the deep temperature structure in the mid-latitudes is a robust feature of aerosol-induced climate change, probably insensitive to model sub-grid physics. The dynamic response involving the inter-hemispheric Hadley circulation is weak in the case of CO2 and presumably other hemispherically symmetrical forcing (such as solar and volcanic activities).

The importance of SST pattern has been noted previously (Ramanathan et al., 2005; Xu and Ramanathan, 2010; Friedman et al., 2013; Xie et al., 2013), and our study reveals a fundamental difference in the mid-latitude atmospheric responses to CO2 and aerosol forcing. This difference can be exploited to improve the detection and attribution of climate change (Lu et al., 2008; Santer et al., 2013). Because aerosol forcing involves stronger mid-latitude storm track adjustments, our result also has implications for the attribution and projection of extreme events (e.g. blockings).

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The authors wish to thank Isaac Held, Paulo Ceppi, and Lantao Sun for discussions, and Joe Barsugli for sharing codes for EP flux. Y.X. is supported by the Regional and Global Climate Modeling Program (RGCM) of the U.S. Department of Energy's Office of Science (BER, DE-FC02-97ER62402) and the National Center for Atmospheric Research (NCAR) Advanced Study Programme (ASP) postdoctoral fellowship; and S.P.X. by the National Science Foundation (NSF). NCAR is funded by the NSF.

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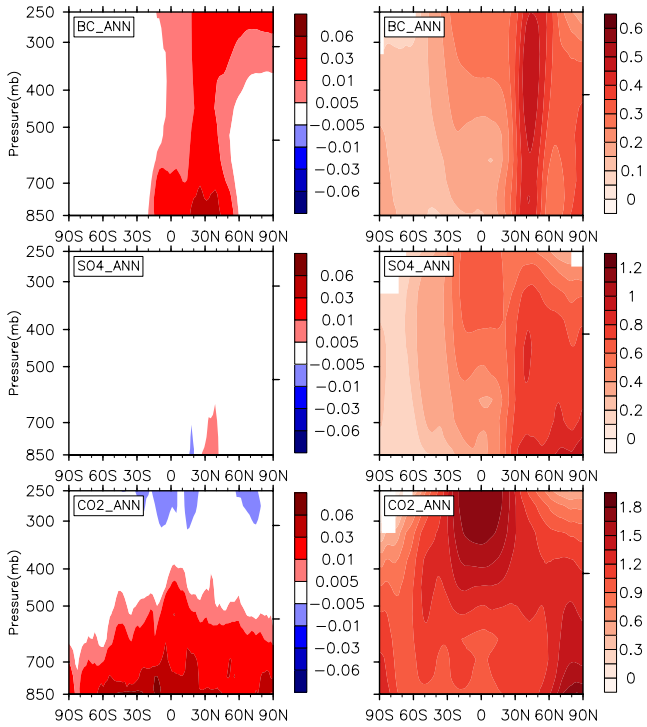

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641 Fig. 1: (Left) Heating rate (°C/day) due to increase of BC, SO4 and CO2 atmospheric
642 concentration. The heating rate is diagnosed by contrasting two sets of five-year atmospheric-
643 only simulations with pre-industrial and present-day emissions/concentrations, respectively.
644 (Right) Annually averaged atmospheric temperature in response due to the forcing of BC, SO4
645 and CO2. The color scale for SO4 is reversed. The magnitude of color scale is chosen
646 considering the difference in top-of-atmosphere forcing (Table S1).

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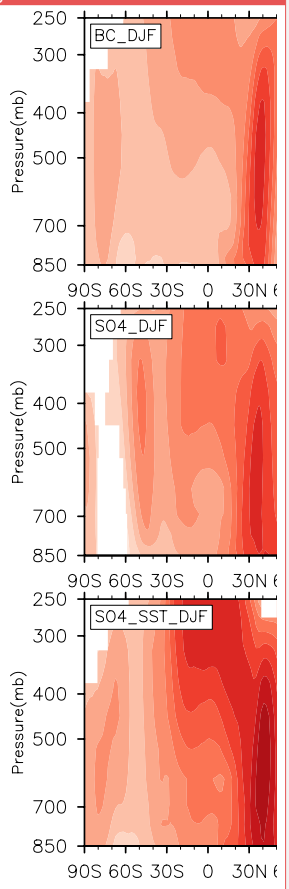

