

Responses to Anonymous Referee #1

The authors investigated how the East Asian dust activity impacts the North Pacific storm track during springtime. The authors first investigate a physical connection between the dust activity and the poleward shift of the storm track using reanalysis and observational datasets. They find that shortwave absorption due to dust aerosols results in mid-tropospheric heating, affects the baroclinicity in the storm track region, and shifts the storm tracks. This physical explanation is supported using a WRF simulation, with and without dust, for the year 2018.

The manuscript is well written, and I enjoyed reading it. The physical mechanisms are clearly explained. However, I do have some remaining concerns for the paper. As the authors mention, interannual variability of dust is tightly connected to circulation, such as jets and storm tracks (dust must have been transported to the Pacific by winds). There could be a mode of circulation across East Asia and the Pacific that favors both dust import into the Pacific and a poleward shift of the storm track. Hence, from the observations, the causal direction is unclear. The authors do show model experiments which have clear causality; however, the model experiment and the observational analysis are not well connected. Therefore, I suggest a major revision is needed to clarify this causality. Below are my detailed comments and suggestions to better connect the two sections.

Responses: We greatly appreciate these comments and suggestions. The manuscript has been improved by considering these comments and suggestions. Our detailed responses are given point by point below in blue. The revised text is highlighted in red.

Major Comments:

1. Figures 3 to 6 show results from regression analysis, where atmospheric variables are regressed onto EADI. I expected the units to be in 'per EADI'. How is the regression being calculated?

Responses: We thank the reviewer for raising this point, which indeed reflects an ambiguity in our original description. The regressions in Figures 3–6 are performed against the standardized interannual EADI, so the units of the plotted coefficients are those of the response variable itself, and they should be read as “per one standard

deviation of EADI_IA” rather than “per mg m⁻²”.

Calculation of the regression coefficients. Denoting the resulting interannual dust index (EADI_IA) by D_t ($t = 1980, \dots, 2022, N = 43$) and the interannual anomaly of any variable at a given grid point by Y_t , the dust index is first normalized by its own standard deviation,

$$\hat{D}_t = \frac{D_t}{\sigma_D}, \quad \sigma_D = \sqrt{\left(\frac{1}{N}\right) \sum_t D_t^2} = 19.1 \text{ mg m}^{-2}$$

so that $\hat{D}$ is dimensionless with unit variance. The quantity shown in Figures 3–6 is the least-squares slope of Y and $\hat{D}$,

$$\beta = \frac{\sum_t Y_t \hat{D}_t}{\sum_t \hat{D}_t^2}.$$

Because $\hat{D}$ is dimensionless, β carries the physical unit of Y (e.g., dagpm², K m s⁻¹, K, W m⁻², 10⁻⁶ K m⁻¹, or K day⁻¹) and represents the anomaly of Y associated with a one-standard-deviation increase of EADI_IA. For example, the 2.8 dagpm² centre in Figure 3a means that $\mathbf{Z}'\mathbf{Z}'_{300}$ over that region is increased by about 2.8 dagpm² when EADI_IA is one standard deviation (19.1 mg m⁻²) above normal.

To state more clearly about regression analysis, we have revised the relevant statements in **Section 2.2 (Lines 121–130)** in the revised manuscript to the following: “*To isolate interannual variability, Fourier analysis is applied at each grid point to these spring-mean time series. The first four harmonics, which represent fluctuations with periods longer than about 10 years, are defined as the interdecadal component. The residual after removing the time mean and these harmonics is defined as the interannual component (Awan and Bae, 2016; Zhu et al., 2021). All quantities analysed below refer to interannual anomalies unless otherwise stated. Regressions throughout this study are performed against a dust index that has been normalized by its own standard deviation. Specifically, for a dust index $\mathbf{D}$ with interannual standard deviation σ_D and standardized form $\mathbf{D} = \frac{\mathbf{D}}{\sigma_D}$, the regression coefficient of an interannual anomaly field $\mathbf{Y}$ is obtained as the least-squares slope*

$$\beta = \frac{\sum_t Y_t \hat{D}_t}{\sum_t \hat{D}_t^2}.$$

Because $\hat{D}$ is dimensionless, β retains the physical unit of Y and represents the response of Y to a one-standard-deviation increase of the dust index.”

2. Figures 8 and 9 show results from the WRF simulation. As the EADI in 2018 is around 300, the responses here are for an EADI difference of 300. On interannual time scales, the EADI variability is an order of 10. If I multiply 1/30 to Figure 8 and compare it with Figure 3, the results from Figure 8 are very small. This suggested to me that the impact of dust-induced heating on the poleward shift, while the mechanism is there, is very small, and there could be another factor that affects both dust transport and storm tracks. However, because I'm not clear how the regression was calculated, this comparison could be inaccurate. Could the authors clarify and show that “responses per EADI” are comparable in the regression analysis and the modeled responses? In short, it would be helpful if the results are presented per EADI.

Responses: We thank the reviewer for this comment, which goes to the heart of how the statistical and the modelling results should be compared. We agree that the two parts were not well connected in the original manuscript.

We first clarify the scaling. In our proposed mechanism, the storm track response is forced by shortwave absorption within the dust plume over the North Pacific, not by the dust burden over the source region. The EADI is a proxy for source-region dust activity, and the ratio between the source-region and the trans-Pacific burden is not fixed, because it depends on lifting height, transport efficiency, and wet removal. The appropriate comparison is therefore between the North Pacific dust burdens associated with the two perturbations. Figure R1 shows these burdens over a common North Pacific domain (purple box). The regression gives 4.0 mg m^{-2} per standard deviation of EADI_IA, and the WRF-Chem CTRL experiment for 2018 gives 33.3 mg m^{-2} . The relevant factor between Figure 7 (former Figure 8) and Figure 3 is thus about 1/8 rather than 1/30. We also note that WRF-Chem underestimates the source-region burden much more strongly (83.7 versus 334.7 mg m^{-2} in MERRA-2) than the trans-Pacific burden (33.3 versus 72.6 mg m^{-2}). The model deficiency lies mainly over the source region rather than in the oceanic plume that actually forces the response.

