Response to Reviewer #2

Summary

This manuscript aims to analyze the dominant patterns of summer ozone over China in recent years, and associated circulations. While the topic is of importance to the field, the conclusions drawn from the study are not convincing to me.

1. The general patterns of ozone pollution and the association with meteorology have been reported in previous papers.

The authors need to clarify the novelty and scientific contribution of this study.

The methods in general lack novelty.

Reply:

The novelty of this study was sufficiently explained from three perspectives, listing as ***(1)-(3)***. Also, we revised the manuscript to present the novelty in a clearer way.

(1) In most of previous studies related to ozone pollution, the most popular topic was the relationship *meteorological elements* (e.g., temperature, precipitation, etc.) and O_3 concentrations in *single city*. These kind of studies **did not included the analysis of large-scale atmospheric circulations**, the diagnosis of **dominant patterns** and their **varying features**, and the **signals for interannual variability**.

Furthermore, in the Sect. 1 (Introduction), we referred a review article published in 2017 and point out "Wang et al. (2017) reviewed the meteorological influences on ozone events, **but the referenced findings were published mainly before 2010**, when measurements in China were still scarce."

These kind of studies was quite different from our submitted manuscript. The detailed novelty was illustrated in the following point (2).

(2) Actually, Zhao and Wang (2017) also talked about the dominant pattern of surface ozone and the impact of WPSH. Here, we emphatically explained the novelty of this study by the differences with Zhao and Wang (2017). That is, using the following **four sub-points**, we emphasized this novelty.

(2.1) We revealed **two dominant patterns, their varying sorts** in different years and their **associated anomalous atmospheric circulations.** Although the north-south differential pattern was the first mode in 2014 (Zhao and Wang 2017), 2015 and 2016, it was sorted in the second place in 2017 and 2018 (Figure S5 in the revised manuscript). That is, our study not only revealed the two dominant patterns, what is more important, also **showed the varying features of the dominant patterns.** In the recent two years, the most dominant pattern was different from that in previous years, which is **a new feature and might related to the climate status**. Additionally, the comprehensive atmospheric circulations were analyzed, including the **location** of west Pacific subtropical high (WPSH), the **East Asia deep trough** and other atmospheric anomalies. In Wang and Zhao (2017), they solely focused on the impacts of the WPSH, particularly on the **accumulative enhancement** of WPSH.

(2.2) We clearly explained the anomalous atmospheric circulations related the O_3 pollution **both in North China and in South China**. However, in Wang and Zhao (2017), the **physical mechanisms to impact O_3 in North China was still not sufficiently explained** (referring to the *weak correlation* coefficients in the ***green boxes*** in Figure R1 d–f). We speculated the reason for insufficient explanations on O_3 conditions in North China might be that the impacts form the mid-high latitudes were significant which was not involved in Zhao and Wang (2017). In our study, we found **both of the WPSH and the East Asia deep trough** had impacts on the O_3 concentrations in the east of China (Table 1). Furthermore, we **paid more attentions to the O_3 concentrations in North China** where the surface O_3 polluted levels were much higher than in the Yangtze River Delta and Pearl River Delta. The **WPSH and East Asia deep trough jointly modulated** the local meteorological conditions to influence the O_3 concentrations.

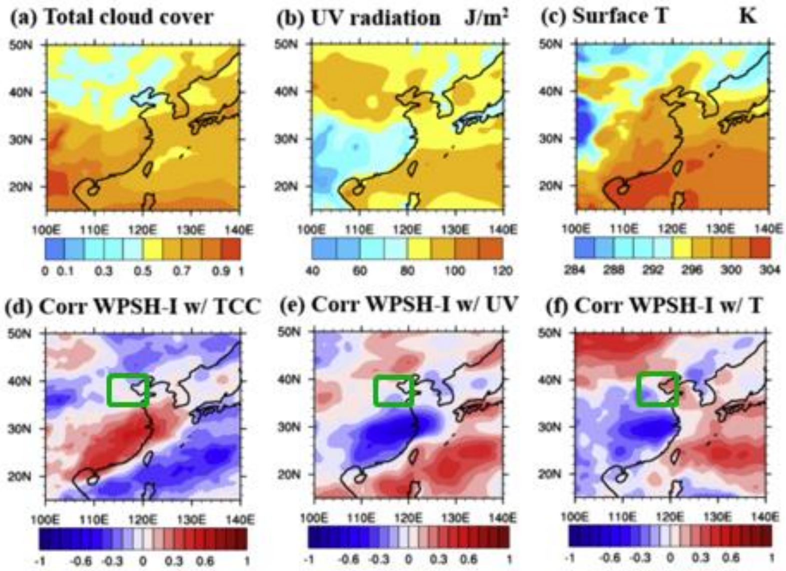

Fig. 6. (Upper panel) the summer mean fields of meteorological parameters and (lower panel) their correlations with the daily WPSH-I_anomalies: total cloud cover (a, d), downward UV radiation at the surface (b, e), and near-surface air temperature (c, f).