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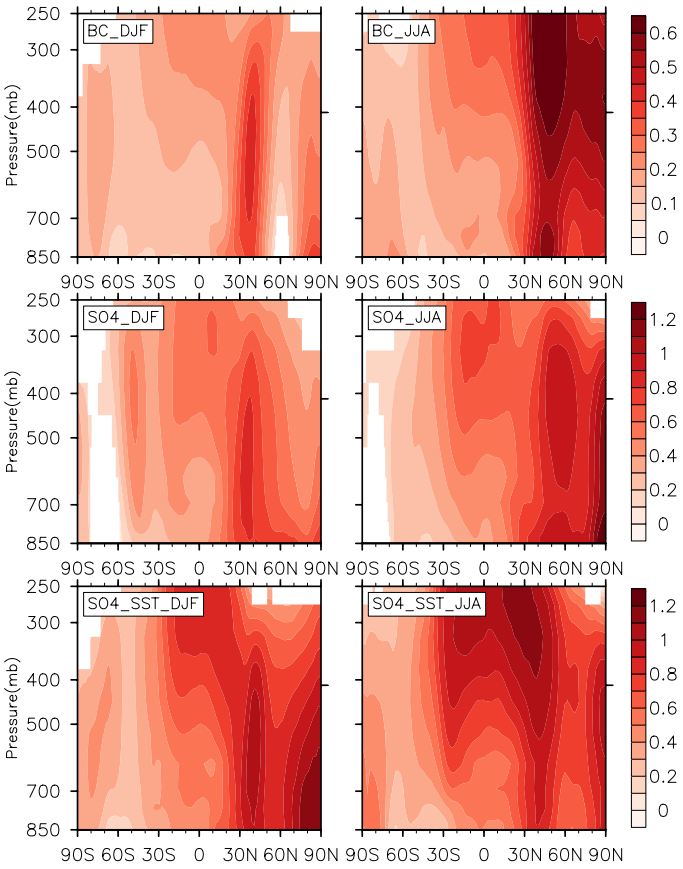

Fig. 2: Temperature response (°C) as a function of latitude and pressure to BC (1st row), SO4 (2nd row), and SO4-induced SST perturbation (SO4_SST) (3rd row). The left and right columns are the DJF and JJA average, respectively. Note that the color scales for SO4 and SO4_SST are reversed.

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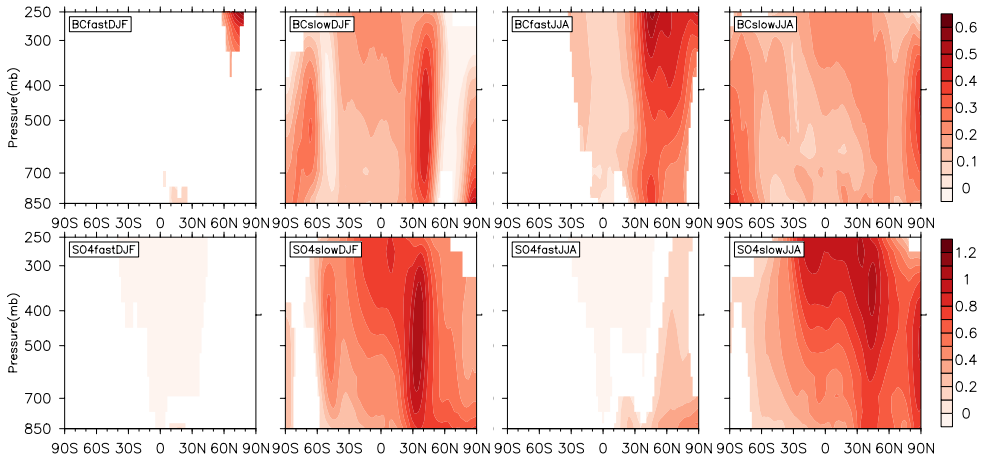

664

665 Fig. 3: Similar to Fig. 2, but for fast (1st and 3rd column) and slow components (2nd and 4th

666 column) of temperature response (in °C). The fast component is calculated by running the

667 atmospheric-only (fixed SST) simulation with perturbed atmospheric compositions, while the

668 slow component is the difference between the total (Fig. 2) and fast component. The color scale

669 for SO4 is reversed.

