Responses to reviewer(s) comments

Anonymous Referee #2:

This paper investigated the co-occurring of ozone and PM2.5 pollution of eastern China in summer. Four synoptic weather patterns (SWPs) were detected and the air pollution feature under each SWP was analyzed. The paper is not well organized and difficult to follow. The authors should revise the manuscript carefully to meet the standard of ACP. The detailed comments are listed below.

RESPONSE: Thank you so much for your valuable comments. We have carefully addressed your concerns. We have also reorganized our manuscript thoughtfully as suggested.

Major comments:

This paper investigated the co-occurring of ozone and PM2.5 pollution in summer. However, the probability of PM2.5, ozone and compound pollution in each site could not be found in the manuscript. Please show their distribution at beginning of the manuscript. Their distribution under each SWP should be also shown to see the impacts of different weather patterns.

RESPONSE: Thanks for your suggestion. We have now included a figure S11 (supplementary material) to represent the calculation for the probability of compound pollution. Particularly, we found significant O_3-$PM_{2.5}$ compound pollution events over five urban clusters during the study period, especially in the BTH region. Furthermore, BTH-NYRD under Type 1 and BTH region under Type 2 could be concluded as a result of O_3-$PM_{2.5}$ co-occurring pollution due to a greater occurrence of compound pollution. More information regarding spatial distributions of O_3, $PM_{2.5}$ and compound pollution under each SWP were given in Fig. 12.