Figure R1. The Figure 6 in Zhao and Wang (2017). The summer mean fields of meteorological parameters (a–c) and their correlations with daily WPSH: total cloud cover (a, d), UV radiation (b, e) and near surface air temperature (c, f). The added green boxes indicate the location of North China.

Table 1. Correlation coefficients between the time series of PAT1 (PAT2) and the key indices of atmospheric circulations and meteorological conditions. "**" and "*" indicate that the correlation coefficients were above the 99% and 95% confidence level, respectively.

PAT1	**$MDA8_1$**	**EAT_1**	**$WPSH_1$**
	0.97^{**}	0.28^{**}	0.39^{**}
PAT2	**$MDA8_2$**	**EAT_2**	**$WPSH_2$**
	0.77^{**}	0.30^{**}	0.32^{**}

$MDA8_1$ is the NCH-area averaged MDA8, while the $MDA8_2$ is the MDA8 difference between NC and YRD. EAT_1 and EAT_2 indicate the intensity of the East Asia deep trough and were calculated as the mean –Z850, shown in the black boxes in Figure 7 and Figure 9, respectively. $WPSH_1$ ($Z500_{(125^0E,\ 20^0N)} - Z500_{(125^0E,\ 30^0N)}$) and $WPSH_2$ ($Z500_{(110^0E,\ 20^0N)} - Z500_{(110^0E,\ 30^0N)}$) represents the location of WPSH.

(2.3) The number and distribution of the sites are more sufficient and updated. In the EOF analysis of Zhao and Wang (2017), the number of O_3 sties was **only 191** in 2014 even in a larger study region than ours (Figure R2). The number (fewer than 200) and distributions (uneven) of the sites were limited, due to the establishment progress of the observation sites of atmospheric components in 2014.

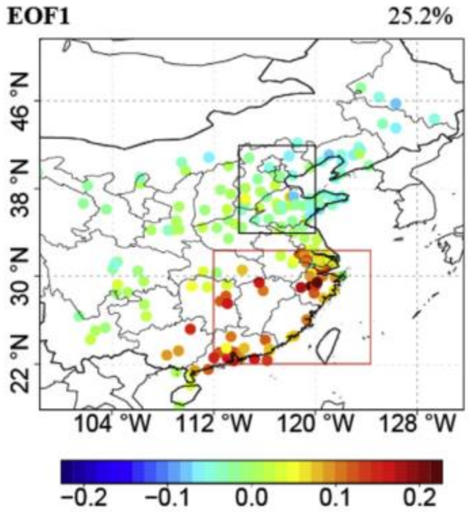

Fig. 3. The EOF1 of daily summer MDA8 ozone in 2014. The black rectangle outlines North China (NC); the red rectangle outlines South China (SC).

Figure R2. The Figure 3 in Zhao and Wang (2017), i.e., the EOF1 results in 2014 (also the sites distribution)

Since the severe air pollution events in 2013, the air pollution issues gained more attentions from the Chinese government and society, which aided to start the extensive constructions of operational monitoring stations of atmospheric components and resulted in continuous increasing number of sites (Figure S1). **The number of sites in eastern China (110ºE–125ºE, 22ºN–42ºN) was 677, 937, 937, 995 and 1007 from 2014 to 2018.** It is obvious that the data in 2014 were deficient, while the observations were broadly distributed in eastern China and continuously achieved since 2015. Thus, the summer O_3 data from 2015 to 2018 were processed (e.g., unifying the sites and eliminating the missing value) and ***868 sites in eastern China were employed here*** to reveal some new features of surface ozone pollutions and associated anomalous atmospheric circulations.

Although the number of sites in 2014 in our denser data source were nearly 4 times that in Zhao and Wang (2017), **the data in the green box in Figure S1 were almost a blank.** That is why our study period was 2015–2018. To make this point clear, we **added Figure S1**. From 2015 to 2018, the selected 868 sties relatively even. Certainly, the sites were almost located around the urban area, due to their observed purposes (related to air pollutions).

