Response to the Comments from Reviewer #1:

Reviewer #1: This manuscript investigates the independent and synergistic effects of ENSO and Tibetan Plateau snow cover on winter $PM_{2.5}$ variability over China. The topic is interesting and potentially important for understanding interactions between climate and air quality.

Response:

- We would like to thank the reviewer very much for the positive and valuable feedback on our manuscript and providing us with suggestions and guidance. We have revised our manuscript to address your comments and suggestions, as illustrated below.

Major comments:

In CESM, the enhanced snow cover scenario over the Tibetan Plateau is simulated by prescribing a fixed albedo (0.8). Is this setup overly idealized, potentially exaggerating the snow effect? Why not use a more realistic snow cover anomaly as the forcing?

Response:

- We thank the reviewer for this important question. We believe that the prescribed albedo value of 0.8 does not constitute an exaggeration of realistic snow cover conditions over the northern Tibetan Plateau, and we provide the following evidence and clarification.

- We calculated the snow albedo over the northern Tibetan Plateau from reanalysis data for every winter from 1979 to 2021. The results show that the annual maximum albedo reaches or exceeds 0.80 in 15 out of 44 years, confirming that an albedo of 0.8 is physically realistic and frequently observed over this region. The $CESM_{TPSC}$ experiment does not uniformly prescribe a fixed albedo. The surface albedo is increased to 0.8 only where the model-simulated values are lower, while grid points with albedo already exceeding this threshold remain unchanged. This design avoids artificially reducing high-albedo surfaces and ensures a physically consistent perturbation. This approach is in line with previous studies, where albedo values of 0.8 or higher are representative of fresh snow conditions (Cohen and Rind, 1991;

Wang et al., 2021). We have added the following clarification:

- **“$\mathrm{CESM}_{\mathrm{TPSC}}$, in which surface albedo over the northern Tibetan Plateau (86°-94°E, 35°-40°N) was set to a minimum of 0.8 to represent enhanced snow cover conditions (Cohen and Rind, 1991), following Wang et al. (2021). Specifically, when the model-simulated albedo falls below 0.8, it is reset to 0.8 to represent increased snow cover over the northern Tibetan Plateau. Grid points where albedo already exceeds this threshold retain their original values.”**

- **“To quantify this relationship, we define a Tibetan Plateau Snow Cover (TPSC) index as the wintertime area-averaged snow cover over the northern TP (86°-94°E, 35°-40°N), described by the blue box in Fig. 3d. The TPSC index associated snow albedo exhibits pronounced interannual variability throughout 1979-2021, with notably elevated values in recent years (Fig. A7).”**

- **“To assess the causal impact of TP snow cover, we performed a targeted CESM experiment ($\mathrm{CESM}_{\mathrm{TPSC}}$) in which surface albedo over the northern TP (86°-94°E, 35°-40°N) was prescribed with a minimum value of 0.8. Surface albedo represents the reflectivity of the land surface, integrating contributions from all surface components including snow, soil, and vegetation. A minimum value of 0.8 was imposed to simulate persistent high snow cover conditions, consistent with the characteristically high reflectivity of snow-dominated surfaces (Cohen and Rind, 1991).”**

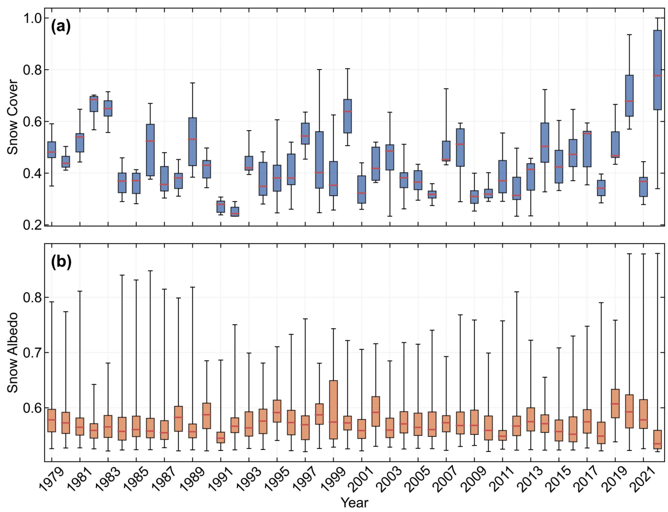

Figure A7. Interannual variations in winter (a) snow cover extent and (b) snow albedo over the northern Tibetan Plateau (86°-94°E, 35°-40°N) during 1979-2021. In each boxplot, the central red line denotes the median value, the box boundaries indicate the interquartile range (25th-75th percentiles), and the whiskers represent the minimum and maximum values.

