

Dear reviewer #1,

We sincerely appreciate your careful review of our manuscript and your valuable suggestions for improving the paper. We have thoroughly considered all comments and revised the manuscript accordingly. Below are our point-by-point responses. *Italicized text* indicates the reviewers' comments, while the regular text represents our responses. The specific revisions are highlighted in red, and all corresponding changes have been marked in the manuscript in the same manner.

Sincerely,

Xiadong An

On behalf of all authors

Anonymous Referee #1

In the revised manuscript "Nonlinear effects of the stratospheric Quasi-Biennial Oscillation on ENSO modulating PM_{2.5} over the North China Plain in early winter" by An et al. my comments were adequately addressed.

The paper is therefore recommended for publication in ACP after addressing a few remaining technical comments.

Response: Thank you for your positive evaluation of our work and for recommending it for publication in ACP. We will carefully address all the remaining technical comments to further improve the manuscript.

TECHNICAL COMMENTS:

1. l.13: concentrations -> concentration

Response: Thank you for pointing this out. We have changed “is” to “are” and retained the use of “concentrations” in line 13.

2. l.58: *winter climate -> and winter climate*

Response: Thank you for the suggestion. We have revised “winter climate” to “and winter climate” in line 59.

3. l.77: *Further -> For further*

Response: Thank you for the comment. We have changed “Further” to “For further” in line 78.

4. l.135, 136: *what do the numbers in parentheses mean? are these 1-sigma uncertainties?*

Response: Thank you for your question. The numbers in parentheses indicate the PM_{2.5} concentration changes during the WQBO phase, corresponding to “WQBO” in the parentheses in the sentence.

5. l.281: ???

which can capable of quantifying -> with the help of these models we would be capable to quantify

Response: Thank you for pointing this out. We have revised the sentence to “with the help of these models we would be capable to quantify” in line 287.

Supplement:

1. l.61: *represent -> representing*

Response: Thank you for the suggestion. We have changed “represent” to “representing” in line 61.

2. l.63: *Kala -> Kara*

Response: Thank you for pointing this out. We have corrected “Kala” to “Kara” in line 63.

Dear reviewer #2,

We again appreciate your careful review of our manuscript and the valuable suggestions for improving our work. We have thoroughly addressed all comments and revised the manuscript accordingly. Below are our point-by-point responses. *Italicized text* represents your comments, while the regular text contains our responses. The specific revisions are highlighted in blue, and all corresponding changes have been marked in the manuscript in the same way.

Sincerely,

Xiadong An

On behalf of all authors

Anonymous Referee #2

The authors performed several changes to their original manuscript, but the current version still needs a number of improvements for clarity.

Response: Thank you for your constructive feedback. We have carefully revised the manuscript to improve clarity and address the issues raised.

1. My comment on nonlinear diagnostics was probably unclear; I am referring to the reanalysis-based quantities (e.g. EP fluxes). I believe daily $PM_{2.5}$ cannot be regarded as "high resolution" (please revise L140 accordingly). The meaning of "high resolution" at L282 is also unclear: what do you mean? High frequency $PM_{2.5}$ measurements?

Response: Thank you very much for your clarification, and we apologize for our insufficient understanding of your point. In fact, EP fluxes based on monthly data are also widely used (e.g., Ma et al., 2021). In this study, we mainly use EP fluxes to indicate the propagation direction of planetary waves, rather than to examine the propagation of eddy momentum fluxes and heat fluxes, which to some extent reduces the requirement for high temporal resolution data. In addition, high-temporal-resolution meteorological data may contain many weather signals of different scales as well as noise.

For example, when selecting PM_{2.5} pollution events corresponding to QBO and ENSO events, we can only use monthly data, since the currently available QBO and ENSO indices are provided only at a monthly resolution. If we analyze daily data for these monthly-scale pollution events, we can only examine the entire month, which may include signals of various scales and thus be unfavorable for drawing clear conclusions. That said, we acknowledge that you have raised a very thought-provoking point, and we will continue to explore this line of thinking in our future research.