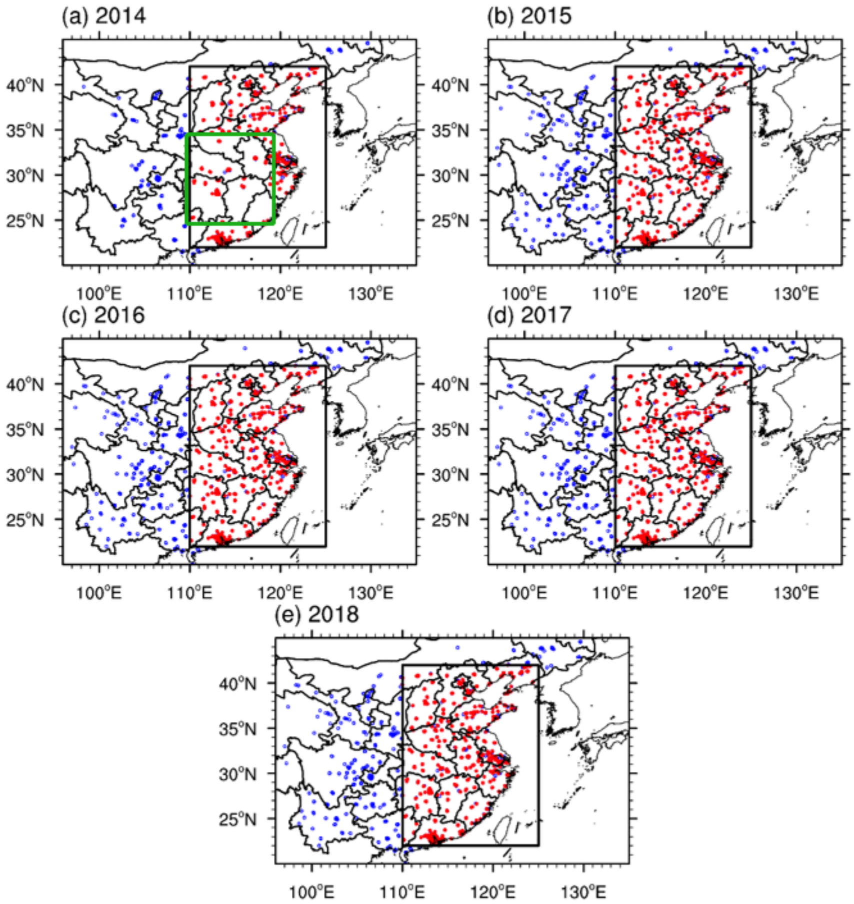

Figure S1. The distribution of measurement sites of atmospheric components (blue and red points) from 2014 to 2018. The red sites indicate the employed sites in this study related to O_3 pollution.

(2.4) In our study, we also discuss the **implications to interannual variability** in Sect 5, and pointed out that the **composites results from the daily data also provided useful signals for the interannual variability on the climate time-scale**. For example, the anomalous atmospheric patterns in 2016 were benefit for the occurrence of the north-south differential pattern of summer mean O_3 concentrations. Differently, the atmospheric circulations in 2018 resulted in positive O_3 anomalies in the whole eastern China.

The aforementioned four points, especially (1) (2) and (4), were **novel and we did not see similar researches so far**. Actually, there were some publications about the relationship meteorological elements (e.g., temperature, precipitation, etc.) and O_3 concentrations in single city, which provide basis for our study. **These kind of studies did not included the analysis of atmospheric circulations, the diagnosis of**

dominant patterns and their varying features, and the signals for interannual variability. As for the results in Zhao and Wang (2017), we clearly and convincingly discussed the differences between their and our studies. Furthermore, in the Sect. 1 (Introduction), we referred a review article published in 2017 and point out "**Wang et al. (2017) reviewed the meteorological influences on ozone events, but the referenced findings were published mainly before 2010,** when measurements in China were still scarce."

(3) The methods in this study were mainly the empirical orthogonal function (EOF) analysis and the composite approach, which were widely and classically used in the meteorology, even in the recent years. In addition to the approach, **the data sources and the conclusions were latest and novel**.

Related references:

Wang, T., Xue, L. K., Brimblecombe, P., Lam, Y. F., Li, L., Zhang, L.: Ozone pollution in China: A review of concentrations, meteorological influences, chemical precursors, and effects, Science of The Total Environment, 575, 1582-1596, doi:10.1016/j.scitotenv.2016.10.081, 2017.

Zhao, Z. J., Wang, Y. X.: Influence of the west pacific subtropical high on surface ozone daily variability in summertime over eastern china, Atmospheric Environment, 170, 197–204, https://doi.org/10.1016/j.atmosenv.2017.09.024, 2017.