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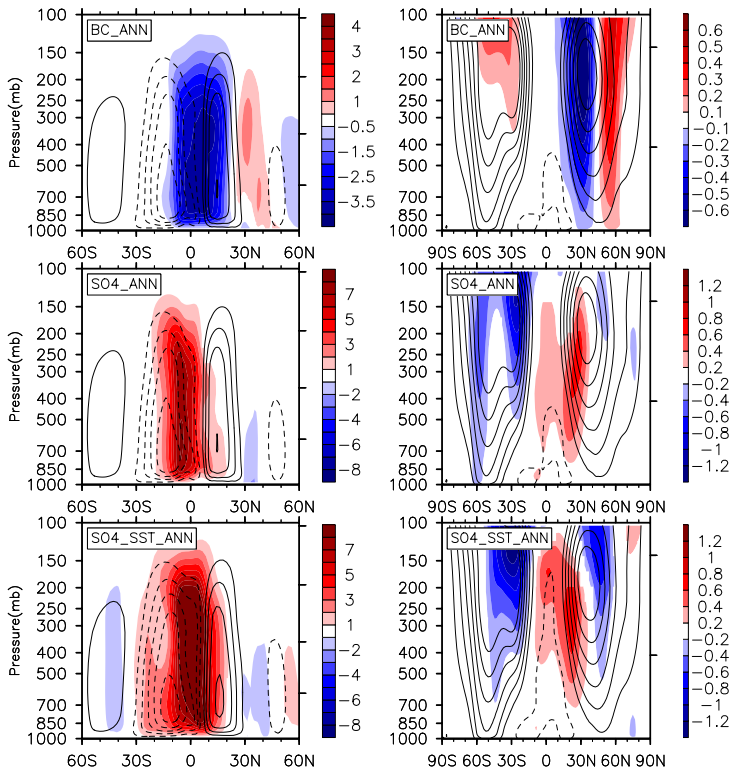

679

680 Fig. 4: (left) Zonal mean meridional stream function change (10^9 kg/s), in response to BC (1st
681 row), SO4 (2nd row), and SO4-induced SST perturbation (SO4_SST) (3rd row). Climatological
682 stream function is shown in contour lines with an interval of 40. The negative values (blue
683 shading and dashed lines) of the stream function indicate that the meridional flow is counter-
684 clockwise. (right) Zonal mean zonal wind (U) change under various cases. The climatological jet
685 stream is around 30ºN to 60ºN at 250 mb (line contours). Under SO4 forcing, the NH jet stream
686 shifts significantly equatorward.

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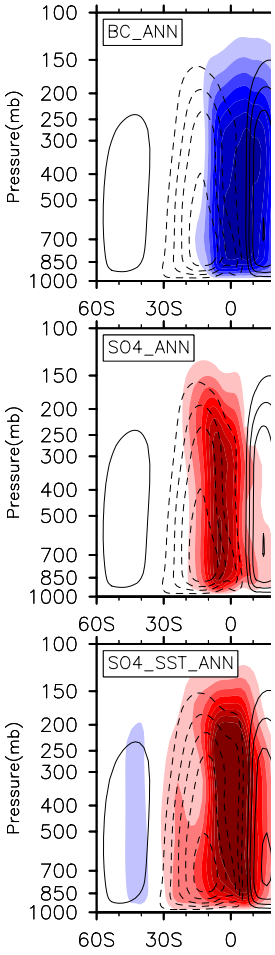

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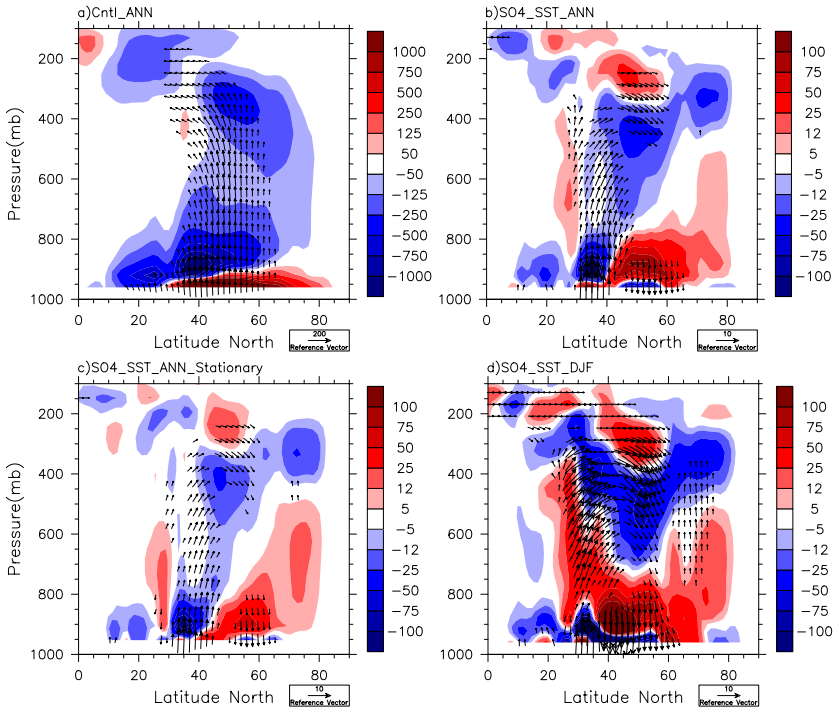