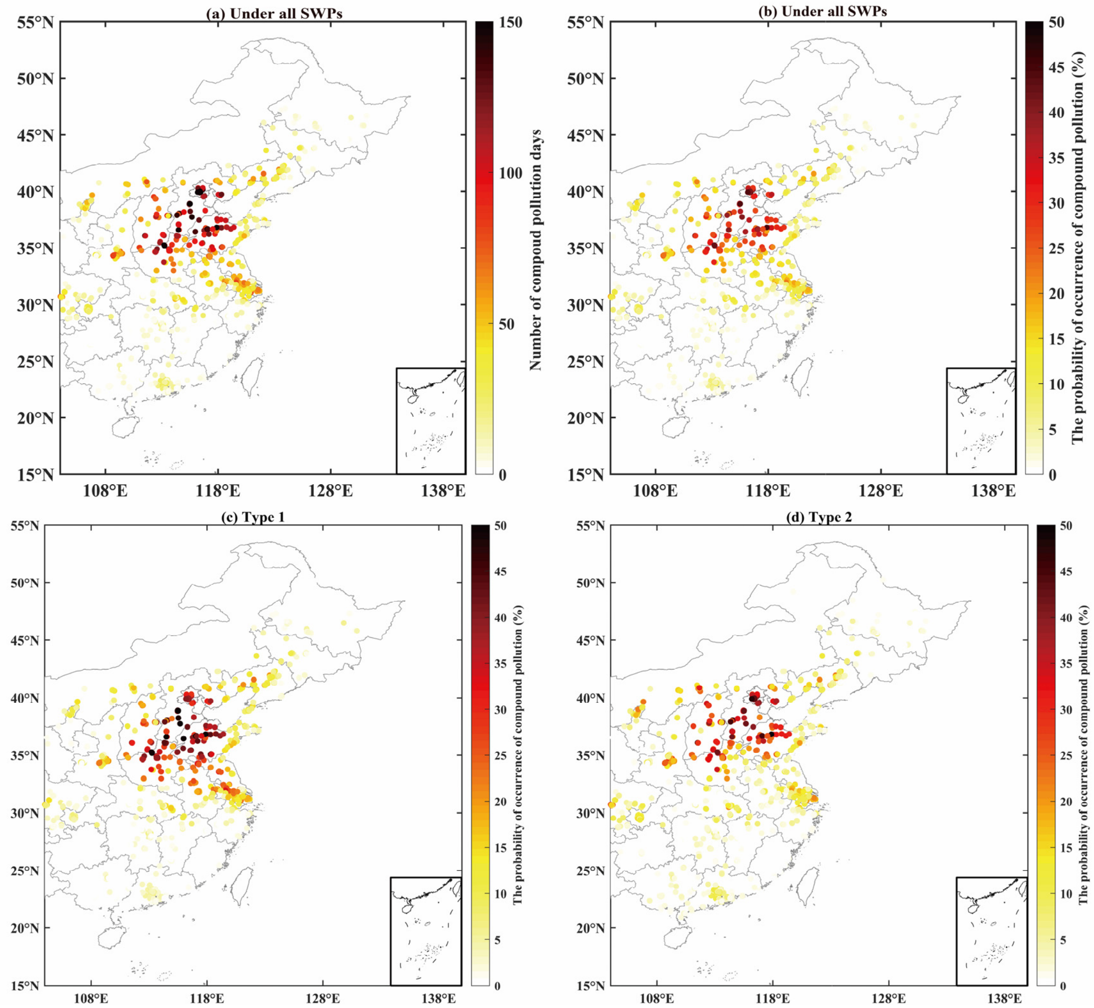

Fig. S12. The number (a) and probability (b) of occurrence of compound pollution days under all SWPs in each site, (c) and (d) is the same as (b), but for Type 1 and Type 2.

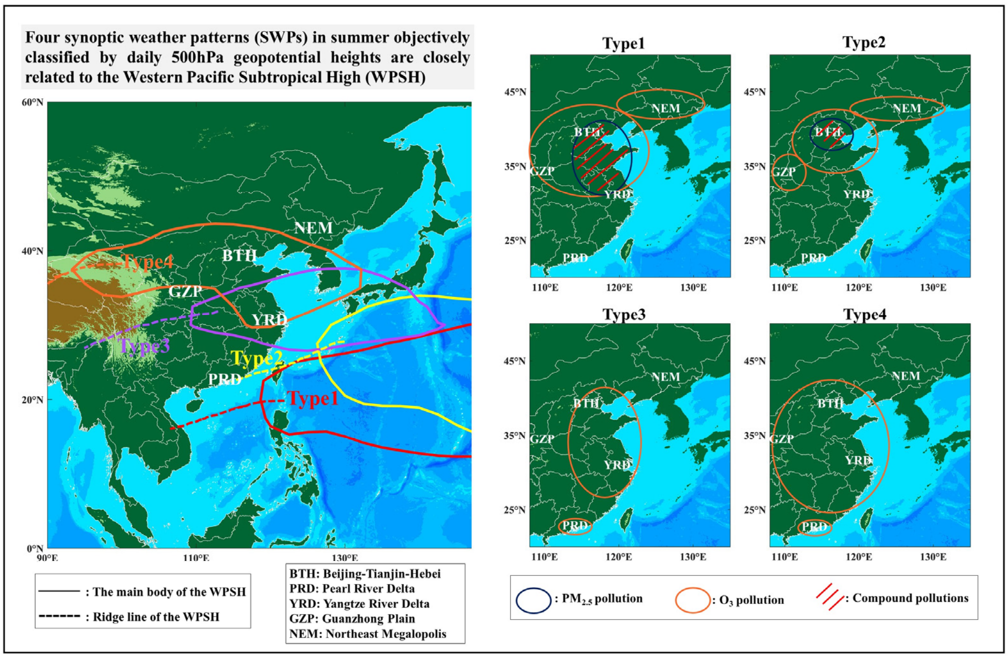

Fig. 12. Schematic diagrams describing the relationships between the WPSH, four SWPs and summertime O_3 and $PM_{2.5}$ pollution in various regions.

In this work, four synoptic weather patterns were detected and their difference were compared. The physical understanding the SWPs could be improved. In my opinion, Type 1 and type 2 represents normal WPSH pattern during early and late summer, respectively. Type 3 and type4 reflects two splitting states (southern mode and northern mode) of the WPSH, which mainly occurs in late summer. The climate background of early and late summer is quite different from each other. Thus, the SWPs of early and late summer should be compared separately.