Revision:

In the last paragraph of Introduction:

……Basing on a case study in 2014, further studies showed that a strong west Pacific subtropical high (WPSH) was unfavourable for the formation of O_3 in South China (Zhao and Wang, 2017), **however the physical mechanisms to impact O_3 in North China was still not sufficiently explained**.

Wang et al. (2017) reviewed the meteorological influences on ozone events, but the referenced findings were published mainly before 2010, when measurements in China were still scarce. Since 2015, O_3 measurements in eastern China were steadily and widely implemented, but the O_3-weather studies mainly focused on

meteorological elements (e.g. temperature, precipitation etc.) and **several synoptic processes** (Xu et al., 2017; Xiao et al., 2018; Pu et al., 2013). The dominant patterns of daily ozone in summer in east of China are still unclear. **Actually, in our study, we found the most dominant pattern was different with that in Zhao and Wang (2017) and the dominant patterns also showed interannual variations.** The findings of this study basically help to understand the varying features of surface ozone pollution in eastern China, their relationships with large-scale atmospheric circulations and the implications for the climate variability……

In the Datasets and methods:

……Nationwide hourly O_3 concentration data since May 2014 are publicly available on http://beijingair.sinaapp.com/. Since the severe air pollution events in 2013, the air pollution issues gained more attentions from the Chinese government and society, which aided to start the extensive constructions of operational monitoring stations of atmospheric components and resulted in continuous increasing number of sites (Figure S1). The number of sites in eastern China (110°E–125°E, 22°N–42°N) was 677, 937, 937, 995 and 1007 from 2014 to 2018. It is obvious that the data in 2014 were deficient, while the observations were broadly distributed in eastern China and continuously achieved since 2015. Thus, the summer O_3 data from 2015 to 2018 were processed (e.g., unifying the sites and eliminating the missing value) and 868 sites in eastern China were employed here to reveal some new features of surface ozone pollutions and associated anomalous atmospheric circulations……

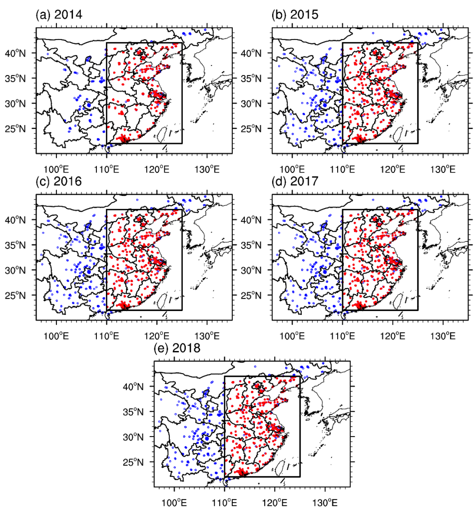

Figure S1. The distribution of measurement sites of atmospheric components (blue and red points) from 2014 to 2018. The red sites indicate the employed sites in this study related to O_3 pollution.

2. The presentation of this paper is also confusing. I had a hard time following the manuscript. The authors presented 14 figures, but most of them are quite confusing without clear explanations. There are a number of issues that should be addressed in order to make this paper suitable for publication. I have the following major comments and some minor comments.

Overall, the language of the manuscript should be further polished. There are several grammatical errors, which should be edited carefully.

Reply:

(1) Many apologies for the confusing writing. In the revised version, we almost rewrite the texts and decrease the number of Figures from 14 to 11. Some necessary information, e.g., the distribution of sites and cities, were added in the supplementary. An important Figure S2 was moved to the main texts as Figure 8.

(2) Most of the Figures were replotted to show the information in a clearer way.

(3) The incorrect figure references and statements were revised throughout the manuscript.

(4) The English were improved by the native English-speaker.

Major Comments:

1. (1) The spatial and temporal patterns of ozone could also be driven by anthropogenic emissions. The manuscript gave me an impression that ozone pattern in China is purely driven by circulation, which is not true. It's possible that the North-South pattern is mainly driven by emission variations.

(3) Also, the inter-annual variability in ozone may also be related to the emission changes in past years. The authors need to discuss how emission variations would affect their analysis.

Reply:

There was no doubt that the ozone pollutions closely related to the anthropogenic emissions. **In the old version of manuscript**, we presented it as "Due to their **close relationship with anthropogenic emissions** (Li et al., 2018), the high O_3 concentrations in China are mainly observed in urban regions" and "Surface O_3 pollution was **closely linked to the anthropogenic emission**s that dispersed and concentrated in the large cities".