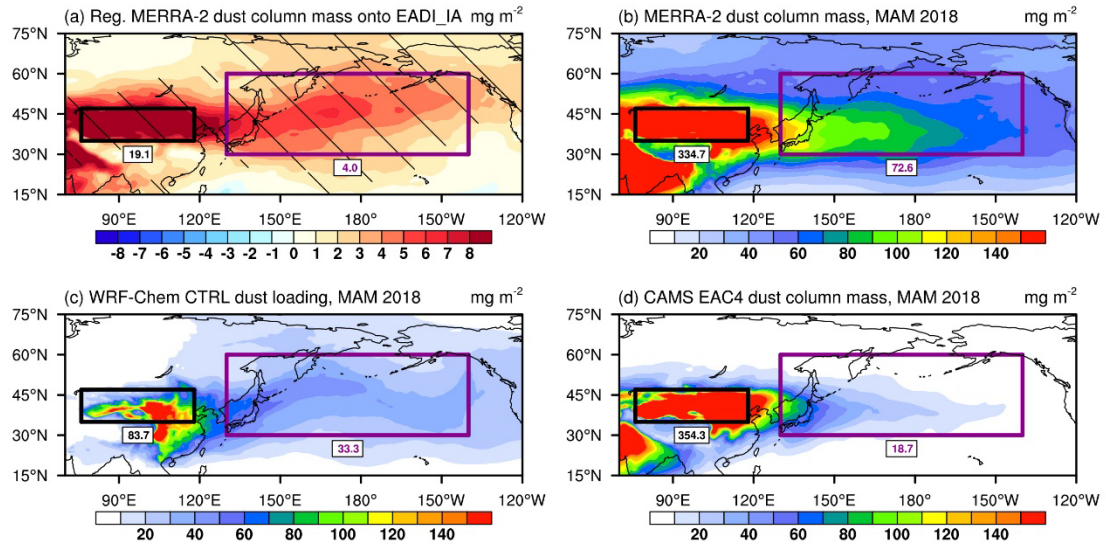


Figure R1. Spring (MAM) dust column mass density (mg m^{-2}). (a) Regression of MERRA-2 dust column mass onto the standardized EADI_IA for 1980–2022, which gives the response per one standard deviation of EADI_IA. Hatching indicates regions significant at the 95 % confidence level. (b) MERRA-2 dust column mass in MAM 2018. (c) Dust loading in the WRF-Chem CTRL experiment in MAM 2018. (d) CAMS EAC4 dust column mass in MAM 2018. In each panel, the black box marks the dust source region used to define the EADI (35° – 47° N, 76° – 118° E) and the purple box marks the North Pacific domain (30° – 60° N, 130° E– 140° W). The numbers give the area-averaged values within each box.

We define the index over the source region deliberately. It characterizes dust activity at the emission end of the chain, and it is the region where land-based observations best constrain the different products. Observations over the open ocean are too sparse to judge which product is more reliable. For example, the MAM 2018 North Pacific burden differs by nearly a factor of four between MERRA-2 (72.6 mg m^{-2}) and CAMS EAC4 (18.7 mg m^{-2}). **We therefore use the North Pacific burden only as a reference for scaling and emphasize the correspondence of spatial patterns rather than exact amplitudes.**

Even with the corrected scaling, the WRF-Chem response remains weaker than the regression-based amplitude, as noted in the original Discussion. As an indirect check on how much the simulated amplitude depends on the model, we additionally performed a pair of CESM2.1 experiments with and without dust emission (F2000climo configuration, one member, integrated from January to May with the first two months discarded as spin-up). These experiments are not intended to quantify the dust effect. The CESM2 experiment produces a North Pacific dust burden of 34.0 mg m^{-2} , almost identical to WRF-Chem, and the same dipole in both storm track metrics, but the

response is about four to five times larger (Figure S9). Two models forced by essentially the same trans-Pacific dust load thus differ by nearly a factor of five in their storm track response. This spread is consistent with known uncertainties in dust optical properties. **Referee #2** drew our attention to Yuan et al. (2026), who showed that climate models using conventional refractive indices, such as OPAC, overestimate the absorption of Asian dust, whereas the refractive index in our WRF-Chem configuration (Zhao et al., 2012) is less absorptive. The two models may therefore bracket the true dust heating from opposite sides. After rescaling, the amplitudes follow the order of regression, CESM2 and WRF-Chem. The regression lies above both models as expected because it may also contain circulation signals that covary with dust (see our response to Comment 3). We further note that the response need not be linear in dust load, so a simple rescaling between a single high-dust spring and a one-standard-deviation anomaly is itself an approximation.

