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

The paper "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. investigates the combined effect of the QBO and ENSO on the $PM_{2.5}$ concentration over the North China Plain. Main findings are that $PM_{2.5}$ is enhanced for El Nino and westward QBO conditions, while $PM_{2.5}$ is reduced for La Nina and eastward QBO. This effect is explained by variations in wind speed and direction, boundary layer height, and humidity. Overall, the paper is a thorough study, it is well written, and of interest and relevance for the readership of ACP. The paper is therefore recommended for publication in ACP after minor revisions.

Response:

My main comments are:

(1) the authors should include the model equations they assume for their multivariate linear regressions

Response: Thank you for your helpful suggestion. In response, we have added the explicit form of the multivariate linear regression model used in our analysis to the revised manuscript.

Lines 124–129: "To further highlight the impact of the QBO on $PM_{2.5}$ concentrations over the NCP during ENSO events, we applied multivariate linear regression analyses following the approach of An et

al. (2023a). The regression model is formulated as follows:

$$re - NAAA = 0.36 \times BKS + 0.40 \times Niño3 + 0.19 \times QBO. \quad (5)$$

Here, re-NAAA represent the key circulation pattern influencing $PM_{2.5}$ pollution in the NCP. BKS, Niño3, and QBO denote the Barents-Kara Sea sea-ice index, the ENSO index, and the QBO index, respectively."

(2) you should explain a bit why enhanced humidity would lead to enhanced $PM_{2.5}$, but not to precipitation that would wash out air pollution

Response: Thank you for your insightful comment. We have addressed this issue in detail in our response to your specific Comment (4) below. Please refer to that section for further explanation.

Please find more Specific and Technical comments below.

Specific comments:

(1) Fig.1d: what is the source of the SST data?

Response: Thank you for your comment. We apologize for the omission regarding the description of the data. The SST data used in Fig. 1d are derived from the NOAA Extended Reconstructed SST (ERSST) version 5 dataset, which provides global monthly SST at a spatial resolution of 2.0º × 2.0º. We have added this information in the data section and Data availability for clarity.

Lines 90–92: "The sea surface temperature (SST) data used in this study are from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST (ERSST) version 5 dataset, which provides global monthly SST at a spatial resolution of 2.0º × 2.0º from January 1854 to the present (Huang et al., 2017)."

Lines 299–300: "The SST data is publicly available at https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html (last access: 22 June 2025)."

Lines 368–370: "Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., Menne, M. J., Smith, T. M., Vose, R. S., and Zhang, H.-M.: NOAA Extended Reconstructed Sea Surface Temperature (ERSST), Version 5 [dataset], doi:10.7289/V5T72FNM, 2017 (last access: 22 June 2025)."

(2) l.116 onward: You should state more clearly in the text that multivariate regression analyses are performed. The underlying linear models should be given as additional equations.

Response: Thank you for this helpful suggestion. In response, we have clarified in the text that multivariate linear regression analyses were conducted. Additionally, we have included the corresponding regression model equations to explicitly describe the statistical framework used in our study.

Lines 124–129: "To further highlight the impact of the QBO on $PM_{2.5}$ concentrations over the NCP during ENSO events, we applied multivariate linear regression analyses following the approach of An et al. (2023a). The regression model is formulated as follows:

$$re - NAAA = 0.36 \times BKS + 0.40 \times Niño3 + 0.19 \times QBO. \quad (5)$$

Here, re-NAAA represent the key circulation pattern influencing $PM_{2.5}$ pollution in the NCP. BKS, Niño3, and QBO denote the Barents-Kara Sea sea-ice index, the ENSO index, and the QBO index, respectively."

(3) l.120: In the text you should add the information that the regression coefficients in Figs.2b and 2d have opposite sign in most regions of China, while in the North China Plain (NCP), which is the main focus of your work, $PM_{2.5}$ anomalies do not change much.