In the beginning of the second paragraph in Introduction, we directly pointed out "Although deep stratospheric intrusions may elevate surface ozone levels (Lin et al., 2015), **the main source of surface ozone is the photochemical reactions between the oxides of nitrogen (NO_x) and volatile organic compounds (VOC), i.e., NO_x + VOC = O_3.** The concentrations of NO_x and VOC are fundamental drivers impacting ozone production, and are sensitive to the regime of ozone formation, i.e., NO_x-limited or VOC-limited (Jin and Holloway 2015). The changes in fine particulate matter are also a pervasive factor for the variation in ozone concentration."

In the revised version, we enhanced the discussion about the relative impacts of the human activities and the atmospheric circulation **in the following three points**.

(1) The main point of Section 3 is to **find the first two dominant patterns** of ozone concentration and the **varying features** of these patterns.

The main point of Section 4 is to **show the anomalous atmospheric circulation which *resulted in fluctuation of MDA8 on the basis of the existing distribution patterns***, which is evidently different from "The spatial and temporal patterns is purely driven by circulation".

To summarize, what we concerned is the MDA8 anomalies ***on the basis of the existing distribution patterns.***

(2) In eastern China, the economic productions and human actives steadily developed in the recent four years and the emissions of ozone precursors were reasonably supposed to be relatively stable **on the daily time-scale.** Surely, the stability of the emissions is relative and the data of daily emission cannot be obtained. Thus, in the numerical models of atmospheric chemistry, the **emission inventory was monthly or yearly updated**.

(3) As regards the inter-annual time scale, the impacts of anthropogenic emission played **more important roles** on the variations in MDA8 anomalies. The summer mean atmospheric circulation anomalies meant that the daily atmosphere more frequently and more strongly remained in a condition which is similar with the anomalous atmospheric circulations in summer. Thus, the summer mean atmospheric circulations partially modulated the levels of the ozone pollutions, i.e., resulting in fluctuations, rather than changed the basic situations.

In Lu et al., (2019), they explored the contributions to 2016–2017 surface ozone pollution over China and found that "the 2017 ozone increases relative to 2016 are **largely due to higher background ozone driven by hotter and drier weather conditions,** while changes in domestic anthropogenic emissions alone would have led to ozone decreases in 2017". Thus, *even on the interannual time-scale, the impacts of meteorological conditions were still significant*.

Reference: Lu, X., Zhang, L., Chen, Y., Zhou, M., Zheng, B., Li, K., Liu, Y., Lin, J., Fu, T.-M., and Zhang, Q.: Exploring 2016–2017 surface ozone pollution over China: source contributions and meteorological influences, Atmos. Chem. Phys., 19, 8339–8361, 2019

To clearly state, we supplemented some presentations in the first paragraph of section 4 and the third paragraph in the "6. Conclusions and discussions", which were copied as follows:

Revision in the first paragraph of Section 4:

……In eastern China, the economic productions and human actives steadily developed in the recent four years and the emissions of ozone precursors were reasonably supposed to be relatively stable on the daily time-scale. Differently, the daily variations in MDA8 were evidently saw in Figure 2. Therefore, the impacts of daily meteorological conditions significantly contributed to the domain patterns of daily O_3 concentrations and their variations……

Revision in the third paragraph of Section 6:

……In this study, we mainly emphasized the contribution of the meteorological impacts and assumed the emissions of ozone precursors were relatively stable on the daily time-scale. There is no doubt that the human activities were the fundamental driver of air pollution even on the daily time-scale. However, the daily emission data were difficult to be acquired, thus the joint effects of the daily meteorological conditions and anthropogenic emissions needed to be discussed in future work……

2. The authors use ground-based observations of ozone describe the general patterns of ozone, but the distribution of ground-based sites is uneven. Most sites in China are urban sites, and there are few rural sites. There is no information how the authors infer spatial distribution of ozone (i.e. Figure 1) from limited sites.

Reply:

(1) **The number of sites in eastern China (110ºE–125ºE, 22ºN–42ºN) was 677, 937, 937, 995 and 1007 from 2014 to 2018.** The summer O_3 data from 2015 to 2018 were processed (e.g., unifying the sites and eliminating the missing value) and ***868 sites in eastern China were employed here*** to reveal some new features of surface ozone pollutions and associated anomalous atmospheric circulations.

The aforementioned observations were the densest ozone data source in China. The distribution of the ozone observed sites was supplemented as Figure S1.