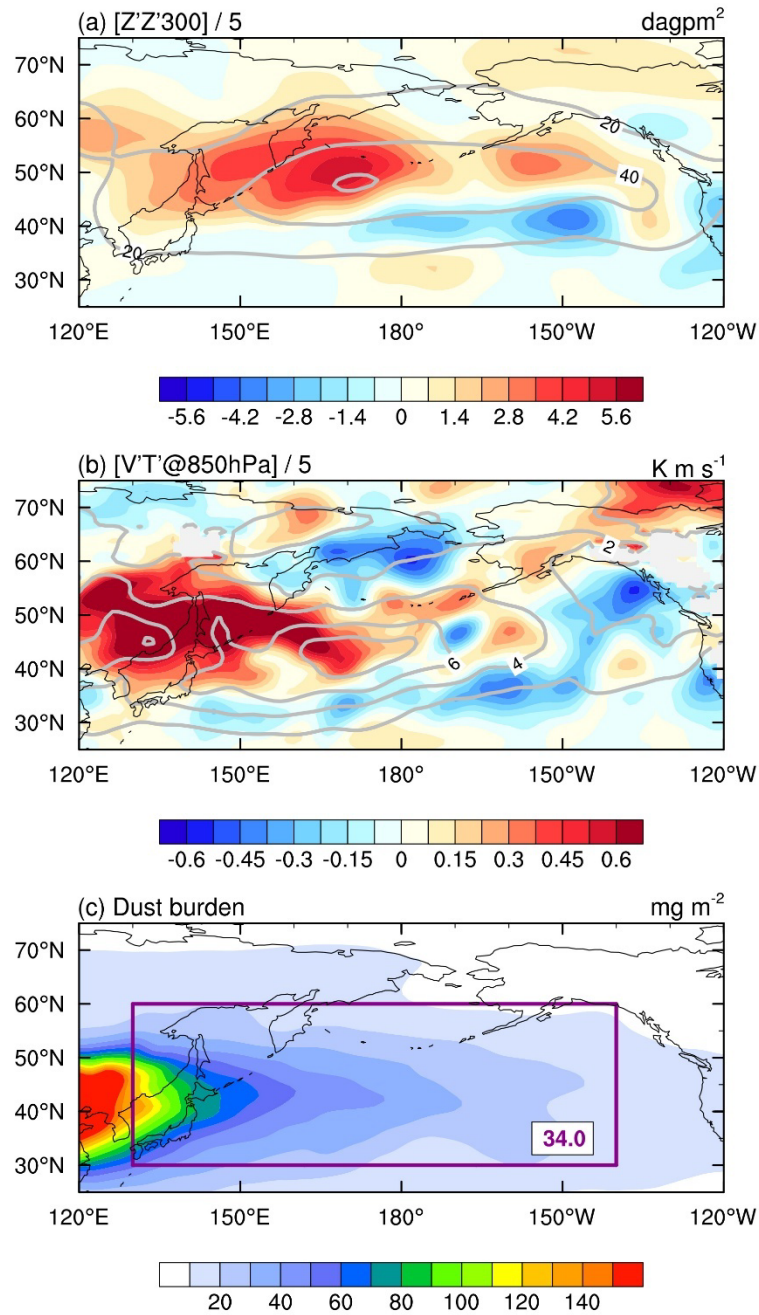


Figure S9. Spring (MAM) differences between the CESM2.1 experiments with and without dust emission (F2000climo configuration). (a) $Z'Z'_{300}$ (dagpm²) and (b) $V'T'_{850}$ (K m s⁻¹), both divided by 5 so that they can be shown on the same colour scales as the regression results (Fig. 3) and the WRF-Chem results (Figs. 7a–b). (c) Dust burden in the experiment with dust emission (mg m⁻²). Grey contours in (a) and (b) show the unscaled values from the experiment with dust emission. The purple box in (c) marks the North Pacific domain (30°–60° N, 130° E–140° W), and the number gives the area-averaged dust burden within it. The model is integrated from January to May, and the first two months are discarded as spin-up.

For these reasons, we are cautious about reading the offset between Figures 7 and 3 as evidence that the dust effect is small. The amplitude of the response differs by a factor of several between models and between datasets. This uncertainty is too large to

interpret the offset between WRF-Chem and the regression as a measure of the dust effect. Following this comment and a related comment by **Referee #2**, we have reframed the modeling section as a process-level verification and removed the quantitative claims based on the model. **Section 3.3** is now titled “*Process-level verification of the proposed mechanism with WRF-Chem sensitivity experiments*”, the statements on causality in Section 3.3, the Abstract, and the Conclusions have been softened, and the model evaluation and heating rate profiles have been moved to the Supplement. We describe the CESM2 experiments in Section 2.3 and rewrite the two paragraphs on model uncertainty in Section 4 as follows.

Revised text (Abstract, Lines 12–23): “*The North Pacific storm track plays a key role in shaping climate across the Arctic and western North America by modulating precipitation and temperature, yet its interannual sensitivity to springtime East Asian dust remains poorly understood. Based on the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis data from 1980 to 2022, we find that anomalously high springtime East Asian dust loading is robustly associated with a systematic poleward shift of the North Pacific storm track on interannual timescales. It is revealed that shortwave absorption by the trans-Pacific dust plume coincides with warming in the 850–400 hPa layer and an anomalous anticyclonic circulation over the North Pacific. This thermal perturbation restructures the meridional temperature gradient and shifts the zone of maximum Eady growth rate poleward, thereby relocating the preferred region for baroclinic eddy development to higher latitudes. The Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) sensitivity experiments reproduce the spatial pattern of the storm track response, supporting the proposed radiative–dynamical pathway. These findings indicate that natural dust aerosols can modulate large-scale North Pacific atmospheric dynamics on interannual timescales and suggest that springtime dust variability should be considered in regional climate assessments.*”

Revised text (Section 2.3, Lines 165–176): “*We design two sets of simulations to test whether dust radiative heating alone can reproduce the physical pathway inferred from the reanalysis. The control experiment (CTRL) incorporates full dust emissions. In contrast, the sensitivity experiment (NoDust) completely disables dust emissions. We attribute the atmospheric differences between the CTRL and NoDust simulations directly to the effects of dust aerosols. We select the year 2018 as our study period*

because the East Asian dust loading during this year significantly exceeded the climatological mean (Figure 2b). To enhance the statistical robustness of our results, we conduct seven ensemble members for each experiment. These ensemble members are initialized one day apart from 19 to 25 February 2018. All simulations conclude on 31 May 2018. We treat February as the model spin-up period and exclude it from the final analysis. Consequently, our analysis focuses strictly on the boreal spring season from March to May 2018. Because the experiments cover a single spring, they cannot reproduce the interannual relationship diagnosed from the reanalysis or determine whether dust is its dominant cause. They are instead designed as a process-level verification of the proposed mechanism. Since the two experiments share identical meteorological initial and boundary conditions, their difference isolates the dust effect from concurrent circulation variability.”

Added paragraph (Section 2.3, Lines 178–182): *“As an additional and indirect check, we also perform a pair of Community Earth System Model 2 (CESM2.1) experiments in the F2000climo configuration, with and without dust emission (one member each). Both runs are integrated from January to May with boundary conditions representative of the 1995–2005 mean, and the first two months are discarded as spin-up. These experiments are not designed to quantify the dust effect. They serve only to illustrate how much the magnitude of the simulated response differs between models.”*

Revised sentence (Section 4, Lines 352–353): *“This study shows that interannual variations in springtime East Asian dust loading are systematically associated with a poleward shift of the North Pacific storm track.”*

Revised paragraph (Section 4, Lines 385–396): *“The WRF-Chem experiments are intended to verify the proposed mechanism rather than to quantify the sensitivity of the storm track to dust. The simulated responses in both temperature and storm track metrics are weaker than those inferred from the observational regression analysis, even after the difference in North Pacific dust burden between the 2018 experiment and a one-standard-deviation EADI anomaly is considered. Several factors may contribute to this discrepancy. The regional model domain excludes dust transported from the Middle East and North Africa (Creamean et al., 2013; Hu et al., 2019; Zhou et al., 2024; Huang et al., 2025), which lowers the simulated dust burden over the North Pacific. East Asian dust also mixes with anthropogenic aerosols during long-range transport, and such*

internally mixed dust aerosols can be more than 50% more absorbing than pure dust (Tian et al., 2018). This enhancement is not represented because anthropogenic emissions were excluded by design. In addition, the four-band shortwave radiation scheme used in our WRF-Chem configuration tends to underestimate dust shortwave heating rates relative to schemes with finer spectral resolution (Feng et al., 2025). Finally, dust particles can act as ice nucleating particles and alter the energy budget through aerosol-cloud interactions (Uno et al., 2009; Zeng et al., 2023; Chen et al., 2024), which are not included in the current configuration.”