Response: Thank you for the valuable comment. We have added a sentence in the text to clarify that the $PM_{2.5}$ concentrations in Fig. 2b and 2d exhibit opposite signs over most regions of China. Moreover, we now explicitly point out that $PM_{2.5}$ anomalies over the NCP—the main focus of our study—do not show significant changes under the two ENSO phases.

Lines 138–140: "In addition, the composited $PM_{2.5}$ anomalies shown in Fig. 2b and 2d during the WQBO phase exhibit opposite signs across most parts of China, while in the NCP, which is the main focus of this study, the $PM_{2.5}$ anomalies do not change much regardless of whether ENSO is in the La Niña or El Niño phase."

(4) l.153: The point with the humidity was not completely clear to me! If humidity is high enough, precipitation would form and wash out air pollution. Please clarify whether or not this is a relevant mechanism during conditions of enhanced humidity in November/December over the NCP. This should

also be clarified in the discussion around l.246.

Response: Thank you for pointing this out. If the relative humidity is abnormally high and accompanied by precipitation, it can indeed lead to the scavenging of atmospheric particles and thus reduce $PM_{2.5}$ concentrations. However, in this study, the relative humidity was only higher than the climatological average. Over the North China Plain, the relative humidity was around 30–60% (Figure R1), which does not reach the level typically associated with precipitation. As shown in Figure R2c, no significant rainfall occurred over the region. Nevertheless, this relatively elevated humidity can enhance the hygroscopic growth of aerosol particles (Zhou et al., 2011), but cannot wash out $PM_{2.5}$. To avoid confusion for readers, we have added further clarification in the revised manuscript.

Line 173: "… La Niña (El Niño) and WQBO composites, despite the absence of precipitation (Fig. S3)."

Line 174: "… higher relative humidity during non-precipitation periods favors the hygroscopic growth of particulate matters …"

Lines 176–177: "These findings suggest that lower (higher) relative humidity under non-rainy conditions during La Niña (El Niño) and EQBO composites …"

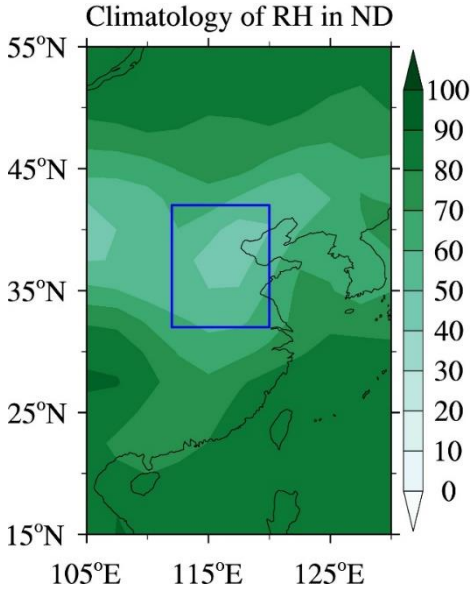


Figure R1. Climatology of relative humidity at 925 hPa during November to December from 1979 to 2020. Blue box represents the North China Plain.