The CESM simulation covers only one winter (November 2010 to February of the following year). Although this year is characterized by neutral ENSO and a TPSC event, is this single-winter simulation sufficiently representative? Without a multi-member ensemble or multi-year integrations, how can we be sure that the simulated response is not dominated by internal variability? The authors should justify why such a short simulation period is adequate.

Response:

- We sincerely thank the reviewer for raising this important concern. We agree that a single-winter simulation is not sufficient to robustly quantify the statistical significance of the response due to internal variability. The role of our model experiments is confirmatory. Our main conclusions are from multi-decadal observational and reanalysis-based analysis spanning 1979-2021 (43 years for circulation analysis) and 2005-2021 (17 years for $PM_{2.5}$). The EOF decomposition, partial correlation analyses, and regression diagnostics are all performed on this long observational record. The CESM experiments are intended to corroborate the physical mechanisms identified statistically, particularly the direction and sign of the $PM_{2.5}$ response, rather than to precisely quantify the magnitude of the forced response. To minimize interference from background climate variability, we selected the winter from November 2010 to February 2011. This period was characterized by neutral ENSO conditions and neutral TP snow anomalies. This allows the imposed perturbations to be interpreted more clearly. We have added clarification in the revised manuscript to explicitly state that the CESM experiments are intended as process-oriented sensitivity tests, and that their results are interpreted qualitatively rather than statistically.

- **"All simulations covered the period from November 2010 to February 2011, during which both Niño 1+2 and TPSC were in neutral phases (Table 1). Surface $PM_{2.5}$ concentrations were derived from the model output by extracting the lowest vertical level of the simulated**

three-dimensional $PM_{2.5}$ field. Given the uncertainties in CESM-simulated $PM_{2.5}$ concentrations, model outputs are interpreted in terms of the direction and spatial pattern of $PM_{2.5}$ changes rather than their absolute magnitudes."

- **"Moreover, the CESM sensitivity experiments are based on a single-winter simulation, preventing a rigorous assessment of statistical significance in the presence of internal atmospheric variability. The model results are therefore interpreted as qualitative sensitivity tests that support the directionality of the identified mechanisms rather than as quantitative estimates of forced responses. Nevertheless, the consistency between EOF analysis, regression diagnostics, and targeted model experiments increases confidence in our main conclusions."**

The credibility of the simulated $PM_{2.5}$ concentrations in CESM has been mentioned in the manuscript, with the authors noting that "model outputs were interpreted in terms of the direction of $PM_{2.5}$ changes rather than their absolute magnitudes." However, given the large uncertainties in absolute concentrations, it remains debatable whether relying solely on the direction of change is sufficient to interpret the underlying physical mechanisms, especially for key processes such as wet scavenging and hygroscopic growth, whose model representation strongly influences the results. Since the current study is based solely on a single model without independent validation, have the authors evaluated the model's performance in simulating the relevant aerosol processes?

Response:

- We thank the reviewer for raising this important point. We acknowledge that CESM has uncertainties in simulating $PM_{2.5}$ concentrations and aerosol processes. To address this concern, we have substantially revised the Model Experiments section to provide a more transparent and rigorous justification of the model's simulation capability and the scope of its interpretation.