Fig. 5: The Eliassen-Palm (EP) flux (vector) and its divergence (contour). (a) The climatology. (b) The change due to SO4-induced SST perturbation (SO4_SST). The convergence (blue) and divergence (red) of the EP flux correspond to a deceleration and acceleration of the westerly mean flow, respectively. (c) Contributions of the stationary eddy to the change shown in (b). This was calculated using 10-day average, instead of daily average. Transient eddies are the difference between the total and stationary contribution (not shown). (d) NH winter (DJF) average, not the annual average shown (b). Note the color scale and reference vectors are different across the panels.

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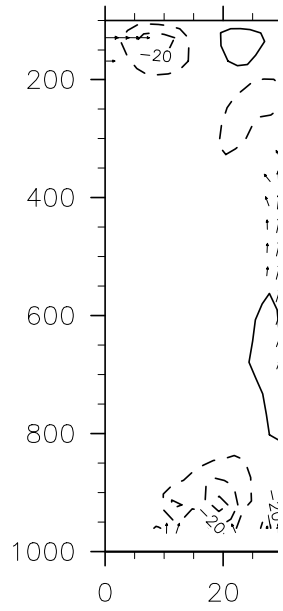

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Supplement materials for

Ocean mediation of tropospheric response to reflecting and absorbing aerosols

Yangyang Xu[1]* and Shang-Ping Xie[2]

[1] National Center for Atmospheric Research, Boulder, CO 80303.

[2] Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093.

*Correspondence to: yangyang@ucar.edu

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Table S1. (a) TOA forcing (W/m^2, shortwave and longwave) due to BC (direct radiative forcing from pre-industrial to present-day; not including snow albedo effect), SO4 (direct and indirect forcing from pre-industrial to present-day, so called "adjusted forcing") and CO2 (from pre-industrial to present-day at 400 ppm). The radiative forcing is diagnosed by contrasting two sets of five-year atmospheric-only simulations with pre-industrial and present-day emissions/concentrations, respectively. (b) Surface temperature change (℃) in response to different forcings in (a). These are calculated from the 60-year average of coupled model simulation. (c) Cumulative precipitation (cm) change in response to different forcings in (a). The relative changes in percentage are shown in parenthesis next to the absolute changes.

	BC	SO4	CO2
(a) TOA net forcing (W/m^2)	0.5	-0.9	1.7
(b) Surface temperature change (℃)	0.21	-0.49	1.15
(c) Cumulative precipitation (cm)	-0.01 (0%)	-2.09 (-2%)	1.73 (2%)

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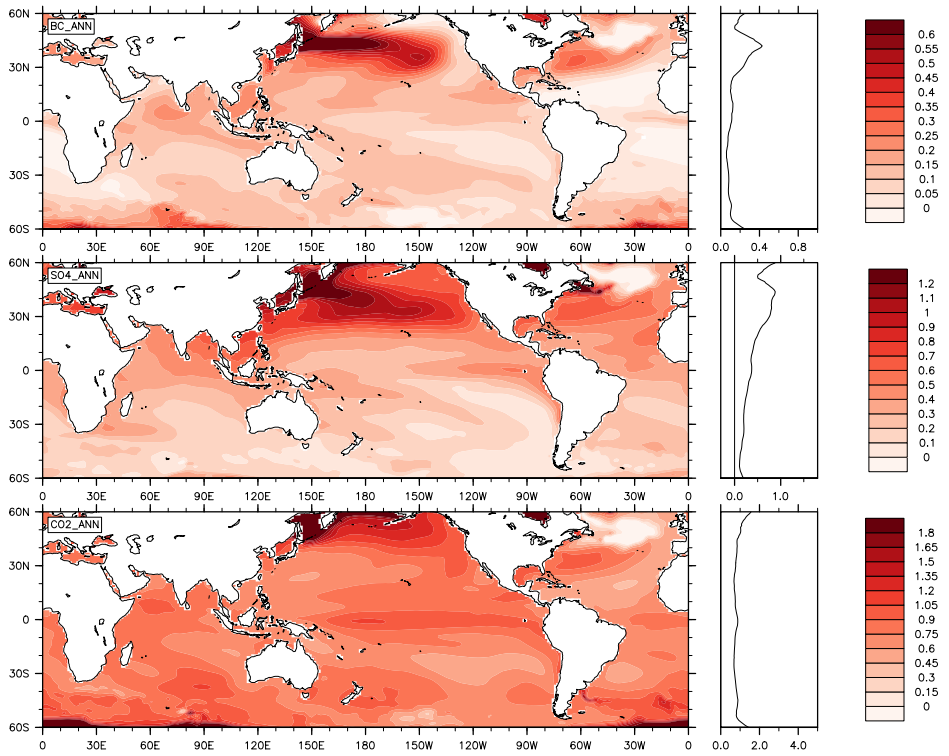