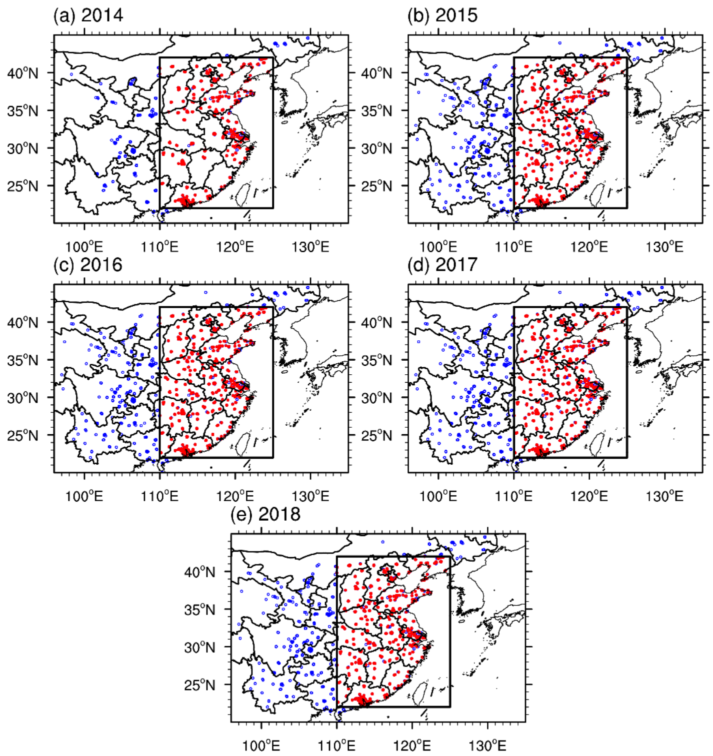

Figure S1. The distribution of measurement sites of atmospheric components (blue and red points) from 2014 to 2018. The red sites indicate the employed sites in this study related to O_3 pollution. The black box was the region of eastern China.

(2) Due to their observed purposes (related to air pollutions), the sites monitoring atmospheric components were **almost located around the urban area**. In the revised version, we pointed out that "**the results of this study were more suitable to the urban O_3 pollution**".

(3) In the former version, to show the spatial distributions, the data of ground-based sites were interpolated using **iterative correction type objective analysis**. Now, to avoid confusions, we **directly show the sited values** in Figure 1, 3, 4,

7 and other Figures in the supplementary, instead of interpolation.

For example, in the revised Figure 1, the numerical values were **not interpolated**, and the features were still clear. That is, the O_3-polluted sites were located closely to each other. Although, the distributions of the sites were somewhat uneven, the conclusions on the contiguous features were substantially influenced. Detailed explanations were added to make this point clear.

Revision:

(1) In the Figure 1, 3, 4 and 7:

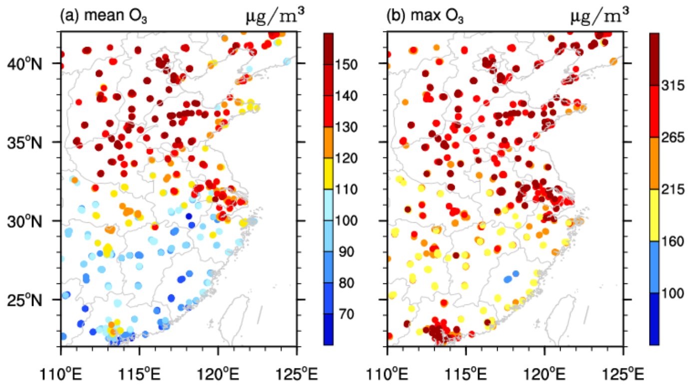

Figure 1. Distribution of the (a) mean values and (b) maximum values of MDA8 (Unit: μg/m³) at the observation sites in summer from 2015 to 2018.