- First, the aerosol microphysical and chemical processes in CESM have been extensively developed and validated in previous studies (Gettelman et al., 2019; Danabasoglu et al., 2020; Wang et al., 2021), providing a well-established physical foundation for the processes central to our mechanistic arguments. Second, to evaluate model performance specifically in the context of this study, we assessed $CESM_{ctrl}$'s ability to reproduce observed surface air temperature, relative humidity, and $PM_{2.5}$ concentrations, as shown in the updated Figure A1. Although the results demonstrate that $CESM_{ctrl}$ generally captures the spatial patterns and interannual variability of these variables, larger uncertainties are found in CESM-simulated $PM_{2.5}$ concentrations. Therefore, in this study, we do not rely on the magnitude of simulated $PM_{2.5}$, but focus on the direction and spatial pattern of changes in response to prescribed forcing. Our interpretation of $PM_{2.5}$ changes is primarily based on the associated meteorological responses (such as circulation anomalies, relative humidity), which are more reliably simulated and directly linked to physical mechanisms. The consistency between model-simulated circulation responses and those derived from observational regression analyses (Figure A6), provides additional confidence in the robustness of the inferred mechanisms.

- **"The Community Earth System Model version 2.1.3 (CESM v2.1.3) was employed to investigate how circulation patterns and $PM_{2.5}$ concentrations respond to SST and snow cover anomalies. The model was configured with a horizontal resolution of 0.94° × 1.25° and 70 vertical layers (Gent et al., 2011), using the FWHIST component. The atmospheric processes were simulated using the Community Atmosphere Model version 6, while chemical and land processes were represented by the Whole Atmosphere Community Climate Model version 6 (Gettelman et al., 2019). The aerosol microphysical and chemical processes in CESM have been extensively developed and validated in previous studies (Gettelman et al., 2019; Danabasoglu et al., 2020; Liu et al., 2021). We assessed CESM's ability to reproduce observed surface air temperature, relative humidity, and $PM_{2.5}$ concentrations in the control simulation ($CESM_{ctrl}$), as shown in Figure A1. The results demonstrate that $CESM_{ctrl}$ generally captures the spatial patterns and interannual variability of these variables. Quantitatively, the mean fractional biases (MFBs) and mean fractional errors (MFEs) for $PM_{2.5}$ fall within the widely adopted model performance criteria of ±60% for MFB and below +75% for MFE (Boylan et al., 2006), indicating acceptable simulation skill. CESM reproduces meteorological variables better than aerosol concentrations, which are subject to larger uncertainties arising from emission inputs, chemical processing, aerosol-cloud interactions, etc (Liu et al., 2021; Danabasoglu et al., 2020).**

- **SST was prescribed to isolate the effects of SST forcing. $CESM_{ctrl}$ was forced with monthly varying climatological SSTs. Two additional sensitivity**

experiments were conducted: (1) $CESM_{ElNiño}$, in which composite winter SST anomalies associated with Niño 1+2 were imposed; and (2) $CESM_{TPSC}$, in which surface albedo over the northern Tibetan Plateau (86°-94°E, 35°-40°N) was set to a minimum of 0.8 to represent enhanced snow cover conditions (Cohen and Rind, 1991), following Wang et al. (2021). Specifically, when the model-simulated albedo falls below 0.8, it is reset to 0.8 to represent increased snow cover over the northern Tibetan Plateau. Grid points where albedo already exceeds this threshold retain their original values. All simulations covered the period from November 2010 to February 2011, during which both Niño 1+2 and TPSC were in neutral phases (Table 1). Surface $PM_{2.5}$ concentrations were derived from the model output by extracting the lowest vertical level of the simulated three-dimensional $PM_{2.5}$ field. Given the uncertainties in CESM-simulated $PM_{2.5}$ concentrations, model outputs are interpreted in terms of the direction and spatial pattern of $PM_{2.5}$ changes rather than their absolute magnitudes."

- **"To further verify the role of El Niño-like SST anomalies, sensitivity simulations were conducted by imposing warm SST anomalies associated with the Niño 1+2 index (Fig. A6). Fig. 5a shows the differences between the $CESM_{ElNiño}$ and $CESM_{ctrl}$ experiments, which isolate the atmospheric and $PM_{2.5}$ response to El Niño forcing. Consistent with the statistical analysis, the imposed El Niño-like SST pattern strengthens the western Pacific subtropical high, induces anomalous southerly winds over eastern China, and enhances moisture transport into southern China (Fig. A6a, b). Consequently, surface $PM_{2.5}$ concentrations decrease markedly in southern China, with reductions of approximately 12 μg m^{-3} over the Sichuan Basin and 6 μg m^{-3} over the Yangtze River Delta (Fig. 5a). In contrast, $PM_{2.5}$ concentrations increase slightly over northeastern China by about 3 μg m^{-3}, further confirming the El Niño-driven north-south dipole structure captured by EOF2."**