We agree that daily PM_{2.5} cannot be considered “high resolution” at line 140 in this context, and have removed that reference. We also have clarified that “high resolution” at line 282 refers to high-frequency (daily or hourly) PM_{2.5} measurements, which can better capture short-term variations.

Lines 147–148: “These conclusions [are also supported by daily observations](#) (Fig. S2).”

Lines 289: “... limitation of the current study is the lack of high-resolution data ([e.g., daily or hourly data](#)) to further investigate the ...”

2. My comment on current Fig. 9 (previous Fig. 8) was not addressed.

Response: I apologize for the misunderstanding. In the previous revised version of the manuscript, we had made modifications to the Figure 8 in the current version but inadvertently overlooked Figure 9. In the latest version, we have also redrawn Figure 9. In addition, Figure S10 is also changed.

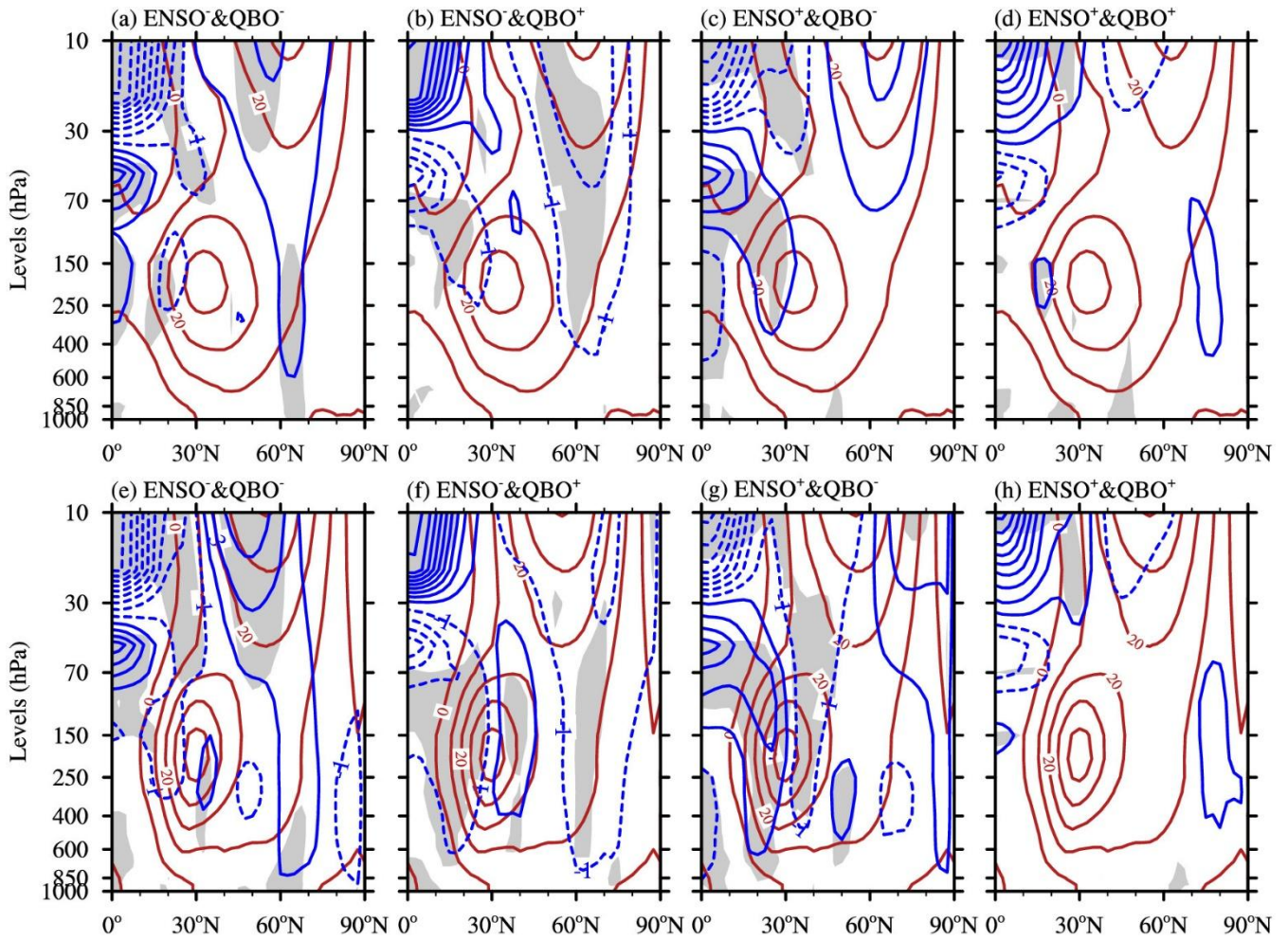


Figure 9: Climatological mean of the zonal-mean zonal winds (red contours with an interval of 10 m s^{-1}) and composite zonal-mean zonal wind anomalies (blue contours with an interval of 2 m s^{-1}) in 0° – 360°E for (a) La Niña and EQBO, (b) La Niña and WQBO, (c) El Niño and EQBO, and (d) El Niño and WQBO. (e)–(f) Same as (a)–(d), but for zonal winds averaged in 0° – 140°E . Solid (dashed) lines represent positive and negative values, respectively. Grey shaded areas indicate significant values of the composite zonal winds at the 90% confidence level.

3. Given the use of ERA5 across several places, the information on data availability needs to be revised.

Response: Thank you for the comment. We have revised the data availability information to clarify the sources and access details. Specifically, ERA5 atmospheric reanalysis data at pressure levels are

available at <https://doi.org/10.24381/cds.6860a573> (Hersbach et al., 2018; last accessed 25 June 2025). Monthly boundary layer height data, as a surface variable, were also obtained from ERA5 (<https://doi.org/10.24381/cds.f17050d7>; Hersbach et al., 2018; last accessed 6 September 2024). These revisions ensure consistency in reporting ERA5 usage throughout the manuscript.