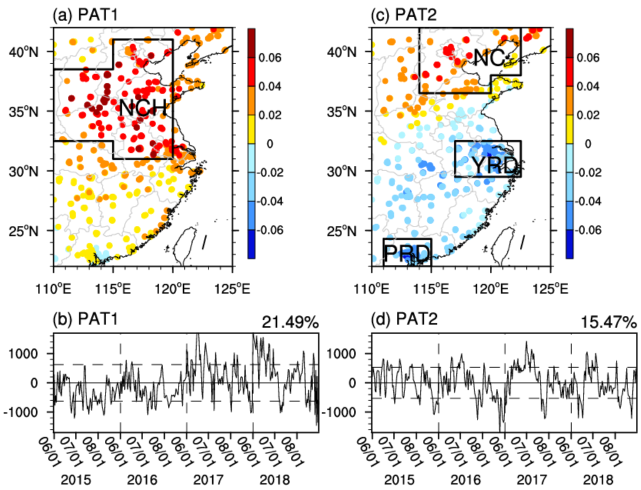

Figure 3. The first EOF pattern (PAT1: a, b) and second EOF pattern (PAT2: c, d) of MDA8 in summer from 2015 to 2018, including the spatial pattern (a, c) and the time coefficient (b, d). The black boxes in panels a and c are the selected North China and Huanghuai region (NCH), North China (NC) Yangtze River Delta (YRD) and Pearl River Delta (PRD). The EOF analysis were applied to the daily MDA8 anomalies at 868 stations to extract the relatively change features of the original data on the daily time-scale. The percentages on panel b and d were the variance contributions of the first and second EOF mode.

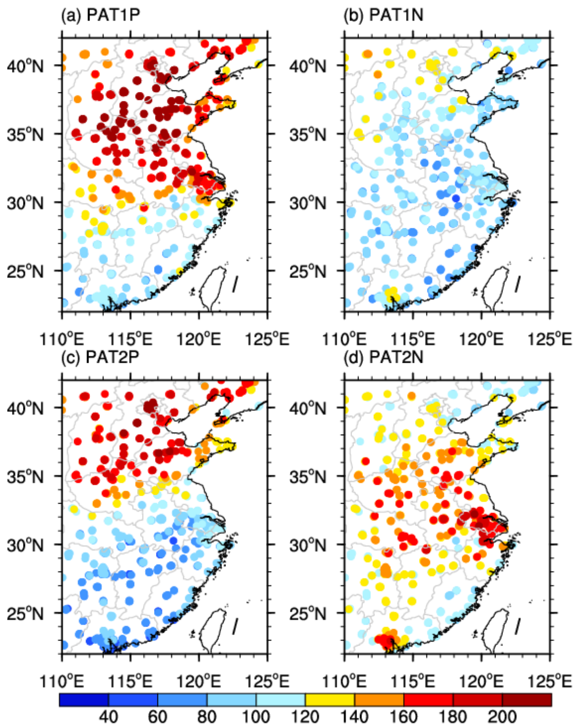

Figure 4. Composites of the MDA8 (Unit: μg/m³) for PAT1 (a, b) and PAT2 (c, d) in summer from 2015 to 2018. Panels a and c were composited when the time coefficient of EOF1 and EOF2 was greater than one standard deviation, while panels b and d were when the time coefficient was less than －1×one standard deviation.

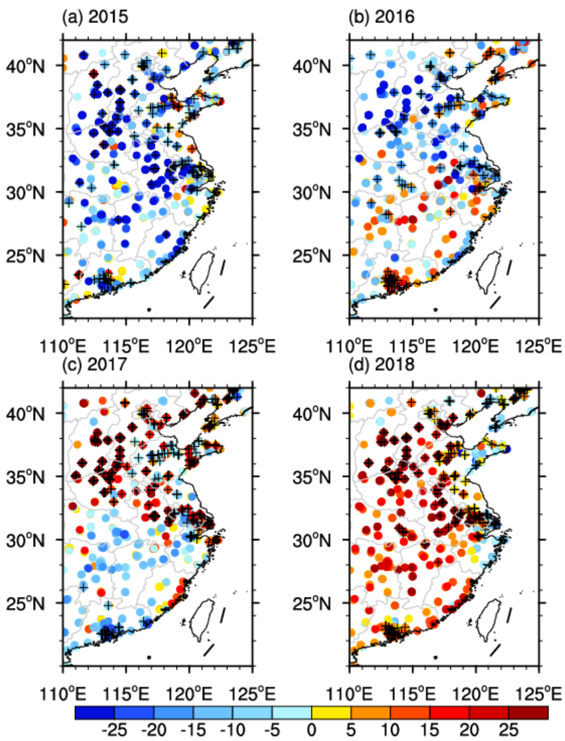

Figure 7. Anomalies in the summer mean MDA8 (Unit: μg/m³) in 2015 (a), 2016 (b), 2017 (c) and 2018(d), relative to the mean during 2015–2018. The black pluses indicate indicate that the maximum MDA8 was larger than 265 μg/m³.