RESPONSE: Thank you for your comments. For most of the days, Type 1 and type 2 can represent both regular WPSH pattern during early and late summer. Type 3 and type 4 may demonstrate the two splitting states (southern mode and northern mode) of the WPSH, which mainly occurs in the late summer. Particularly, characteristics of circulation of these synoptic patterns have been described and compared in section 3.2:

"The location of Type 1 related western ridge point and northern boundary of the WPSH at 500 hPa is around 120°E and 30°N, respectively, (Fig. 4a and Table S2). The southwestern flow of this WPSH could chemically transport water vapor to the YRD region, resulting in a southwestward prevailing wind across the YRD region and westward flow from the north of the WPSH forming a convergence area at 850 hPa. These conditions were also associated with high temperature and humidity during the summer with Meiyu season, which Meiyu season is a climate phenomenon with continuous cloudy and rainy days generally occurring during June and July every year in the middle and lower reaches nearby Yangtze river, Taiwan of China, central/southern Japan, and southern Korea. For Type 2, the westerly trough could deepen as the WPSH shifts northward slightly from Type1 or retreats southeast from Type 3 (Fig. 4b). The southerly wind from the ocean could interact with the northern periphery of the WPSH. As a result, the sea-land interaction could affect the southeastern region across China,

while northern China could be mainly controlled by the westerly trough. In compared with Type 2, the impacts of Type 3 could shift the boundary of WPSH to a higher latitude, with a westward extension (Fig. 4c), which disintegrating the closed high-pressure monomer along the eastern coast of China and remaining the main body of the WPSH over the ocean (Figs. 4c and S4). This has led to a condition completely controlled by the monomer of the WPSH over the YRD region, resulting a hot and dry weather at the end the rainy season at the beginning of mid-summer. Figure. 4d indicated that the location of the WPSH monomer was more northern and western with respect to other SWPs, controlling northern China for a long time, the western ridge point was around 95°E and the northern boundary is around 40°N.

Figure 5 presents the daily and annual variations of the SWPs in the summers of 2015–2018. The advance of the WPSH in eastern China occurs in June and July, while a gradual withdrawal of the WPSH mainly occurs in August. Particularly, Type 1 and Type 2 represent normal WPSH characteristics during early and late summer. Type 3 and Type 4 could reflect a split of the WPSH, which mainly occurs in late summer. Consequently, there were 167, 117, 52 and 32 days for the Type 1, Type 2, Type 3 and Type 4 over the study period, respectively. Since WPSH movement is generally affected by the weather phenomenon of its surrounding climate systems (such as typhoons, the Tibetan high, etc.) (Ge et al., 2019; Liu and You, 2020; Shu et al., 2016; Wang et al., 2019), it could result in a short-term southward retreat during the advancement of WPSH (e.g., around 10 August 2018) and a short-term northward advance during its process of retreat (e.g., 21 and 29 August 2016). In general, the WPSH could represent the evidences of intra-seasonal and interannual changes over China, which will inevitably modify the changes of weather, climatic and environmental conditions in eastern China.".

More information for local meteorological factors under the influences of the above climatic background, including related environmental impacts, have now been noted in section 3.4.

The abstract is not well written and following information should be included: 1) The distinct feature of each synoptic weather pattern; 2) the pollution features under each SWP; 3) which SWP mostly favors the co-occurring of ozone and PM2.5 pollution; 4) where the co-occurring of ozone and PM2.5 pollution happens.

RESPONSE: Thanks for your suggestion. We have revised the abstract to be more focusing on the co-occurrence of O_3 and $PM_{2.5}$ pollution under Type 1 and Type 2 synoptic weather patterns, including more details in the results. The revised abstract is as follow: "Surface ozone (O_3) pollution during summer (June-August) over eastern China has become more severe, resulting in a co-occurrence of surface O_3 and $PM_{2.5}$ (particulate matter with aerodynamic diameter ≤ 2.5 μm in the air) pollution recently. However, the mechanisms regarding how synoptic circulation pattern could influence this compound pollution remains unclear. This study here applied a T-mode principal component analysis (T-PCA) method to objectively classify the occurrence of four synoptic weather patterns (SWPs) over eastern China, based on geopotential heights at 500 hPa during summer (2015-2018). Four SWPs of eastern China are closely related to the western Pacific subtropical high (WPSH), exhibiting, significant intraseasonal and interannual variations. Based on ground-level air quality information and meteorological observations, remarkable spatial and temporal disparities of surface O_3 and $PM_{2.5}$ pollution were also found under the impacts of the four SWPs.