Lines 297–299: “ERA5 atmospheric reanalysis data at pressure levels are available at <https://doi.org/10.24381/cds.6860a573> (Hersbach et al., 2018; last access: 25 June 2025). Monthly boundary layer height data, as a surface variable, were also obtained from ERA5 (<https://doi.org/10.24381/cds.f17050d7>, Hersbach et al., 2018; last access: 6 September 2024).”

Specific comments

1. L31 *The Silver's work gives a different message than yours, please revise*

Response: Thank you for your comment. We have revised the text to more accurately reflect Silver’s work.

Lines 30–31: “The declining trend of PM_{2.5} concentrations in recent years appears to be slowing, despite the Chinese government’s comprehensive emission control measures implemented since the 2010s (Silver et al., 2025).”

2. L77 *It seems that a "For" is missing, but I am not sure what you mean. At least the period of the dataset should be given.*

Response: Thank you for your comment. We have added “For” at the beginning of the sentence and specified the period of the dataset to improve clarity.

Line 78: “For further ...”

Line 78: “... monthly PM_{2.5} data spanning 1960 to 2020, as provided by Zhong et al. (2022a, 2022b).”

3. L78 *I don't see how detrending removes the influence of emissions; or do you mean doing a regression?*

Response: Considering that China’s emissions first increased and then decreased (as shown by the blue solid line in Figure RR1), to minimize the influence of this emission trend, we removed the quadratic

trend from the original data rather than simply using regression analysis to remove a linear trend. After removing the quadratic trend, the correlation coefficient between the observed $\text{PM}_{2.5}$ concentrations and the $\text{PM}_{2.5}$ concentrations from emissions is 0.08 (p-value = 0.69), whereas for the original observed $\text{PM}_{2.5}$ concentrations, the correlation coefficient with emissions is 0.40 (p-value = 0.03). This indicates that removing the quadratic trend partially eliminates the influence of emissions on the observed $\text{PM}_{2.5}$ concentrations. To avoid causing confusion for readers, we have added more details in the revised manuscript.