- **"To assess the causal impact of TP snow cover, we performed a targeted CESM experiment ($CESM_{TPSC}$) in which surface albedo over the northern TP (86°-94°E, 35°-40°N) was prescribed with a minimum value of 0.8. Surface albedo represents the reflectivity of the land surface, integrating contributions from all surface components including snow, soil, and vegetation. A minimum value of 0.8 was imposed to simulate persistent high snow cover conditions, consistent with the characteristically high reflectivity of snow-dominated surfaces (Cohen and Rind, 1991). The CESM results**

reproduce a coherent cooling response over the northern TP and a corresponding weakening of the subtropical westerly jet, which leads to increases in surface relative humidity and reductions in both planetary boundary layer height and near-surface wind speed over northern China (Fig. A6), supporting positive $PM_{2.5}$ anomalies over the BTH region (Fig. 5b). These modeled responses are consistent with the observational regression analysis, reinforcing the physical credibility of the identified snow-forcing mechanism."

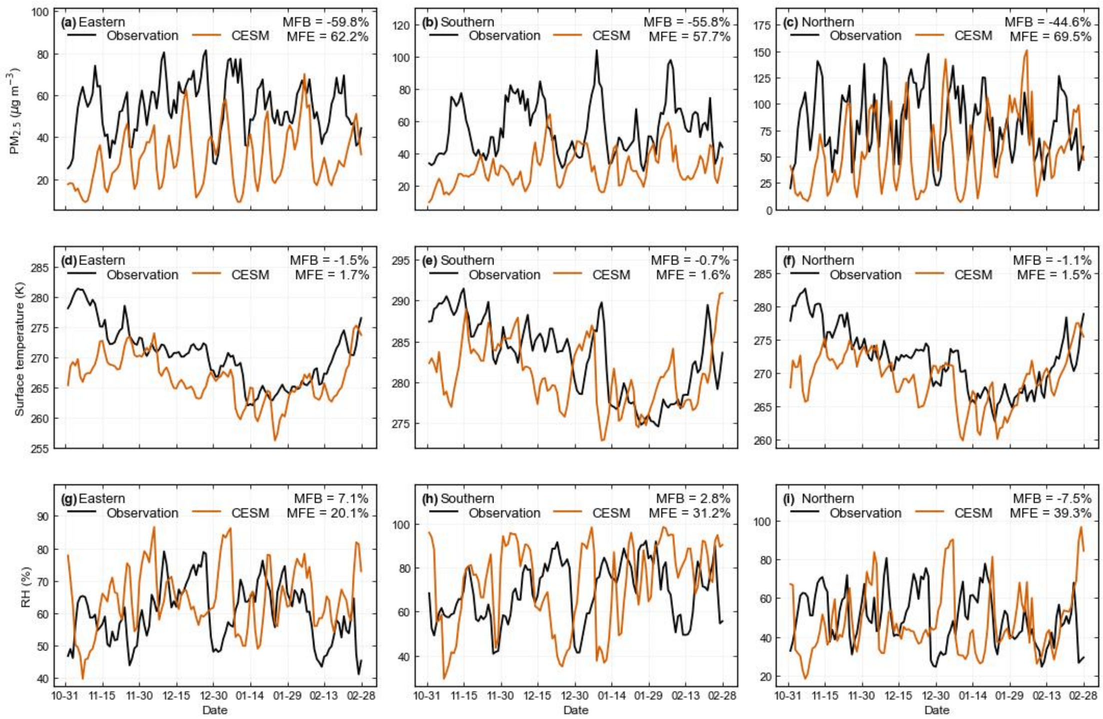

Figure A1. Model evaluation of the $CESM_{ctrl}$. Simulated and observed daily (a-c) surface $PM_{2.5}$ concentration (μg m^{-3}), (d-f) surface air temperature (K), (g-i) relative humidity (%) over eastern China (110°-135°E, 15°-50°N), southern China (110°-135°E, 15°-30°N) and northern China (110°-135°E, 35°-50°N), during November 2010 to February 2011. The mean fractional biases (MFBs) and the mean fractional errors (MFEs) of all simulations meet the model performance criteria of within ± 0.6 for MFB and less than + 0.75 for MFE (Boylan and Russell, 2006).