741

742 Fig. S1: Sea Surface temperature change (℃) change in response to BC, SO4 and CO2 forcings.

743 These are calculated from the 60-year average of coupled model simulation. Color scale for SO4

744 is reversed.

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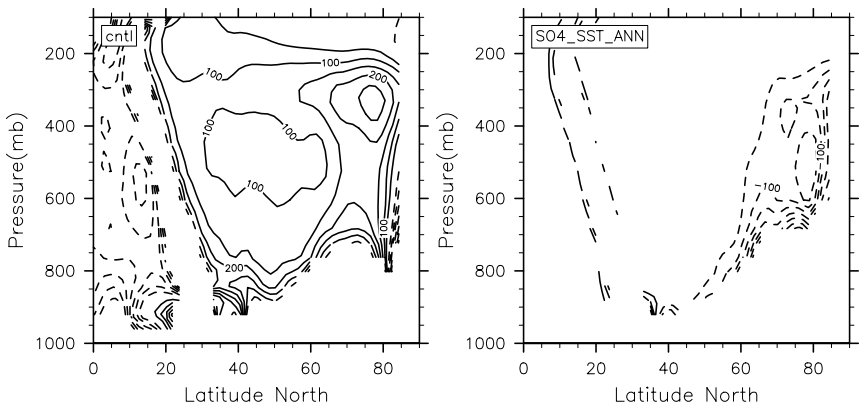

Fig. S2: Refractive index in the climatology (left panel) and its change due to SO4-induced SST perturbation (right panel). The contour plot is limited to 0–400, following Figure 8 of Limpasuvan and Hartmann (2000), to highlight the contours in the mid-latitude regions where the wave activities are strongest.

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Moved up [7]: mean zonal wind (U) change under various cases. The climatological jet stream is around 30°N to 60°N at 250 mb (line contours). Under SO4 forcing, the NH jet stream shifts significantly equatorward.

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Deleted: c) shows the boreal winter (DJF) average, not the annual average that is shown in Fig 4. Note the reference vector changes across the panels (200, 10, 20).
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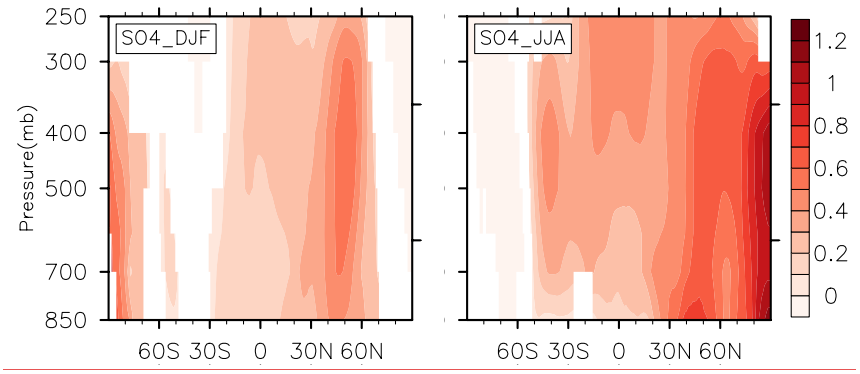

Fig. S3: Similar to the 2nd row of Figure 1, but showing the trend of temperature changes (°C/decade) during 1940-1970 in the 20th century transient climate simulation using the same model (CESM1) with time-evolving aerosol-only forcing. During this period, SO_2 emissions rapidly increased. Color scale is reversed to be consistent with Fig. 1. GHG forcing is fixed in this simulation. An ensemble of three simulations was conducted.

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