Lines 81–84: “After removing the quadratic trend, the correlation coefficient between the observed $\text{PM}_{2.5}$ concentrations and the $\text{PM}_{2.5}$ concentrations from emissions is 0.08 (p-value = 0.69), whereas for the original observed $\text{PM}_{2.5}$ concentrations, the correlation coefficient with emissions is 0.40 (p-value = 0.03). This indicates that removing the quadratic trend partially eliminates the influence of emissions on the observed $\text{PM}_{2.5}$ concentrations.”

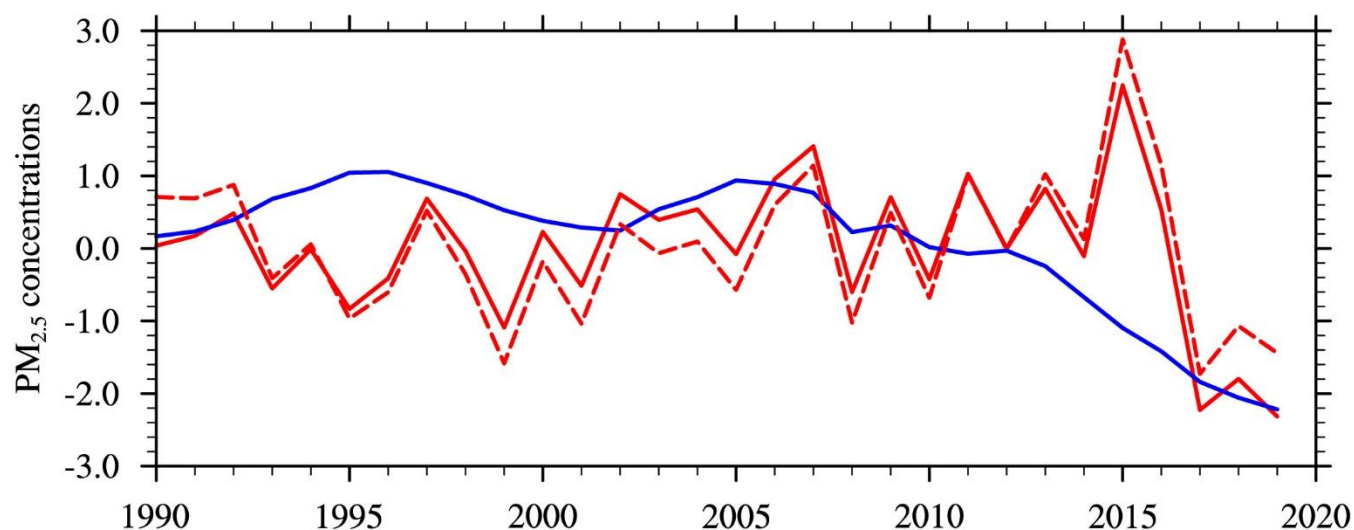


Figure RR1: Time series of standardized $\text{PM}_{2.5}$ concentration anomalies for November–December. The red line represents the regionally averaged $\text{PM}_{2.5}$ concentration anomaly over the NCP (32° – 42°N , 112° – 120°E) based on the $\text{PM}_{2.5}$ dataset provided by Yang (2020). The red solid line represents the original values, while the dashed line represents the values after removing the quadratic trend. The blue line shows $\text{PM}_{2.5}$ concentration anomalies due to emissions over China, derived from the Multi-resolution

Emission Inventory model for Climate and air pollution research (MEIC), available at http://meicmodel.org.cn/?page_id=541&lang=en. The climatology is based on the period 1990–2019.

4. L80 still missing a reference

Response: Thank you for pointing this out. We have added the appropriate reference at line 87 in the revised manuscript to address this issue.

Line 87: “... ([Hersbach et al., 2018](#)).”

5. L88 BLH is a surface variable, hence no pressure level

Response: Thank you for the comment. We have removed the description regarding the pressure level at line 93.

Lines 92–93: “Monthly boundary layer height data were downloaded from the ERA5, with a horizontal resolution of [0.25°×0.25° since 1940](#).”