Added paragraph (Section 4, Lines 398–410): *“The magnitude of the simulated response also differs considerably between models. A pair of CESM2 experiments with and without dust emission reproduces the same meridional dipole in both storm track metrics (Figure S9), but the response is about four to five times larger than in WRF-Chem for a similar North Pacific dust burden. Part of this spread likely arises from dust optical properties. Climate models using conventional refractive indices such as Optical Properties of Aerosols and Clouds (OPAC) tend to overestimate the absorption of Asian dust (Yuan et al., 2026), whereas the refractive index adopted in our WRF-Chem configuration (Zhao et al., 2012) is less absorptive (Jin et al., 2016). The two models may therefore bracket the true dust heating from opposite sides. After rescaling to a common dust burden, the amplitudes follow the order regression, CESM2 and WRF-Chem. The regression estimate should be regarded as an upper bound, because it may include circulation anomalies that covary with dust, and the response need not scale linearly between a single high-dust spring and a one-standard-deviation anomaly. Taken together, the reanalysis and the two models consistently support the radiative pathway, but the quantitative sensitivity of the storm track position to interannual dust variability remains uncertain by a factor of several. Constraining it will require multi-model, multi-year dust sensitivity experiments with observation-constrained dust optical properties, realistic aerosol mixing, and aerosol-cloud interactions.”*

3. The North Pacific storm track location shifts on interannual timescales due to processes other than dust activity. What is the relative magnitude of the dust-related storm track variability, inferred from the WRF simulations, compared to the full variability? I can imagine doing this by rescaling the responses in Figure 8 per EADI, multiplying it by the interannual variability of EADI, and then comparing with the full interannual variability. The authors mention that the regressed results are about 15% of

climatology, but as I mentioned before, it is difficult to get a grasp of this number without clearly knowing how regression has been done.

Responses: We agree that the North Pacific storm track shifts on interannual timescales for many reasons other than dust, and that the dust-related fraction should be quantified. We attempted the calculation suggested by the reviewer. However, as shown in our response to Comment 2, converting a model response to a response per EADI carries a model-to-model uncertainty of about a factor of five. Propagating this through the rescaling gives a dust-related fraction anywhere between a few per cent and several tens of per cent, which we do not find informative. We therefore approached the question from the observational side, which also responds to a suggestion by **Referee #2**.

We defined two storm track position indices from the reanalysis as the difference between the area-averaged interannual anomalies over a northern box and a southern box on the poleward and equatorward flanks of the climatological storm track (solid and dashed boxes in new Figure S3a and S3b), separately for $Z'Z'_{300}$ and $V'T'_{850}$. Positive values denote a poleward-displaced storm track. Their correlations with EADI_{IA} are 0.47 and 0.39, and with dust PC1 0.43 and 0.36, all significant at the 95% level (Figure S3c). The relationship is thus insensitive to how the dust index is defined. The EADI explains about 22% and 15% of the interannual variance in the $Z'Z'_{300}$ and $V'T'_{850}$ position indices. These values are upper bounds, because they include any component arising from circulation anomalies that affect dust and the storm track at the same time. Put differently, at least about 78% of the interannual variability in storm track position is unrelated to East Asian dust. We now state this at the end of Section 3.1, and we describe dust as one contributor among several rather than the dominant control. **This is also why we changed the title to "*Springtime East Asian dust heating contributes to interannual poleward shift of the North Pacific storm track*".**

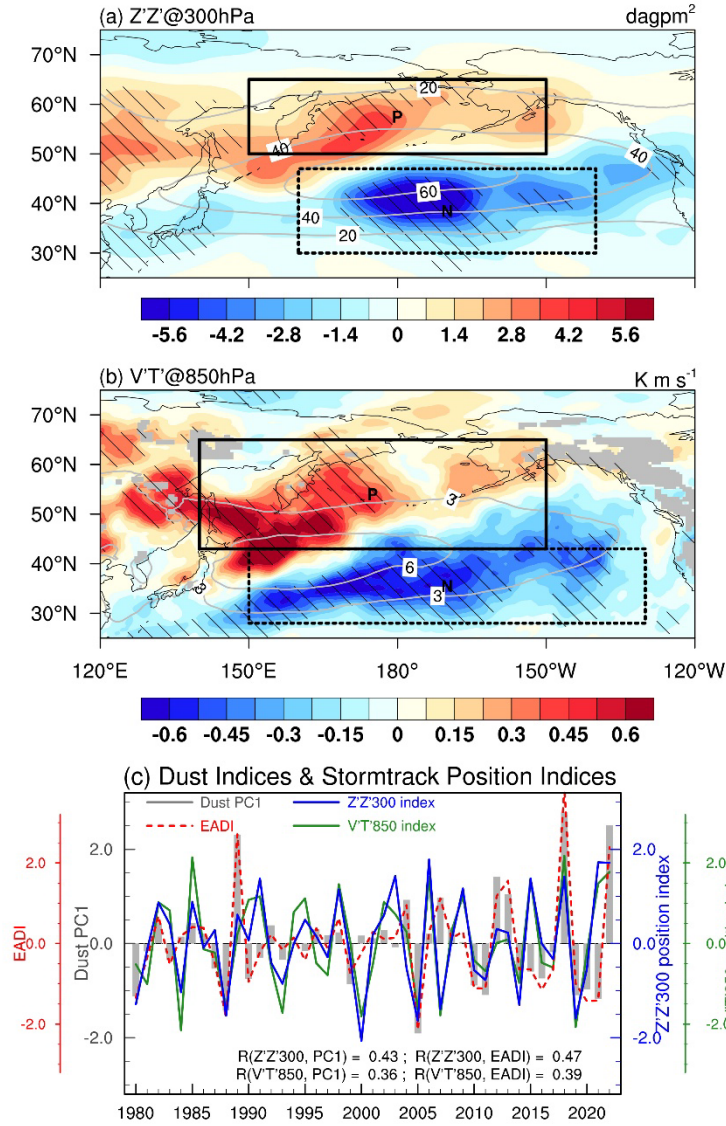


Figure S3. (a, b) Same as Figure 3, with the black solid (dashed) boxes denoting the northern (southern) regions used to define the storm track position indices. For (a) $Z'Z'_{300}$, the northern and southern boxes are 50°–65°N, 150°E–150°W and 30°–47°N, 160°E–140°W. For (b) $V'T'_{850}$, they are 43°–65°N, 140°E–150°W and 28°–43°N, 150°E–130°W. (c) Time series of the standardized interannual components of dust PC1 (grey bars), the EADI (red dashed line), and the $Z'Z'_{300}$ (blue line) and $V'T'_{850}$ (green line) position indices during 1980–2022. Each position index is defined as the area-averaged value over the northern box minus that over the southern box. The correlation coefficients between the storm track position indices and the dust indices are shown in (c).

We also take this opportunity to remove a possible source of confusion. The "about 15% of the climatological mean" in Section 3.1 refers to the ratio of the regressed $Z'Z'_{300}$ anomaly to its local climatological mean, which is a different quantity from the explained variance discussed here. The revised text keeps the two apart.