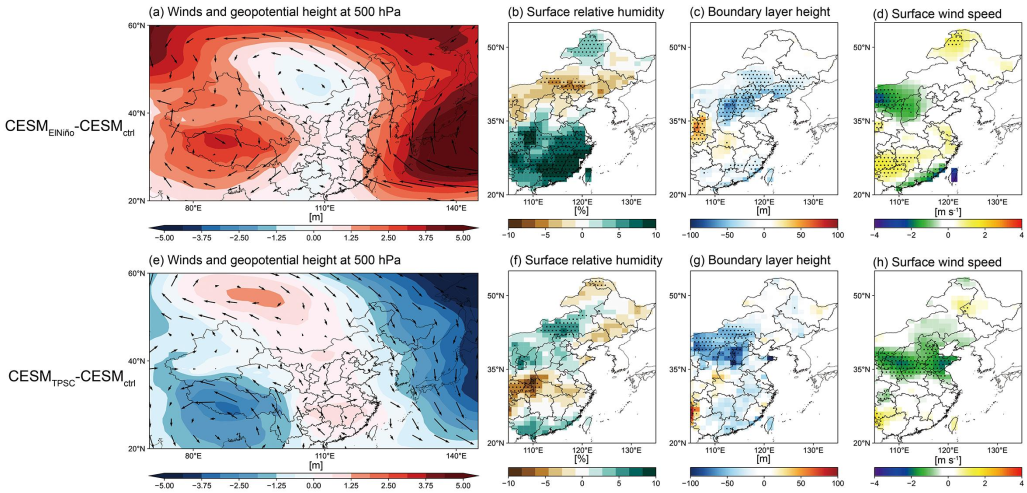

Figure A6. CESM simulated responses of (a, e) geopotential height (m, contour) and wind fields (m s^{-1}, vector) at 500 hPa, (b, f) surface relative humidity (%), (c, g) planetary boundary layer height (m) and (d, h) surface wind speed (m s^{-1}) during winter to Niño 1+2, and higher albedo forcing over the northern TP.

References

Gettelman, A., Mills, M., Kinnison, D., Garcia, R., Smith, A., Marsh, D., Tilmes, S., Vitt, F., Bardeen, C., and McInerny, J.: The whole atmosphere community climate model version 6 (WACCM6), Journal of Geophysical Research: Atmospheres, 124, 12380-12403, 2019.

Danabasoglu, G., Lamarque, J. F., Bacmeister, J., Bailey, D., DuVivier, A., Edwards, J., Emmons, L., Fasullo, J., Garcia, R., and Gettelman, A.: The community earth system model version 2 (CESM2), Journal of Advances in Modeling Earth Systems, 12, e2019MS001916, 2020.

Liu, Y., Dong, X., Wang, M., Emmons, L. K., Liu, Y., Liang, Y., Li, X., and Shrivastava, M.: Analysis of secondary organic aerosol simulation bias in the Community Earth System Model (CESM2.1), Atmospheric Chemistry and Physics, 21, 8003-8021, 2021.

Boylan, A. G. Russell, PM and light extinction model performance metrics, goals, and criteria for three- dimensional air quality models. Atmos. Environ. 40, 4946-4959 (2006).

The authors attribute EOF1 to emission changes, but the physical attribution of EOF2 still requires further robustness testing. Since $PM_{2.5}$ concentrations are the combined result of emissions and meteorological conditions, and emission control policies vary significantly across different regions of China, demonstrating that PC1 correlates with national total emissions is insufficient to rule out the potential influence of the spatial variability of emissions on the EOF2 structure. Could the residual emission variability affect the dipole pattern?