Particularly, there were two SWPs sensitive to compound pollution (Type 1 and Type 2). Type 1 is characterized by a stable WPSH ridge with axis at about 22°N and the rain belt located in the south of Yangtze River Delta (YRD). High temperature, moderate humidity and low precipitation occurred in the region from BTH to northern YRD (BTH – NYRD), resulting in a co-occurrence of O_3 and $PM_{2.5}$ pollution. Additionally, air pollutants can be transported by the prevailing southerly winds from southern plains and accumulated in the southern BTH, resulting in a worsen pollution. Type 2 exhibits a WPSH dominance (the ridge axis ~25°N) and rain belt (over the YRD) in a higher latitude compared with Type 1. High temperature, medium-high humidity and low precipitation over the BTH were the conducive factors related to the occurrence of the compound pollution events under Type 2. Furthermore, low boundary layer height (BLH) and high frequency of light-wind days (FLWD) could create favorable conditions for pollution maintenance. Overall, synoptic weather patterns have played an important role as driving factors of surface O_3-$PM_{2.5}$ compound pollution in a regional context. In addition to the impacts of local emissions, our results may provide further insights regarding how regional environmental changes due to co-occurrence of high $PM_{2.5}$ and high O_3 level may be driven by the effects of meteorological factors. Overall, our findings demonstrate the important role played by synoptic weather patterns in driving regional surface O_3-$PM_{2.5}$ compound pollution, in addition to the large quantities of emissions, and may also provide insights into the regional co-occurring high $PM_{2.5}$ and high O_3 level via the effects of certain meteorological factors.”.

Other comments:

1. Line 26: Please describe details of SWPs here.

RESPONSE: The details of SWPs are given as follows: “Type 1 is characterized by a stable WPSH ridge with axis at about 22°N and the rain belt located in the south of Yangtze River Delta (YRD).” And “Type 2 exhibits a WPSH dominance (the ridge axis ~25°N) and rain belt (over the YRD) in a higher latitude compared with Type 1”. See lines 30-37 of page 2 in the revised version.

2. Line 30: How about the ozone pollution over the regions where are not controlled by the WPSH or the prevailing westerlies. Where are these regions?

RESPONSE: Most of the regions we focus on are controlled by the WPSH or the prevailing westerlies under four SWPs except for PRD region under Type 3 and Type 4. In the revision, we have focused on the SWPs which are more prone to the compound pollution.

3. Line 34: Please explain the meaning of “some local areas”.

RESPONSE: “Some local areas” refers to “the BTH region under impacts of Type 1 and Type 2”. Thanks and revised.

4. Line 35: Please clarify where the co-occurring surface O3 and PM2.5 pollution happens.

RESPONSE: The co-occurring surface O_3 and $PM_{2.5}$ pollution happened in the BTH – NYRD regions under Type 1 and BTH region under Type 2.

5. Line 35-36: How the WPSH affects the boundary layer height and frequency of lightwind days?

RESPONSE: The area controlled by the WPSH usually have shallow BLH and high FLWD. In the revised manuscript, we have added the structural characteristics of the boundary layer to better explain the causes of compound pollution.

6. Line 36: What does the "different roles" mean? Please provide some explanations.
RESPONSE: It should be "an important role". Sorry for incorrect description and thanks.

7. Line 118-120: In abstract, it is mentioned that high temperature, moderate humidity and slight precipitation favors the ozone formation. It is not consistent with the statements here.
RESPONSE: Thanks for your comment. Indeed, hot and dry air can enhance the photochemical reactions of O_3. Eastern China has a monsoon climate with dry winters and humid summers, so moderate humidity actually presents negative anomaly for summers, and it could be considered as a dry summer. In addition, we also analyzed the RH condition under different pollution scenarios (Fig. S14), and found RH is low-medium when O_3-only pollution occurs, and moderate RH would favor the co-occurrence of O_3 and $PM_{2.5}$. Therefore, the results were not inconsistent. In order to address the comments, we have now revised this description as follow: "High temperature, moderate humidity and low precipitation occurred in the region from BTH to northern YRD (BTH – NYRD), resulting in co-occurring O_3 and $PM_{2.5}$ pollution".