Regarding causality, we accept the reviewer’s central point. The regressions are concurrent and cannot by themselves exclude a mode of East Asia–Pacific circulation variability that favors both dust export and a poleward-shifted storm track. We have taken several steps to narrow this possibility. We already removed ENSO in the original analysis. We have now repeated the regression after also removing the concurrent spring NAO signal, and the dipole pattern and its significance are essentially unchanged (Figure S4).

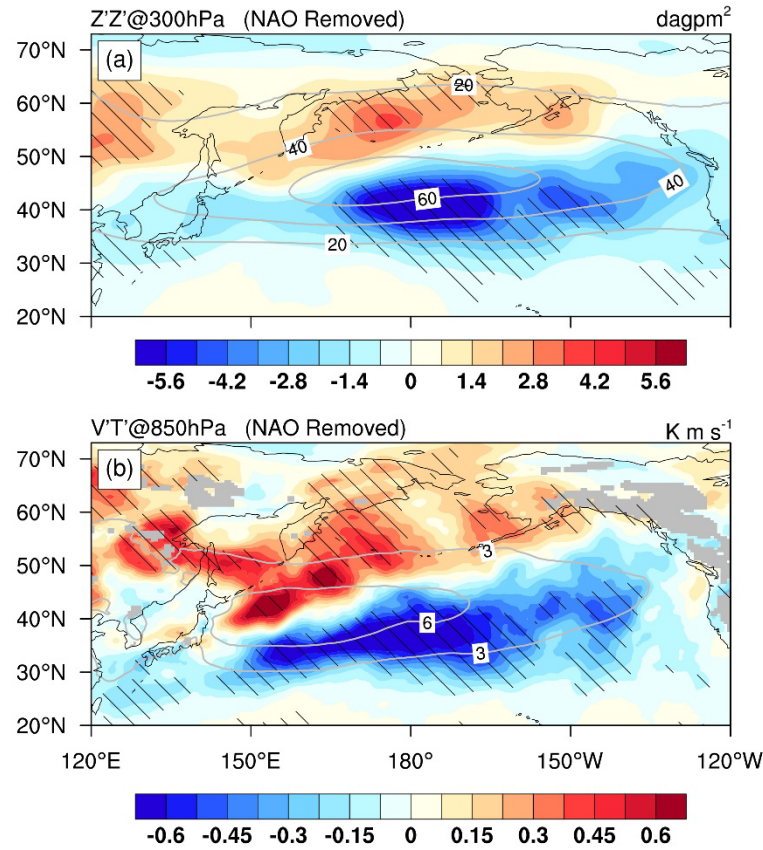


Figure S4. Same as Figure 3, but with the concurrent spring (MAM) NAO signal linearly removed from all variables before the regression. Grey contours denote the climatological spring mean of (a) $Z'Z'_{300}$ and (b) $V'T'_{850}$. Hatching denotes the anomalies statistically significant at the 95% confidence level based on the Student’s t test.

We have further repeated the regression using an independent, satellite-vegetation-based estimate of East Asian spring dust emissions (Fu et al., 2026). This dataset is constructed from GIMMS (1982–2015) and MODIS (2001–2023) vegetation products, which agree closely over their overlap period (Figures S5a-b). The regressions of $Z'Z'_{300}$ and $V'T'_{850}$ onto this emission index reproduce the same dipole with the same sign, location and significance (Figures S5c-d). This check is meaningful for two

reasons. Dust emission is governed by source-region surface wind, vegetation, and soil state, which carry little information about the trans-Pacific transport circulation. The result is also independent of the MERRA-2 assimilation system, in which the same model produces dust burden and circulation and could, in principle, share errors. The agreement between a reanalysis-based index and a vegetation-based emission estimate therefore makes it less likely that the storm track signal is an artefact of the transport circulation or of the assimilation system. We do not claim that this fully settles the question. Source-region surface wind is itself part of the large-scale circulation, and a common driver acting on both the emission and the storm track cannot be excluded with concurrent reanalysis data alone. We state this limitation explicitly in the revised Section 3.1.