6. L124 This paragraph does not seem motivated, provide context

Response: Thank you for your comment. We agree that the motivation for this paragraph was not clearly stated. We have revised the paragraph to provide proper context by explaining why this analysis is conducted and how it relates to the main research question.

Line 129: “[Given that PM_{2.5} concentrations over the NCP are affected by multiple factors, such as ENSO and the QBO, ...](#)”

7. L127 "NAAA" should be a subscript of "re". I do not understand what are both terms. I understand "re-NAAA" has units of concentration, as PM_{2.5}? Please explain how these coefficients are identified.

Response: Thank you for your comment. We apologize for the unclear notation. Here, “NAAA” refers to the northeast Asian anomalous anticyclone, which was identified by An et al. (2022, 2023). It plays a crucial role in influencing PM_{2.5} concentrations over the NCP and is considered an indicator of the pollution potential over this region. In this study, the positive geopotential height anomalies over northeast Asia shown in Figure 6c resemble the main pattern of the NAAA. Other factors in Eq. 5, such

as ENSO and Arctic sea ice, also reported by An et al. (2023), are important climate factors affecting the NAAA. In this study, we additionally include the QBO as a contributing factor. The prefix “re” stands for “reconstructed”, meaning that we reconstructed the NAAA index using several climate factors including ENSO, QBO, and the Arctic sea ice index, instead of directly using the NAAA index obtained from EOF analysis as in An et al. (2022, 2023). The NAAA index represents atmospheric circulation and is expressed using the 500 hPa geopotential height, hence its unit is meters (m). Therefore, “re-NAAA” reflects the reconstructed NAAA, a key circulation for winter air pollution in the NCP. We have clarified the notation and added these details in the revised manuscript.

Lines 133–134: “Here, re-NAAA represents the reconstructed northeast Asian anomalous anticyclone index (unit: m), a key circulation pattern influencing PM_{2.5} pollution in the NCP, which was identified by An et al (2023a).”

Lines 135–136: “Among them, ENSO and Arctic sea ice have already been identified by An et al. (2023a) as key factors influencing the NAAA.”

8. L280 I don't think models can be used for validation, maybe for further analysis?

Response: Thank you for your comment. We agree that numerical models may be more suitable for further analysis rather than strict validation. In our study, the main objective was to reveal the nonlinear role of the QBO in modulating the ENSO–PM_{2.5} relationship based on observations. Using numerical models such as WRF-Chem or GEOS-Chem and further analysis in future work could help to further investigate the underlying mechanisms and quantify the contributions of emissions and meteorological factors. We have revised it.

Line 287: “... and further analysis ...”

9. L300 "research" is singular, and "it out"

Response: Thank you for pointing this out. We have corrected the sentence so that “research” is treated as singular and revised “them out” to “it” for grammatical accuracy.

Line 308: “... carried it out.”

10. L303 who is XD?

Response: Thank you for your comment. “XD” refers to XA, and we have revised the text to spell out the full name to avoid ambiguity.

Line 309: “XA prepared ...”

11. Text S1 I still can't understand why you can just refer to NOAA

Response: Thank you for your comment. The table of ENSO events used in this study was primarily compiled by Jan Null, based on NOAA’s sea surface temperature data. This is likely because NOAA’s dataset is among the most widely used sources for sea surface temperature. Therefore, we mainly refer to NOAA.

12. Fig.S1 caption is not grammatically correct

Response: Thank you for pointing this out. We have revised the caption to read: “[Figure S1: Map showing Hebei, Beijing, and Tianjin, China.](#)”

13. Fig.S2 I do not understand if, as stated, this uses a different dataset from the paper

Response: Thank you for your comment. Figure S2 uses the same PM_{2.5} dataset (Yang, 2020) as the main text. It is included to provide additional visualizations and support the robustness of our results. We have clarified this point in the revised caption and supplementary text.

