Authors' Response to Comments of Reviewer #4

Referee comments are in black. Author responses are in blue and revised manuscript in blue marked by underline.

This manuscript presents a comprehensive observational analysis of PM2.5 heavy pollution radiative forcing (RF) in the Bohai Rim region during autumn and winter of 2014–2023, with a focus on the influence of vertical meteorological profiles and the relative importance of various factors on RF and precipitation using machine learning approaches. The study addresses a relevant topic, and the authors have made substantial improvements in the revised version. Below are some minor comments and suggestions for further improvement.

Response: We are very grateful for your important and constructive comments and suggestions. We have made our best efforts to modify the manuscript and supplementary file according to your comments and suggestions.

1. The authors state that "the number of clusters (=5) was determined by the elbow method and representativity." It would be helpful to show the elbow plot in the supplementary materials for transparency.

Response: The following figure shows the elbow plot, which has been added in the supplementary materials. The figure shows the Sum of Squared Errors (SSE) of k-means clustering of T using the cluster numbers from 2 to 8. The number 5 is near the "elbow point" where adding more clusters yields diminishing returns in reducing within-cluster variance.

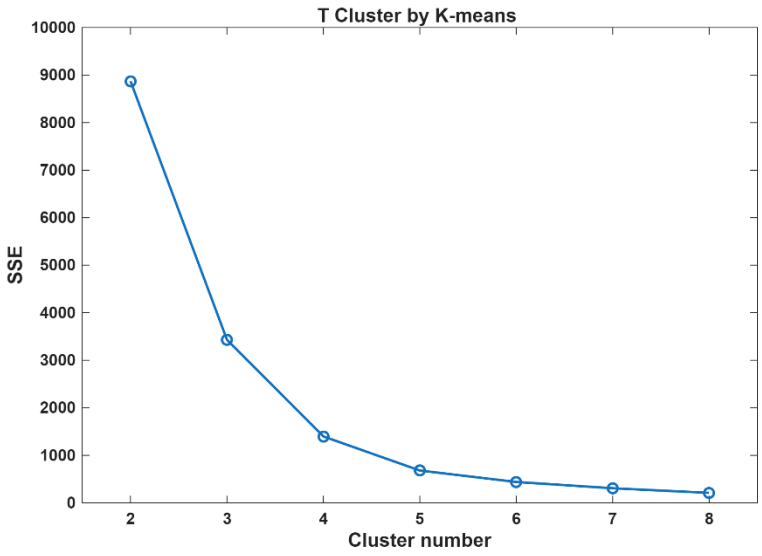

Figure 1 (Figure S1 in supplementary materials). The Sum of Squared Errors (SSE) of k-means clustering of T using the cluster numbers from 2 to 8. The number 5 is nearing the "elbow point" where adding more clusters yields diminishing returns in reducing within-cluster variance.

2. The hyperparameter tuning (number of trees, leaf size) is described, but the final chosen values are not explicitly stated (e.g., "number of trees from 20 to 100" – was 100 selected?). Please specify the final parameters used.

Response: The reason for not explicitly stating the number of trees is that it is not a fixed value; we determine the optimal number of trees by repeated tests from 20 to 100, calculating R^2 and MSE, and selecting the optimal number of tree (the one yielding the lowest MSE or the highest R^2) for training for different prediction variables in different regions. Consequently, there are different optimal parameters for different prediction variables (there are seven prediction variables in our work: pollution RF for surface, TOA, and atmosphere in clear sky and all sky, and daily total precipitation), and different optimal parameters also apply to different regions. Thus, we have modified the statements as "Through repeated tests, we obtained the optimal hyperparameter of the number of trees from 20 to 100 for different prediction variables in each grid…."

3. Figure 4 shows notable regional heterogeneity. The authors note that the NB region shows high RF despite moderate PM2.5 concentrations. The explanation (aerosol vertical profiles, composition, transport) is mentioned but could be elaborated

slightly. For instance, do the authors have any insight into whether this is due to differences in aerosol absorption (e.g., black carbon) or vertical distribution? A brief comment would strengthen the discussion.

Response: We agree that elaborating on the underlying mechanisms would strengthen the discussion. In the revised manuscript, we have added a brief but more detailed explanation. Specifically, it was added as "For instance, the longer heating season in the NB region may result in higher emissions of absorbing aerosols (such as black carbon), leading to a stronger atmospheric heating effect per unit aerosol mass. Besides, aerosols concentrated at higher altitudes over the ocean due to the regional transport may increase their radiative efficiency due to altered surface-atmosphere interactions."

4. Figure 8 and 9 are information-rich. Consider adding a brief explanatory note in the caption to guide readers on how to interpret the importance rankings across regions and sky conditions.

Response: We have modified and added a brief explanatory note in the caption for figure 8 and figure 9 as: "Figure 8. The Random Forest's importance of PM2.5, winds, and temperature at four levels (500, 700, 850, and 1000 hPa) to the radiative forcing on regional heavy pollution days at the surface (first row: a and b), top of atmosphere-TOA (second row: c and d), and in the atmosphere-Atmos (third row: e and f) in clear-sky (first column: a, c, and e) and all-sky (second column: b, d, and f) in different regions. The x-axis indicates different impact factors, while the y-axis denotes different regions. The larger the circle and the redder the color, the greater the importance. Conversely, the smaller the circle and the bluer its color, the less its importance. "

and "Figure 9. The percentage of regional grids with maximum importance factor (including PM2.5, winds, and temperature at four levels) to the radiative forcing on regional heavy pollution days for surface (first row: a and b), TOA (second row: c and d), and atmosphere-Atmos (third row: e and f) in clear sky (first column: a, c, and e) and all sky (second column: b, d, and f) in different regions. The x-axis indicates different impact factors, while the y-axis denotes different regions. The larger the circle and the redder the color, the higher the percentage. Conversely, the smaller the circle and the bluer its color, the closer the percentage is to 0."