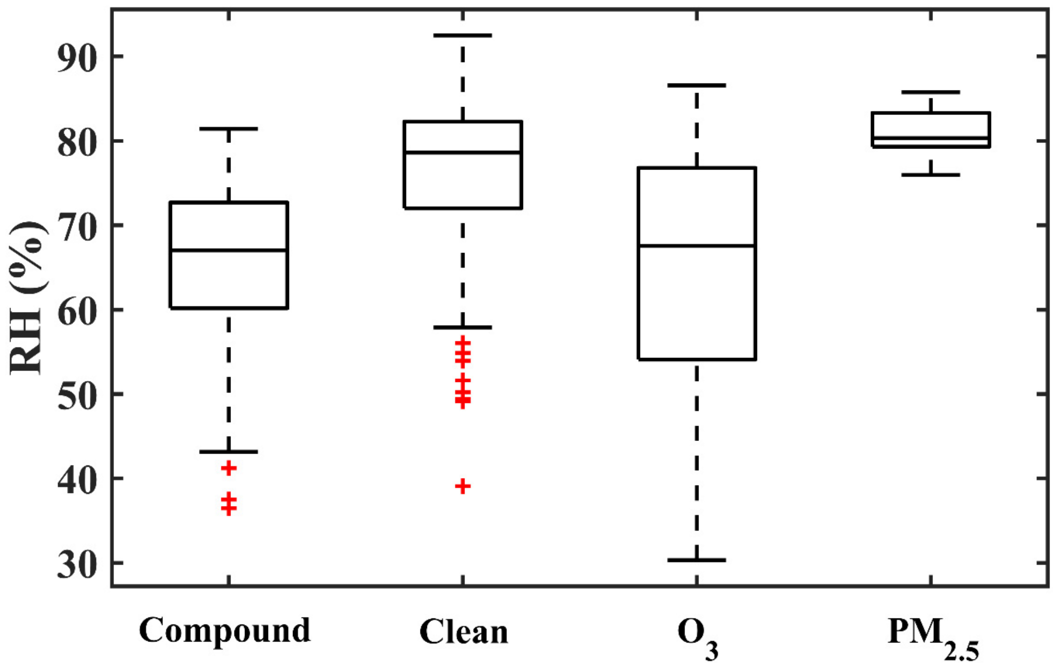

Fig. S14. Box-Whiskers for the RH under compound pollution, clean, O3-only, PM2.5-only period. In the Box-Whiskers plot, the central box represents the values from the lower to upper quartile (25th to 75th percentile). The vertical line extends from the maximum to the minimum value. The middle solid line represents the median, and the red plus represents the outlier.

8. Line 124: It is not consistent with the conclusions in abstract. In abstract, it is found that the warm moist flow brought by the WPSH result in co-occurring surface O3 and PM2.5 pollution.

RESPONSE:

Sorry for the unclear description. We have revised our conclusion as follow: "On one hand, the appropriate warm moist flow brought by the WPSH can promote hygroscopic growth of the fine particulate matter in some local areas (i.e., BTH-NYRD under Type 1 and BTH under Type 2), resulting in the increase of $PM_{2.5}$ concentrations. On the other hand, transboundary O_3 was transported to these local areas at the same time, which may contribute to the co-occurring surface O_3 and $PM_{2.5}$ pollution".

9. Line 148: I cannot find the position of the urban agglomeration in Figure 1a. Please check.

RESPONSE: We have changed the Figure 1a, and the black boxes shown in Figure 1a indicate the locations of key urban clusters.