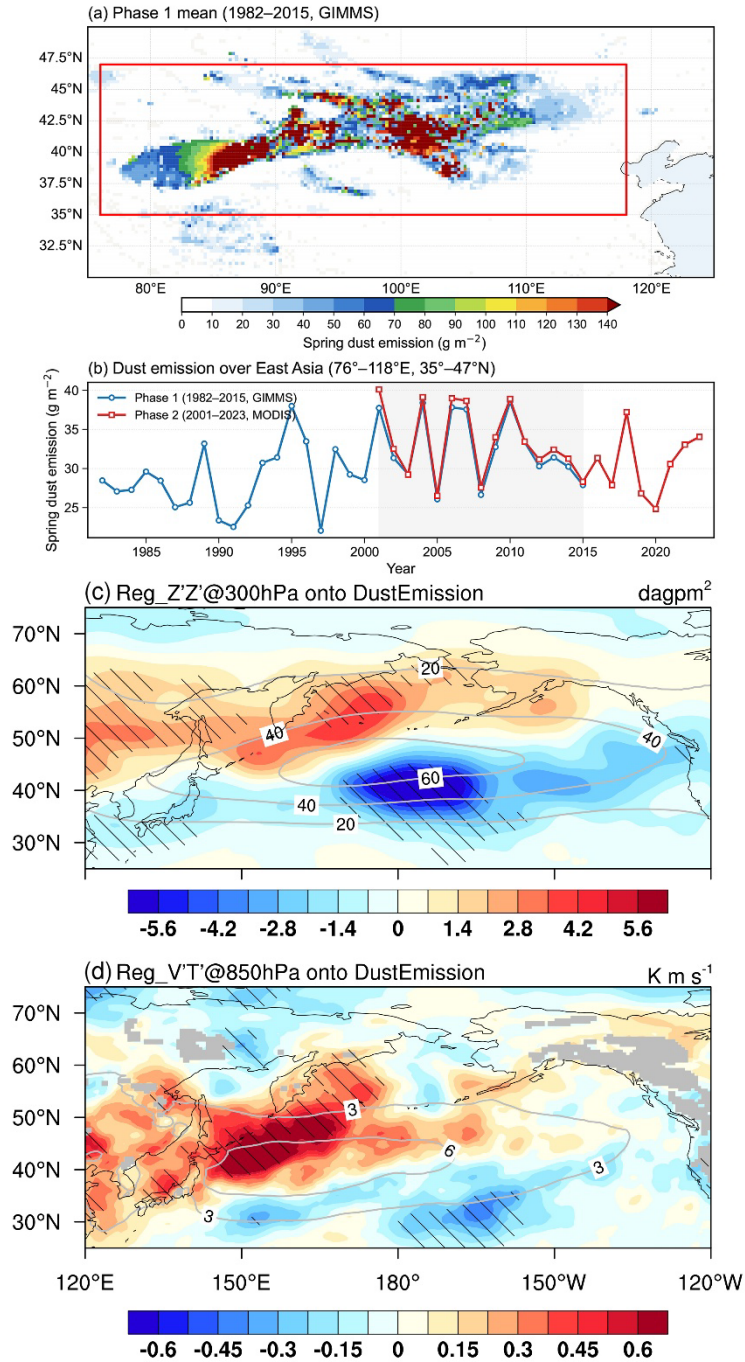


Figure S5. East Asian spring dust emission from Fu et al. (2026) and the associated storm-track anomalies. (a) Mean spring dust emission (g m^{-2}) for 1982–2015, derived from GIMMS vegetation data. The spatial distribution for 2001–2023 derived from MODIS data is similar and is not shown. The red box marks the EADI source region (35°–47° N, 76°–118° E). (b) Time series of spring dust emission averaged over the red box in (a). The blue line is based on GIMMS (1982–2015) and the red line on MODIS (2001–2023). Grey shading marks their overlap period (2001–2015). (c, d) Regressions of spring (MAM) (c) $Z'Z'_{300}$ (dagpm^2) and (d) $V'T'_{850}$ (K m s^{-1}) from MERRA-2 onto the standardized interannual component of the dust emission index for 1982–2022. The index is built from the GIMMS-based series for 1982–2000 and the MODIS-based series for 2001–2022. Grey contours show the climatology. Hatching marks regions significant at the 95 % confidence level.

The WRF-Chem experiments address the same question from a different direction. The CTRL and NoDust ensembles share identical meteorological initial and boundary conditions, so their difference isolates the dust radiative effect from any concurrent circulation variability. That the dust-only perturbation reproduces the mid-tropospheric warming, the anticyclonic anomaly, the meridional redistribution of baroclinicity, and the poleward dipole in both storm track metrics shows that the pathway is physically viable and can operate without a circulation precursor. We now make this point in Section 2.3. At the same time, and as discussed under Comment 2, a single-year experiment cannot show that dust is the dominant cause of the interannual relationship, and we no longer suggest that it does.

Taken together, the reanalysis and the model results support dust radiative heating as a physically plausible contributor to interannual shifts of the North Pacific storm track, explaining up to about one fifth of the variance in its position. We have revised the manuscript throughout to reflect this more cautious framing. The statement at the end of Section 3.1 has been rewritten, and the two new paragraphs on the position indices and the robustness checks have been added there. The description of the WRF-Chem experiments in Section 2.3 now explains what the experiments can and cannot establish. The specific changes are given below.

Added sentences (Section 2.1, Lines 99–105): *“We also use the satellite-vegetation-based estimate of East Asian spring dust emission from Fu et al. (2026) as an independent dust metric. It is derived from Global Inventory Modeling and Mapping Studies (GIMMS; 1982–2015) and MODIS (2001–2023) vegetation products, which agree closely over their overlap period. Regressions onto this emission index are performed for 1982–2022, the period covered by both datasets. Both the spring North Atlantic Oscillation (NAO) index and the preceding-winter (December to February) Oceanic Niño Index (ONI) are obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center.”*

Added paragraph (Section 3.1, Lines 235–241): *“To further quantify this relationship, we define storm track position indices as the difference in area-averaged $Z'Z'_{300}$ and $V'T'_{850}$ between a northern box and a southern box on the poleward and equatorward flanks of the climatological storm track (Figures S3a-b). Positive indices therefore denote a poleward displacement of the storm track. Both position indices covary with*

the interannual variations of the EADI and dust PCI (Figure S3c), with correlation coefficients ranging from 0.36 to 0.47, all significant at the 95% confidence level. The EADI alone explains about 22% and 15% of the interannual variance in the $Z'Z'_{300}$ and $V'T'_{850}$ position indices, respectively. The remaining variance likely reflects internal atmospheric variability and other drivers, including large-scale circulation anomalies that may influence both dust emission and the storm track.”

Added paragraph (Section 3.1, Lines 243–249): *“The relationship is robust to the choice of dust index and to the removal of other circulation modes. The dipole in Figure 3 is essentially unchanged when the concurrent spring NAO signal is removed in addition to ENSO (Figure S4). Regressing the storm track metrics onto the independent emission estimate of Fu et al. (2026) reproduces the same dipole with the same sign and location (Figure S5). Because dust emission is governed mainly by source-region surface wind and land surface conditions, this agreement suggests that the storm track signal is not simply an artefact of the circulation that transports dust across the Pacific. Source-region wind is nevertheless related to the large-scale circulation, so a common driver cannot be fully excluded with reanalysis data alone.”*

4. Discussions around Figure 4 can be improved. Firstly, the clear-sky TOA and SFC SW responses seem weak. They are statistically significant; however, their magnitudes are smaller than the noise outside (e.g., the Bering Strait). Second, the difference between clear-sky and all-sky SW responses for both TOA and SFC shows the impacts of clouds (Figs. 4 a,c,d f). There is a clear north-south dipole, indicating increased clouds to the north and decreased clouds to the south (Figs. 4d,f). This suggests that it corresponds to the poleward shift of the storm tracks. Therefore, the results in Figs. 4d,f do not help identify the thermal driver but show the storm track shift response from different variables. In general, I think the TOA and SFC SW results are not central to the physical mechanism. I would suggest removing them for clarity or having them in the supplementary materials. Panels b and e are very clear.

Responses: We agree. The all-sky minus clear-sky difference at the TOA and the surface mainly reflects the cloud dipole that accompanies the storm track shift, so these panels show a consequence of the shift rather than its thermal driver. We also accept that the clear-sky TOA and surface responses are weak relative to the noise elsewhere in the domain. Figure 4 now retains only the shortwave absorption within the

atmospheric column under clear-sky and all-sky conditions, which is the quantity that directly represents dust heating. The TOA and surface panels have been moved to the Supplement as Figure S6, and the text in Section 3.2 has been shortened accordingly.