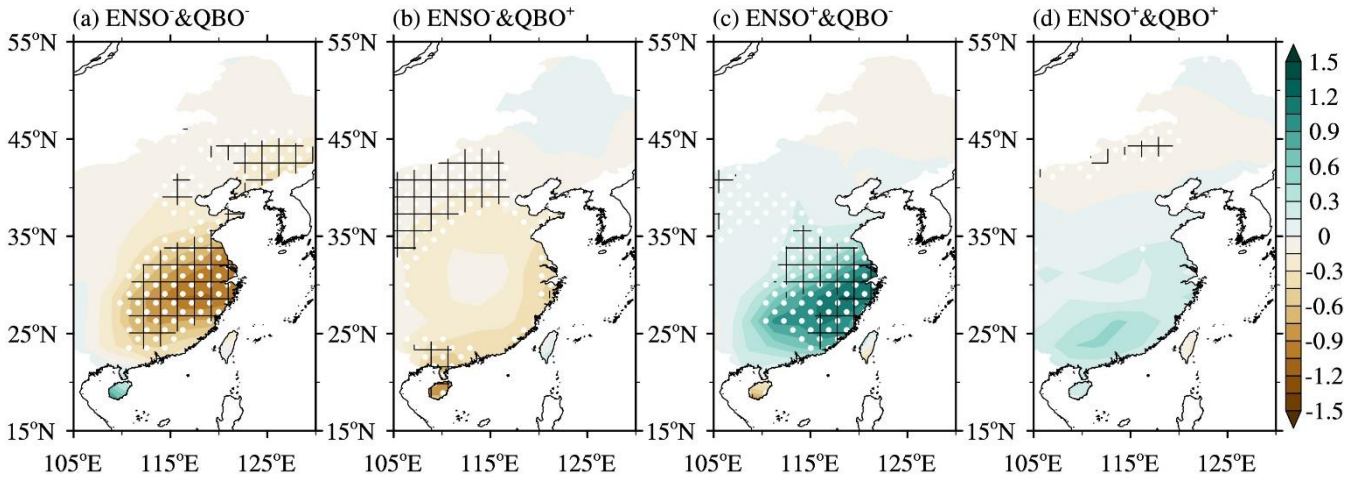


Figure R2: Composite patterns of precipitation (shading; unit: mm day^{-1}) for (a) La Niña and EQBO, (b) La Niña and WQBO, (c) El Niño and EQBO, and (d) El Niño and WQBO. White dotted (black grid) areas indicate significant values at the 80% (90%) confidence level.

(5) l.442: In addition to the white dots, there are also stippled areas in Fig.2. Do these areas refer to another different level of significance? I would suppose that the white dots refer to 80%, and the black grid areas to 90% of significance, like in Fig.5. Please explain and correct!

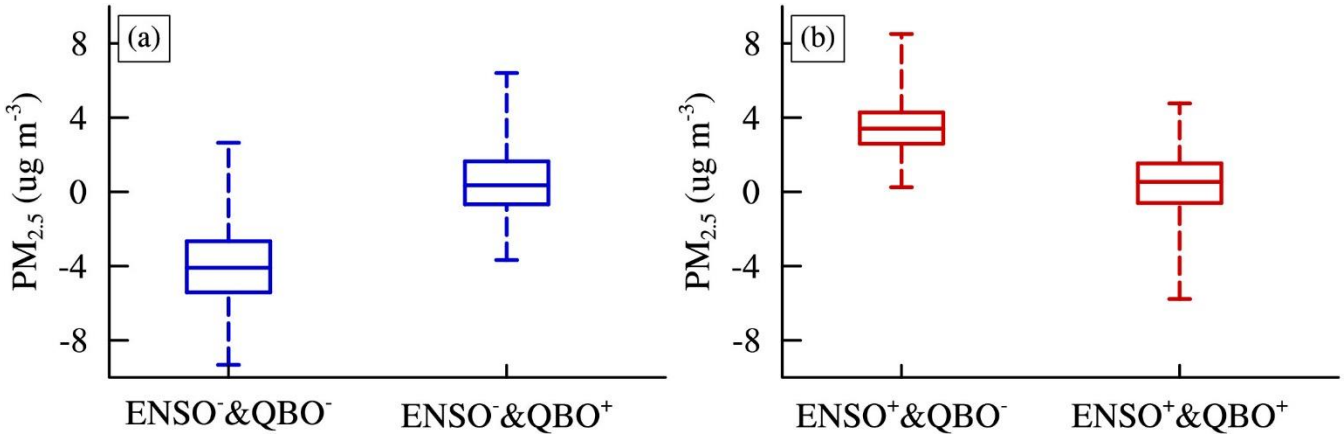
Response: Thank you for your careful review. As you correctly supposed, the white dots and stippled areas indicate the same significance levels as shown in Fig. 5. We have now added some explanation in the revised text.

Line 502: "White dots (black grids in (a)–(f)) indicate areas of significance at the 80% (90%) confidence level."