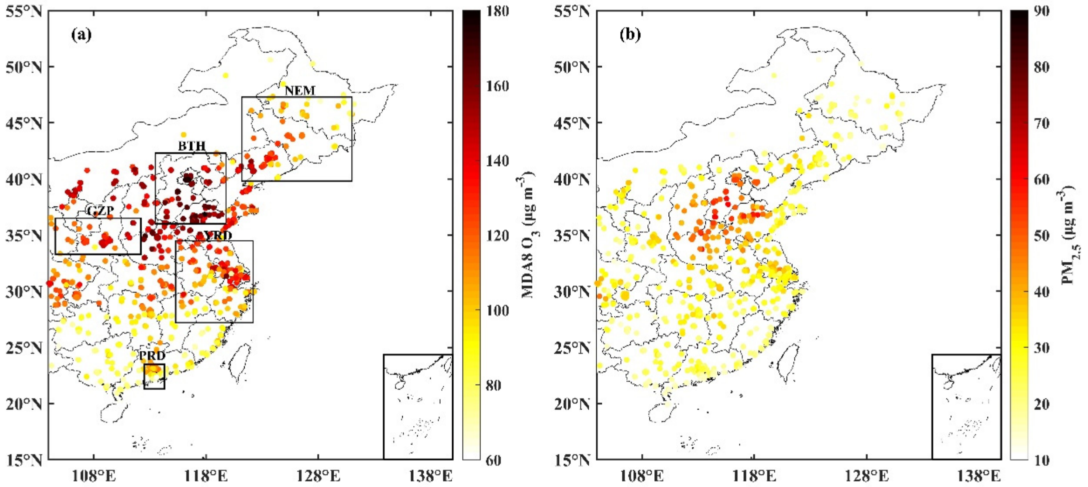

Fig. 1. Average concentration of MDA8 O_3 (a) and $PM_{2.5}$ (b) in eastern China during summers of 2015–2018. Stations and key urban clusters (black boxes) are shown in (a).

10. Line 207: Please show the temporal variations of co-occurring events.

RESPONSE: We have added the temporal variations of co-occurring events in Fig. 3. The asterisks indicate the co-occurred events under Chinese standard (WHO interim target 1, IT-1), and the circles indicate the co-occurred events under WHO IT-2 in Fig. 3. The specific description is "China has implemented strict policies for emission control, and the effects of these policies were remarkable. However, despite a decrease in $PM_{2.5}$ in the last five years, there was also an increase in ozone pollution over China (Fan et al., 2020; Sun et al., 2016), although "double-high" pollution reported on the weather scale has been decreased. As the limit of $PM_{2.5}$ concentration for pollution control is relatively loose in China, previous studies usually referred the interim target 1 (IT-1) of the World Health Organization (WHO) as the standard threshold. Our study pushed forward to the next stage, in which we used IT-2 of WHO (24-h average concentration of $PM_{2.5}$ is 35 μg m^{-3}) as our target limit to count the number of compound pollution days across each region. Based on this target, the pollution days for 4 SWPs were 194, 52, 16, 47, and 20, respectively (Fig. 3). These results indicated a severe situation of compound pollution that is still deserved a public attention."

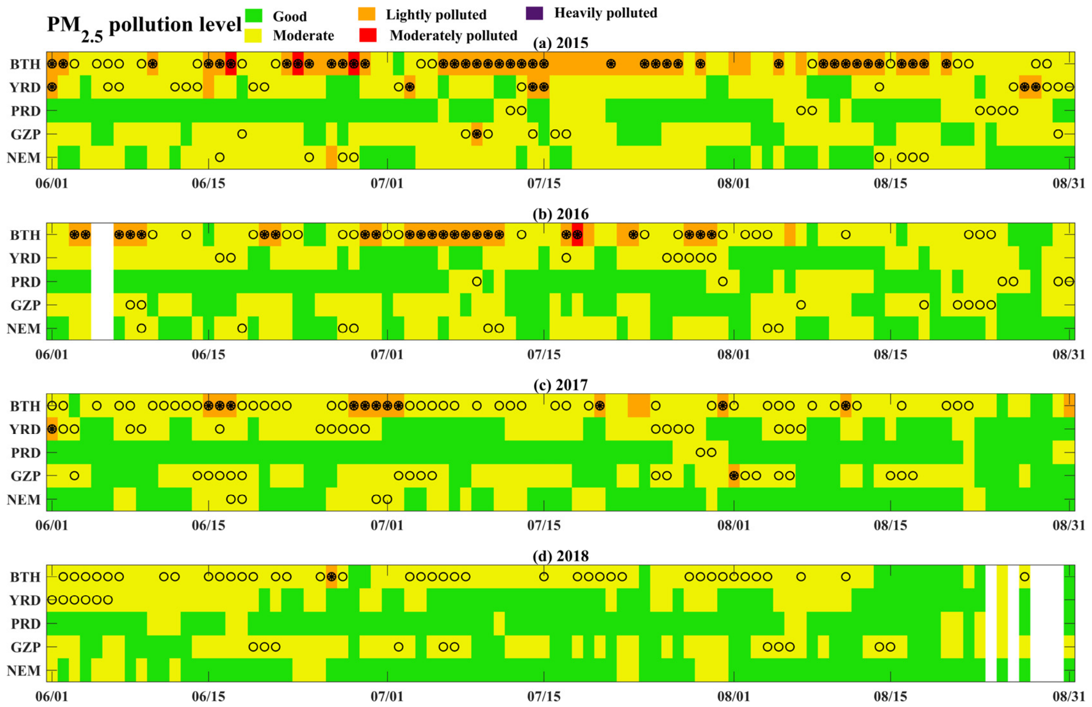

Fig.3. Time series of $PM_{2.5}$ pollution levels in key urban clusters, the black dots indicate the co-occurred events. The asterisks indicate the co-occurred events under Chinese standard (WHO interim target 1, IT-1), and the circles indicate the co-occurred events under WHO IT-2.