Revised paragraph (Section 3.2, Lines 251–262): *“Having established the statistical association between East Asian dust loading and the poleward shift of the North Pacific storm track, we then examine the possible underlying physical mechanisms. Dust aerosols perturb the radiative energy balance by scattering and absorbing solar radiation, which redistributes radiative energy and can modify the large-scale circulation. We therefore first examine the shortwave (SW) absorption within the atmospheric column associated with East Asian dust loading (Figure 4). Under clear-sky conditions, absorption by mineral dust increases the SW energy retained in the atmosphere by $0.3\text{--}0.6\text{ W m}^{-2}$ over the dust polluted region (Figure 4a), directly heating the atmospheric column. The absorption is stronger under all-sky conditions (Figure 4b). When dust resides above cloud layers, the underlying clouds act as a bright reflective surface that enhances multiple scattering between the aerosol and cloud layers and thereby amplifies the atmospheric absorption, consistent with the satellite-based analysis of Xu et al. (2017). These magnitudes are broadly consistent with previous estimates over the North Pacific (Zhu et al., 2007; Hu et al., 2019). The corresponding SW flux changes at the top of the atmosphere and at the surface are shown in Figure S6. Their all-sky minus clear-sky differences exhibit a meridional dipole that mainly reflects the cloud redistribution accompanying the storm track shift, and they are therefore not used here to identify the thermal driver.”*

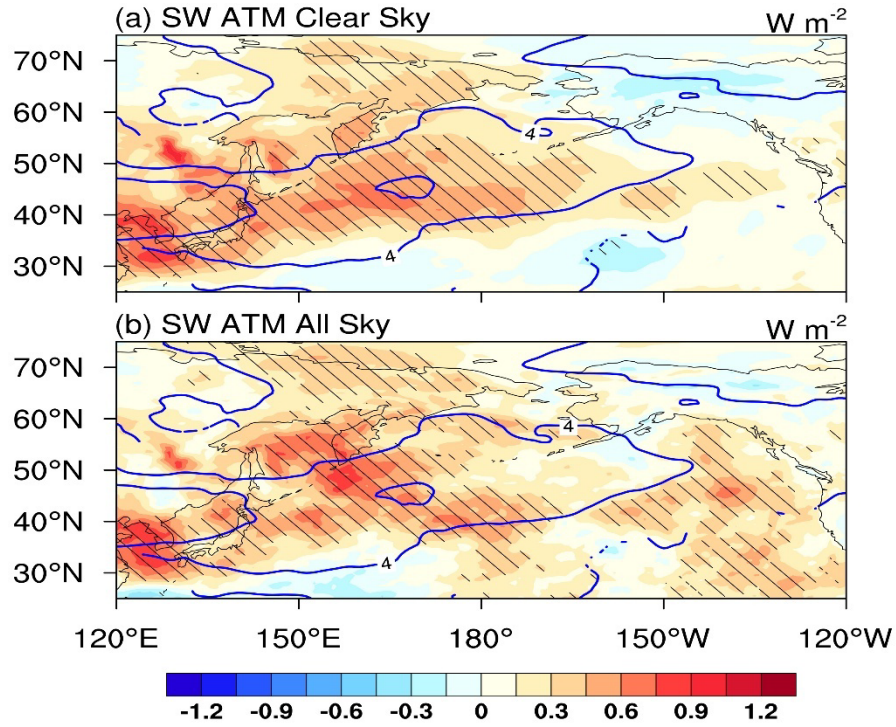


Figure 4. Regressions of anomalies in shortwave radiative fluxes (shading; W m^{-2}) in the atmosphere (ATM) and dust column mass density (blue contour with interval of 2 mg m^{-2}) onto the standardized EADI_IA for (a) clear-sky conditions and (b) all-sky conditions. The regressed fields therefore give the response per one standard deviation of EADI_IA. Positive values denote increased SW absorption within the atmospheric column. Hatching indicates that the regressed anomalies in shortwave radiative fluxes are statistically significant at the 95 % confidence level based on a Student's t test.

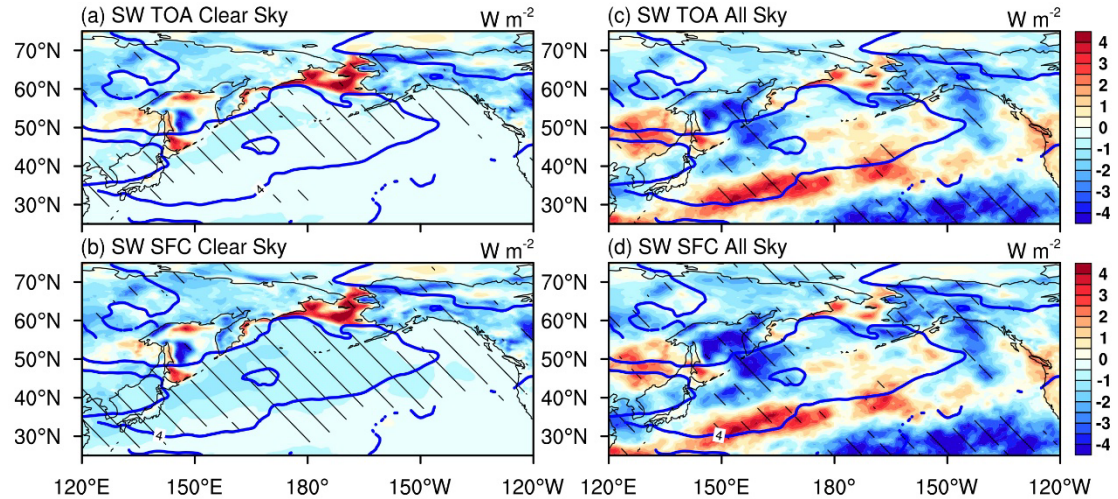


Figure S6. Regressions of anomalies in shortwave radiative fluxes (shading; W m^{-2}) at (a, c) the top of the atmosphere (TOA), and (b, d) at the surface (SFC) and dust column mass density (blue contour with interval of 2 mg m^{-2}) onto the standardized EADI_IA for (a, b) clear-sky conditions and (c, d) all-sky conditions. The regressed fields therefore give the response per one standard deviation of EADI_IA. Positive values denote an increase in net downward SW flux. Hatching indicates that the regressed anomalies in shortwave radiative fluxes are statistically significant at the 95 % confidence level based on a Student's t test. The all-sky minus clear-sky differences mainly reflect the cloud redistribution associated with the storm track shift.

5. Can authors plot climatological MTG and EGR in Figure 6? It would be important to know if the dipole response is also centred around the climatological maximum, as for the storm track metrics.

Responses: Thank you for the suggestion. The climatological spring MTG and EGR have been added to Figure 6a and 6b as grey contours, following the convention used for the storm track metrics in Figure 3. The dipole in both fields straddles the climatological maximum, with the positive centre on its poleward flank and the negative centre on its equatorward flank, in the same way as $Z'Z'_{300}$ and $V'T'_{850}$. This indicates a meridional displacement of the baroclinic zone rather than a change in its overall strength. The corresponding sentences in Section 3.2 have been revised, and the caption now defines the grey contours.