Response:

- We appreciate this insightful comment. The reviewer raises a valid concern that spatially heterogeneous emission control policies across China could potentially imprint on the EOF2 dipole structure independently of meteorological influences. To address this, we examined the correlations between PC2 and anthropogenic emissions (NO_x and SO_2) at multiple spatial scales, including eastern China as a whole, northern China, and southern China separately. In contrast to PC1, which shows strong and statistically significant correlations with national total emissions, PC2 exhibits weak and insignificant correlations with both NO_x and SO_2 across all three sub-regions. This result suggests that the residual spatial variability in emissions does not drive the north-south dipole pattern captured by EOF2. The EOF2 structure is primarily governed by large-scale circulation anomalies and associated local meteorological conditions, as demonstrated by the subsequent regression and correlation analyses in the manuscript. These additional analyses and clarifications have been incorporated into the revised manuscript.

- **"EOF2, accounting for 13.2% of the total variance, reveals a pronounced north-south dipole pattern in winter $PM_{2.5}$ concentrations over eastern China, characterized by positive anomalies in northern China and negative anomalies in southern China. PC2 displays strong interannual variability, with predominantly negative values before 2012 and mainly positive values during 2013-2020. We examined the correlations between PC2 and anthropogenic SO_2 and NO_x emissions across eastern, northern, and southern China. The correlation coefficients between PC2 and SO2 (NO_x) emissions are -0.31 (-0.01), -0.37 (0.07), and -0.33 (-0.11) in eastern, northern, and southern China, respectively. None of these correlations are statistically significant, and critically, they exhibit no north-south dipole structure that could mirror the EOF2 pattern. This confirms that the spatially heterogeneous emission controls do not drive the EOF2 dipole structure. To elucidate the meteorological conditions underlying the EOF2 dipole structure, regression maps of atmospheric circulation and meteorological fields onto the normalized PC2 are shown in Fig. 2. At the 500 hPa level, a pronounced anticyclonic circulation anomaly is observed over northeastern China and Japan, accompanied by a weaker cyclonic anomaly over the southern Tibetan Plateau. This configuration induces anomalous southerly flow across eastern China. In southern China, these southerly winds transport humid air from the South China Sea,**

enhancing precipitation by approximately 0.2 mm month^{-1} and promoting wet removal of $PM_{2.5}$. In contrast, over northern China, the southerly anomalies weaken atmospheric ventilation, as reflected by reduced surface wind speeds (-0.05 m s^{-1}) and a suppressed planetary boundary layer height (-30 m), favoring pollutant accumulation and increasing $PM_{2.5}$ levels. As a result, anomalous southerly flow exerts opposite influences on winter $PM_{2.5}$ concentrations in northern and southern China, which is consistent with previous findings (Zhang et al., 2022; An et al., 2022). These results confirm that EOF2 dipole pattern primarily reflects large-scale meteorological forcing rather than anthropogenic emission variability."

The study uses partial correlation to isolate the effect of Tibetan Plateau snow cover. However, ENSO and Tibetan Plateau snow cover may not be independent of each other. As noted in the manuscript, "winter El Niño has positive impacts on TP snow by increasing storm activity and resultant snowfall, which reinforce snow-albedo feedbacks and strengthen the associated circulation response." In the presence of potential multicollinearity, the results of partial correlation analysis may not be sufficiently robust. The authors should further clarify the correlations among the variables and their impact on the results.

Response:

- We thank the reviewer for this insightful comment. We provide the following quantitative analysis to directly address this concern. The correlation coefficient between the Niño 1+2 index and the TPSC index is -0.28 ($p > 0.24$), which is statistically insignificant. This indicates that the linear dependence between ENSO and TP snow cover is weak, and the two predictors are largely independent of one another. To formally assess the degree of multicollinearity among the three variables (PC2, Niño 1+2, and TPSC), we computed the Variance Inflation Factor (VIF) for each variable using their correlation matrix. The resulting VIF values are 1.87, 1.90, and 1.47 for PC2, Niño 1+2, and TPSC, respectively. VIF values below 5 are generally considered indicative of negligible multicollinearity (O'Brien, 2007), and all three values are well below this threshold. This confirms that multicollinearity among the variables does not pose a meaningful threat to the robustness of the partial correlation results. These analyses and clarifications have been added to the revised manuscript.