(6) Fig.3: to avoid confusion, please use same notation as in Fig.2
(ENSO- instead of ENSO^{-1} and QBO- instead of QBO^{-1})

Response: We appreciate your thorough review. The figure has been revised accordingly, as detailed below:

Figure 3:



(7) Fig.6, Fig.7: Green lines represent the Yellow River and the Yangtze River? Please add this information.

Response: Yes, you are right. We have added some information as you suggested.

Line 519: "The green lines represent the Yellow River and the Yangtze River."

Technical corrections:

(1) l.40: Given its the crucial in shaping global weather and climate -> Given its crucial role in shaping global weather and climate

Response: Thank you. We have revised this sentence as you suggested.

Line 39: "Given its crucial role in shaping …"

(2) reference Austin and Tu (2004) is missing in the References list

Response: Thank you for your careful review. We are sorry for missing the reference Austin and Tu (2004). We have added it in the revised manuscript.

Lines 331–332: "Austin, P. C., and Tu, J. V.: Bootstrap methods for developing predictive models, The American Statistician, 58(2), 131–137, doi: 10.1198/0003130043277, 2004."

(3) l.105: Palmer -> Palm

Response: Thanks. We apologize for the mistake in writing. It has been changed in the revised manuscript.

Line 114: "… the Eliassen-Palm (EP) …"

(4) l.107: reference Chen et al. (2013) is not in the references list, did you mean Chen et al. (2003)?

Response: Thank you for your careful checking. We apologize for this typo. Chen et al. (2013) is Chen et al. (2003). We have changed it.

Line 116: "… method outlined by Chen et al. (2003):"

(5) l.117: It is clearly -> It is evident

Response: Thanks. It has been revised.

Line 132: "It is evident …"

(6) l.119: whether is La Nina or El Nino, these is no -> whether ENSO is in the La Nina or El Nino phase, there is no

Response: Thank you. We have revised it as you suggested.

Line 140: "… whether ENSO is in the La Niña or El Niño phase, …"

(7) l.130: The now question is -> The question now is

Response: Thank you for your careful review. It has been changed.

Lines 153–154: "The question now is whether …"

(8) l.138: Fig.3 -> Fig.4

Response: Thanks. We regret this writing error. We have revised it.

Line 162: "… winter monsoon (Fig. 4)."

(9) l.142: (Fig. 4a and 4c) -> (Fig. 5a and 5c)

Response: Thank you for your detailed comments. We are sorry for the error and have corrected it.

Line 166: "… experiences higher (lower) boundary layer heights (Fig. 5a and 5c), …"

(10) l.148: 4e and 4g -> 5e and 5g

Response: We appreciate your thorough review. We have revised it.

Line 172: "… 5e and 5g, …"

(11) l.155: remining -> remaining

Response: Thank you for your careful review. We have revised it.

Line 180: "The remaining questions …"

(12) l.199: 9c 9e and 9g) -> 9c, 9e, and 9g)

Response: Thank you for your careful checking. The revision has been made as per your suggestion.

Line 225: "… 9c, 9e and 9g), …"

(13) l.203: OBO -> QBO

Response: Thanks. We changed it.

Line 229: "Given that a close connection between the QBO and …"

(14) l.442: areas of significant -> areas of significance

Response: Thank you for your careful checking. We have revised it according to your suggestion.

Line 502: "… dots indicate areas of significance at the 90% confidence level."

(15) Caption of Fig.7: Is interval = 1, or 0.5? Please check!

Response: Thank you for your careful review. The contour interval is 0.5. Since the color bar for shading has already been shown, we have removed the description of the contour interval.

Line 521: "Same as Figure 6, but for the perturbation streamfunction (shading; unit:10^6 m^2 s^{-1}) …"

References

Zhou, Y., Zhang, H., Parikh, H. M., Chen, E. H., Rattanavaraha, W., Rosen, E. P., Wang, W. X., and Kamens, R.: Secondary organic aerosol formation from xylenes and mixtures of toluene and xylenes in an atmospheric urban hydrocarbon mixture: Water and particle seed effects (II), Atmos. Environ., 45, 3882–3890, doi:10.1016/j.atmosenv.2010.12.048, 2011.