11. Line 229: Please focus on the position and strength of WPSH.

RESPONSE: The location of WPSH is shown on Table S2. Description regarding WPHS is now added to lines 266-285 of pages 10-11: "The location of western ridge point and northern boundary of the WPSH at 500 hPa in Type 1 is around 120°E and 30°N, respectively (Fig. 4a and Table S2). …… For Type 2, the westerly trough could deepen as the WPSH shifts northward slightly from Type 1 or retreats southeast from Type 3 (Fig. 4b). …… In compared with Type 2, Type 3 presents the boundary of WPSH in a higher latitude with a westward extension (Fig. 4c), disintegrating a closed high-pressure monomer along the eastern coast of China and the main body of the WPSH over the ocean (Figs. 4c and S4). …… Figure. 4d indicated that the location of WPSH monomer was more western and northern with respect with other SWPs, controlling the northern China for a long time; the western ridge point was around 95°E and the northern boundary was around 40°N.".

Table S2. The location index of the WPSH under four SWPs.

WPSH	Type 1	Type 2	Type 3	Type 4
The western ridge point	120°E	127.5°E	110°E	95°E
The northern boundary	30°N	32.5°N	37.5°N	40°N
The ridge axis	22°N	25°N	32.5°N	37.5°N

12. Line 229: It should be the north advance of WPSH.

RESPONSE: Yes, WPSH is slight shifting northward. We have now revised the content (lines

274-275 page 10).

13. Line 234: Type 1 and type 2 represents normal WPSH pattern during early and late summer, respectively. Type 3 and type4 reflects splitting of the WPSH, which mainly occurs in late summer.

RESPONSE: Thanks for your advice. Based on your suggestions, we have now added the following information to the revised manuscript: (lines 286-290): "The advance of the WPSH in eastern China occurs in June and July, while gradual withdrawal of the WPSH occurs mainly in August, Type 1 and Type 2 represent normal WPSH characteristics during early and late summer. Type 3 and Type 4 could reflect a split of the WPSH, which mainly occurs in late summer.".

14. Line 260: Type1 mainly occurs in June and it explains why the O3 concentration is higher.

RESPONSE: Yes.

15. Line 295: Please show the spatial distribution of the co-occurring surface O3 and PM2.5 pollution under each SWP.

RESPONSE: The spatial distributions of the co-occurring surface O_3 and $PM_{2.5}$ pollution under impacts of each SWP are shown in Fig.12.