- **"After excluding the ENSO signal, PC2 remains significantly correlated with snow cover over the northern TP (Fig. 3d), indicating that interannual variability in winter $PM_{2.5}$ over China is also modulated by TP snow anomalies. To quantify this relationship, we define a Tibetan Plateau Snow Cover (TPSC) index as the wintertime area-averaged snow cover over the northern TP (86°-94°E, 35°-40°N), described by the blue box in Fig. 3d. The TPSC index associated snow albedo exhibits pronounced interannual variability throughout 1979-2021, with notably elevated values in recent years (Fig. A7). The correlation coefficient between the Niño 1+2 index and the TPSC index is -0.28 ($p > 0.24$), indicating that the linear dependence between the two predictors is weak and statistically insignificant. To formally evaluate the degree of multicollinearity among PC2, Niño 1+2, and TPSC, we computed the Variance Inflation Factor (VIF) for each variable. The resulting VIF values are 1.87, 1.90, and 1.47, respectively, all well below the commonly adopted threshold of 5 (O'Brien, 2007), confirming that multicollinearity does not pose a meaningful threat to the robustness of the partial correlation results. Partial correlation analysis, with the ENSO signal removed, reveals a significant positive correlation between the TPSC index and PC2 ($r = 0.49$, $p < 0.05$). In contrast, no statistically significant relationship emerges when a domain-wide TP snow cover index is employed, suggesting that the dynamically relevant snow signal is regionally confined to the northern TP rather than reflecting a plateau-wide forcing."**

References

O'brien, R. M.: A caution regarding rules of thumb for variance inflation factors, Quality & quantity, 41, 673-690, 2007.

Minor comments:

In the third paragraph of Section 3.3, the figure number is incorrectly cited.

Response:

- We thank the reviewer for pointing this out. The figure citations have been corrected in the revised manuscript:

- **"The cooling effect over TP modulates the meridional temperature gradient and weakens the subtropical westerly jet north of the Plateau (Fig. 7a). Associated with enhanced snow cover, 200-hPa zonal wind speeds are reduced by up to 15 m s^{-1}, inducing an anomalous anticyclonic circulation over northern China (Fig. 7b, c). Under the influence of positive geopotential height anomalies, near-surface wind speeds decrease by more than 0.1 m s^{-1}, and the planetary boundary layer height is reduced by approximately 15 m. These stagnant conditions favor pollutant accumulation, while concurrently elevated surface relative humidity enhances aerosol hygroscopic growth (Fig. 7d), together contributing to increased $PM_{2.5}$ concentrations over northern China."**

The model simulation part lacks significance testing; for example, the changes in the horizontal distribution of near-surface $PM_{2.5}$ concentrations in Figure 5 have not been subjected to significance testing.

Response: Revised as suggested.

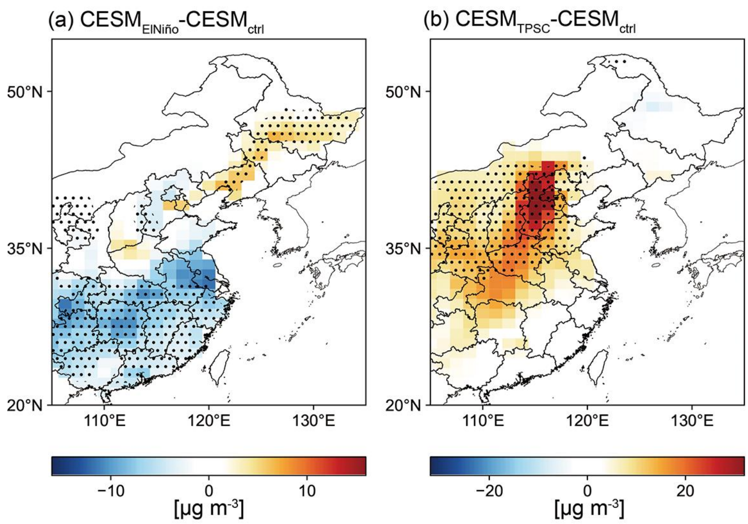

Figure 5. CESM simulated responses of horizontal distribution of near-surface $PM_{2.5}$ concentration (μg m^{-3}) over eastern China during winter to (a) Niño 1+2, and (b) higher albedo forcing over the northern TP. Dotted areas represent statistical significance with 95% confidence according to Student's *t* test.