Revised text (Section 3.2, Lines 300–301): *“As shown in Figure 6a, the 700 hPa MTG increases on the poleward flank and decreases on the equatorward flank of its climatological maximum (grey contours).”*

Revised text (Section 3.2, Lines 316–318): *“At 700 hPa (Figure 6b), the baroclinicity strengthens on the poleward flank and weakens on the equatorward flank of the climatological EGR maximum (grey contours), mirroring the dipole in the storm track metrics (Figure 3).”*

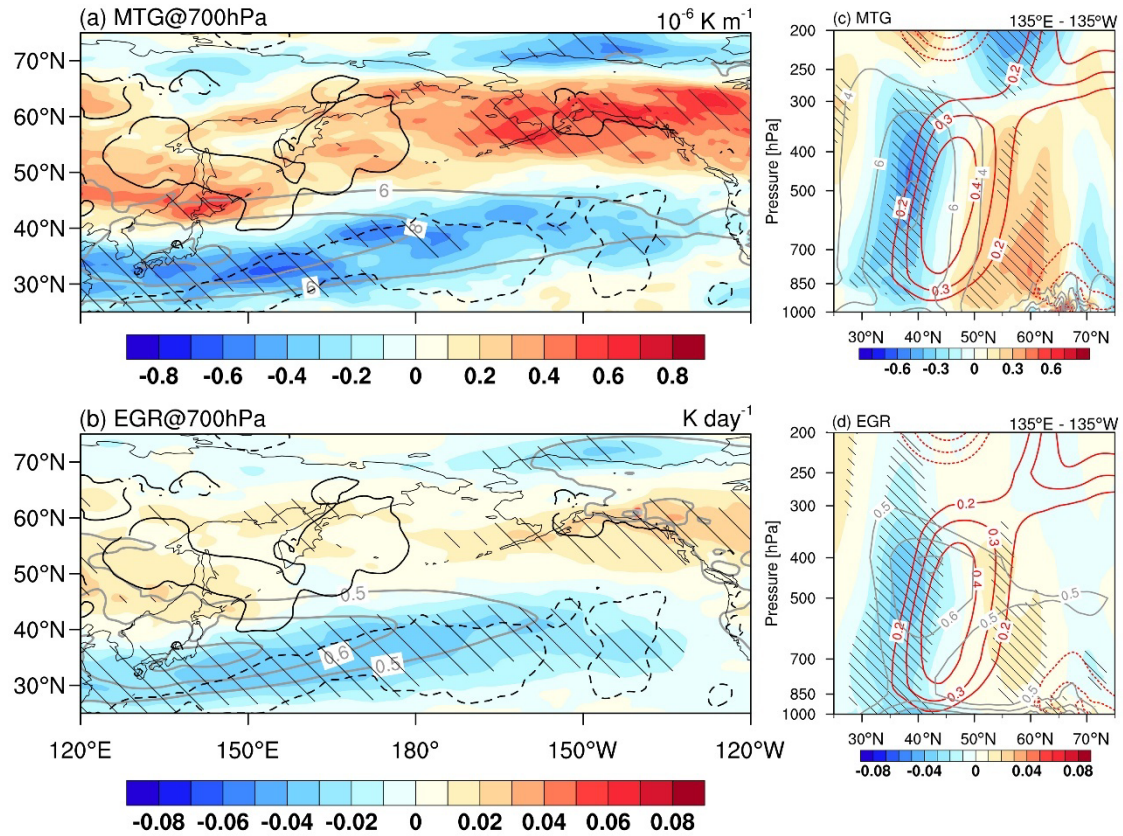


Figure 6. Regressions of anomalies in (a) the 700 hPa meridional temperature gradient (MTG; shading; 10^{-6} K m $^{-1}$) and (b) the 700 hPa maximum Eady growth rate (EGR; shading; K day $^{-1}$) onto the standardized EADI_IA. Panels (c) and (d) display the meridional vertical cross sections of the regressed (c) MTG and (d) EGR anomalies averaged from 135°E to 135°W. Black contours in (a) and (b) denote the statistically significant regions of the regressed $V'T'_{850}$ anomalies shown in Figure 3b. Red contours in (c) and (d) represent the regressed temperature anomalies (K), with solid and dashed lines indicating positive and negative values, respectively. Grey contours in (a, c) and (b, d) denote the climatological spring mean MTG (interval of 2×10^{-6} K m $^{-1}$) and EGR (interval of 0.1 K day $^{-1}$), respectively. Hatching indicates that the regressed MTG and EGR anomalies are statistically significant at the 95 % confidence level based on a Student's t test.

Minor Comments

1. Line 13. yet how -> yet

Responses: Revised.

2. Line 53-54. It would be helpful to clarify which season these studies focused on.
Many are for winter.

Responses: Clarified. We have specified the season of the cited studies in the revised

text.

Revised text (Section 1, Lines 56–58): “Modelling studies demonstrate that East Asian anthropogenic emissions induce an equatorward shift of the subtropical jet and the North Pacific storm track *in boreal winter*, primarily by cooling the surface through aerosol–radiation interactions”

3. Line 107. explicitly isolate -> remove?

Responses: Revised as suggested.

4. Line 152. It would be helpful to mention that the storm track metrics correspond to red and yellow contours since there are many contents in the figure.

Responses: Added. The contour types are now identified in the text.

Revised text (Section 3.1, Lines 186–187): “spatially overlapping with the storm track region, characterized by $Z'Z'_{300}$ (red contours) and $V'T'_{850}$ (orange contours).”

5. Line 258. ‘through thermal wind balance’ here reads as if it is a process. Please revise.

Responses: Revised. The sentence now clarifies that the MTG adjusts the vertical wind shear through thermal wind balance, which in turn modifies the atmospheric baroclinicity.

Revised text (Section 3.2, Lines 298–300) “The dust-related mid-tropospheric warming is concentrated in a zonal band over the central North Pacific (Figure 5a), which is expected to modify the meridional temperature gradient (MTG). Through thermal wind balance, the altered MTG adjusts the vertical wind shear and thereby the atmospheric baroclinicity.”

6. Figure 6. I was trying to match Figs. 3 and 6, but they had different latitudinal bounds. It would be nice to keep them consistent for comparison.

Responses: To facilitate comparison, we have unified the latitudinal range of Figures 3, 4, 5a, and 6a–b to 25°–75°N. In addition, the regions of significant $V'T'_{850}$

change were outlined with black contours in Figures 6a–b (solid for positive and dashed for negative values), so that the baroclinicity response can be directly compared with the storm track response.

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