Figure S2: (a) Composite daily PM_{2.5} time series ($\mu\text{g m}^{-3}$) during November–December for La Niña & EQBO (blue solid line), La Niña & WQBO (blue dashed line), El Niño & EQBO (red solid line), El Niño & WQBO (red dashed line). (b, c) Same as Figure 3 in the main text, but based on daily PM_{2.5} data. [The daily PM_{2.5} data were provided by Yang \(2020\).](#)

14. Fig.S6 I have the impression some plots for the main are repeated. This is confusing; results for the bottom plots are quite different from those in the paper, so these cannot be dismissed as currently done.

Response: Thank you very much for carefully reviewing our manuscript. Indeed, panels a–d in Figure S6 are consistent with the results shown in Figure 5a–d of the main text. In the original manuscript, we

used ERA5 boundary layer height data, while the other data were from NCEP. Following your suggestion to use ERA5 for all analyses, we have replaced the NCEP-based plots with ERA5-based ones in the previous revised version of the manuscript. The boundary layer height plots were not replaced, as they were already based on ERA5. To avoid causing any confusion, we have removed the boundary layer height panels from Figure S6.

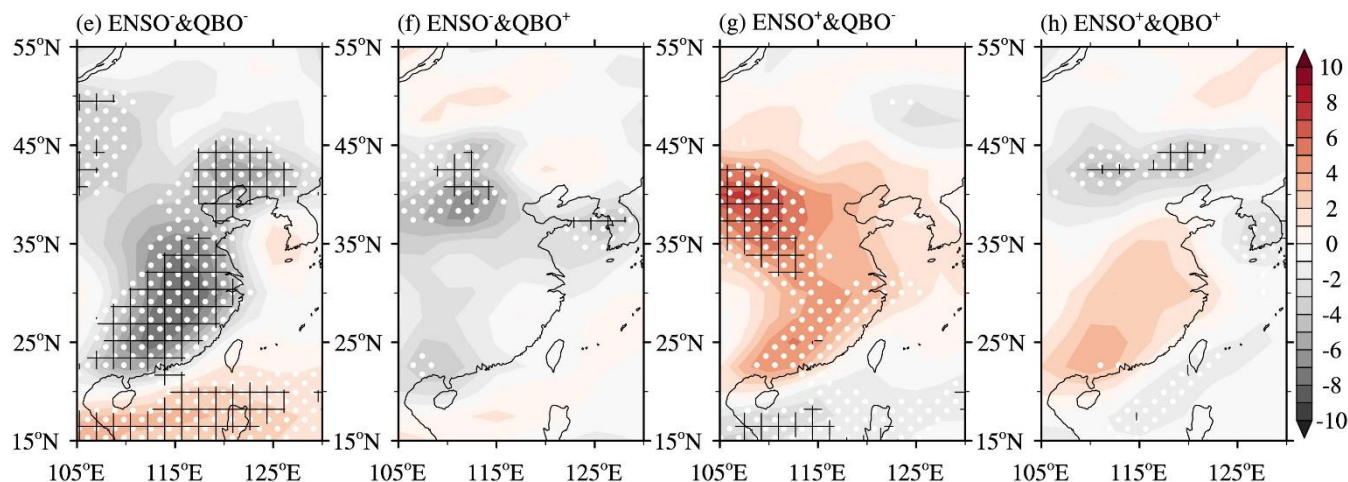


Figure S6: Same as Figure 5e–h in the manuscript, but for NCEP data.

References

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- An, X. D., Chen, W., Sheng, L. F., Li, C., and Ma, T. J.: Synergistic Effect of El Niño and Arctic Sea-Ice Increment on Wintertime Northeast Asian Anomalous Anticyclone and Its Corresponding PM_{2.5} Pollution, *J. Geophys. Res. Atmos.*, 128, e2022JD037840, doi:10.1029/2022JD037840, 2023.
- Ma, T., Chen, W., Huangfu, J., Song, L., and Cai, Q.: The observed influence of the Quasi-Biennial Oscillation in the lower equatorial stratosphere on the East Asian winter monsoon during early boreal winter, *Int. J. Climatol.*, 41(14), 6254–6269, doi:10.1002/joc.7192, 2021.