The naming conventions such as "Niño 1+2+\TPSC+" in Figure 8 are somewhat confusing. It is recommended to unify them into more intuitive expressions (e.g., "Only Niño 1+2+").

Response:

- We thank the reviewer for this helpful suggestion. We acknowledge that the notation used in Fig. 8 may not be immediately intuitive to readers unfamiliar with this framework. However, the terminology follows the convention introduced by Li et al. (2019) and subsequently adopted in related studies (e.g., An et al. 2023), allowing direct comparison with previous work. In this notation, the symbols "&" and "\" have distinct meanings. For example, "Niño $1+2^{+}$&$TPSC^{+}$" denotes years in which both Niño 1+2 and TPSC are simultaneously in their positive phases, whereas "Niño $1+2^{+}\backslash TPSC^{+}$" denotes years in which Niño 1+2 is positive while TPSC is not positive (i.e., including both neutral and negative TPSC years). Therefore, replacing the notation with expressions such as "Only Niño $1+2^{+}$" could still introduce ambiguity regarding the phase of TPSC. To improve readability, we have added a clearer explanation of the notation conventions in the revised manuscript and figure caption.

- **"Composite geopotential height anomalies for different combinations of Niño 1+2 and TPSC phases are shown in Fig. 8. Following Li et al. (2019), the symbol "&" denotes years when two indices occur simultaneously in the specified phase (e.g., "Niño $1+2^{+}$&$TPSC^{+}$" indicates years when both Niño 1+2 and TPSC are positive), whereas the symbol "\" denotes years when only the first index is in the specified phase while the second index is not (e.g., "Niño $1+2^{+}\backslash TPSC^{+}$" indicates years when Niño 1+2 is positive but TPSC is neutral or negative)."**

Although the manuscript discusses the physical mechanisms by which ENSO and Tibetan Plateau snow cover affect $PM_{2.5}$, the comparison with existing studies remains somewhat insufficient. It is recommended to strengthen the connections with previous work in the discussion section to better highlight the incremental contributions of this study.

Response:

- We thank the reviewer for this constructive suggestion. We have substantially revised the Discussion section accordingly:

- **"Previous studies have established that ENSO can significantly modulate winter $PM_{2.5}$ over China through atmospheric teleconnections. For instance, higher (lower) winter $PM_{2.5}$ concentrations are observed over BTH (PRD) during El Niño years (Xie et al., 2022; An et al., 2022; Zhao et**

al., 2022). While these studies have identified a north-south dipole structure in $PM_{2.5}$ and emphasized the role of ENSO, the effect of ENSO on northern China $PM_{2.5}$ remains debated (Zhao et al., 2022), with its influence being more robustly established over southern China. Our results are broadly consistent with these findings and further clarify that El Niño primarily modulates winter $PM_{2.5}$ through large-scale circulation anomalies that enhance moisture transport and wet scavenging in southern China, while its effect on northern China ventilation is comparatively weaker and less definitive.

Beyond ENSO, we identify that elevated snow cover over the northern TP increases snow albedo and cools the atmospheric column via snow-albedo feedbacks, weakening the subtropical westerly jet and inducing anticyclonic anomalies over northern China. These circulation changes promote stagnant conditions and enhance aerosol hygroscopic growth, increasing $PM_{2.5}$ concentrations in northern China. This represents a previously underexplored pathway by which cryospheric anomalies influence surface air quality (Chen et al., 2021; You et al., 2020; Yao et al., 2019), thereby broadening current understanding of how climate modes regulate aerosol distributions. Importantly, El Niño and TP snow cover do not act independently. During their concurrent positive phases, circulation anomalies over East Asia are amplified, leading to a more pronounced north-south $PM_{2.5}$ dipole. Specifically, El Niño exerts a dominant control over $PM_{2.5}$ variability in southern China, whereas TP snow cover plays a more decisive role in northern China."