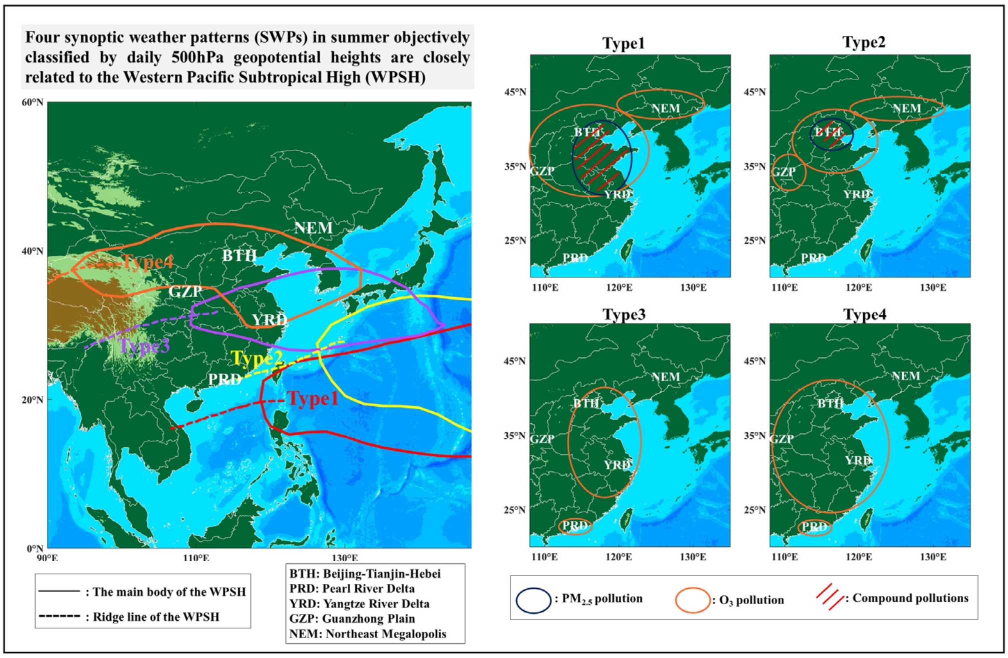

Fig. 12. Schematic diagrams describing the relationships between the WPSH, four SWPs and summertime O_3 and $PM_{2.5}$ pollution in various regions.

16. Line 300: Potential meteorological factors should be included in the results of this paper.

RESPONSE: Thanks for your suggestion. We have now moved the corresponding information to the "Result" section. Please refer to lines 347-376 on pages 13-14.

17. Line 305-310: This part should be mentioned in introduction.

RESPONSE: Thanks for the comment. We have moved this part to the introduction. Please

refer to lines 93-110 on pages 4-5.

18. Line 315-316: It is because the type 1 mainly occurs in early summer.
RESPONSE: We have added more information to describe the occurrence of type 1 in early summer (lines 363-364, page 13).

19. Line 365: Figure S6 shows probability of occurrence of compound pollution days under all four types. Please show the situation under type1.
RESPONSE: The situation under Type 1 and Type 2 are shown in Figure S10.

Figures and tables:
1. Figure 2 and 3: Please Mark the heavy polluted cases with dark color.
RESPONSE: Replotted.

2. Figure 4: Please draw the ridgeline of the subtropical high.
RESPONSE: Replotted.

3. Figure 8 and Figure 11: Please compare the difference of daily mean values. An introduction of daily variations makes things difficult to follow.
RESPONSE: Thanks for your kind suggestion. We have changed Fig. 8 to daily anomalies variation of O_3 and $PM_{2.5}$ under impacts of four SWPs over key urban clusters (Fig. 7). Additionally, original Fig. 8 has now been updated to Fig. S5 instead. Original Fig. 11 has now been the revised Fig. 10, with add average value adding to the revised figure.

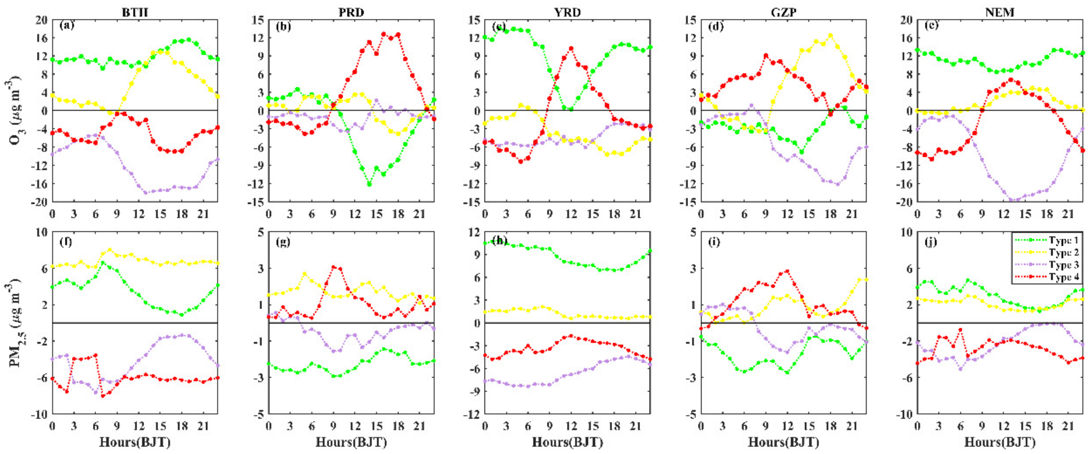

Fig. 7. Daily anomalies variation of O_3 and $PM_{2.5}$ under four SWPs in key urban clusters. The black solid line presents the averaged value of each urban cluster.