(2) In the Datasets and methods:

……Nationwide hourly O_3 concentration data since May 2014 are publicly available on http://beijingair.sinaapp.com/. Since the severe air pollution events in 2013, the air pollution issues gained more attentions from the Chinese government and society, which aided to start the extensive constructions of operational monitoring stations of atmospheric components and resulted in continuous increasing number of sites (Figure S1). The number of sites in eastern China (110°E–125°E, 22°N–42°N) was 677, 937, 937, 995 and 1007 from 2014 to 2018. It is obvious that the data in 2014 were deficient, while the observations were broadly distributed in eastern China and continuously achieved since 2015. Thus, the summer O_3 data from 2015 to 2018 were processed (e.g., unifying the sites and eliminating the missing value) and 868 sites in eastern China were employed here to reveal some new features of surface ozone pollutions and associated anomalous atmospheric circulations……

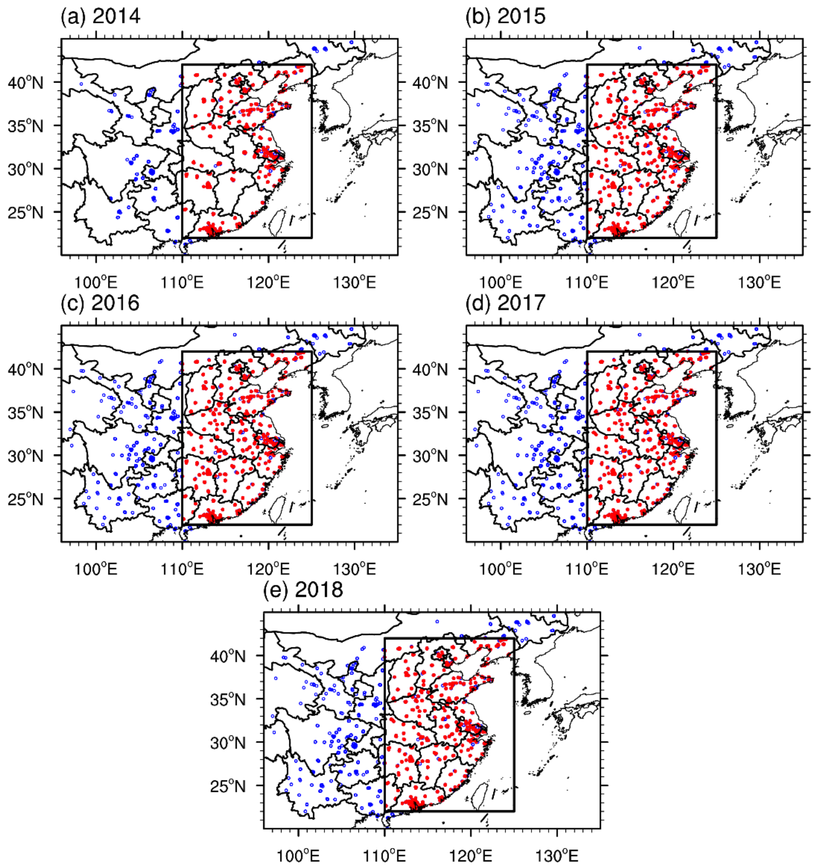

Figure S1. The distribution of measurement sites of atmospheric components (blue and red points) from 2014 to 2018. The red sites indicate the employed sites in this study related to O_3 pollution.

3. The study relies on EOF analysis, but there is almost no explanations of how the EOFs are constructed, and why the first two patterns are indicative of the dominant patterns of ozone pollution. Only 37% variance can be explained with the first two EOFs (∽20% for the first EOF), which is even less than half. I think it's necessary to explain the limitation of this statistical approach.

Reply:

(1) The EOF approach was introduced in the third paragraph of Section 2, which could be found in the revised presentations. The EOF analysis is a widely used statistical method in meteorology to **reconstruct the original variables into several irrelevant patterns** (Wilks, 2011). The EOF analysis, applied to the daily anomalies (MDA8 anomalies at 868 stations in this study), **extracted the relatively change features of the original data on the daily time-scale**. The orthogonal modes included spatial and temporal coefficients, and contained information of some proportion (variance contributions) from the original fields

(2) **Significance test** was supplemented following the test method form North et al., (1982). That is, if the eigenvalue (λ) satisfied the condition as $\lambda_i - \lambda_{i+1} \geq \lambda_i (2/n)^{1/2}$, the eigenvalue λ_i was significantly separated. We performed this significance test on the selected patterns from EOF decompositions, and **confirmed that these dominant patterns in this study were all significant.** Thus, the first two pattern were significantly separated and are indicative of the dominant patterns of ozone pollution.

(3) As regards the contribution variance, we also **performed similar EOF analysis on the surface air temperature and precipitation** (Figure R3, R4). The first contribution variance of temperature (52.3%) was big, indicating uniform change. However, the first contribution variance of **precipitation was only 10.4%**, which is even smaller than that of ozone concentrations. Thus, we believe that the contribution variance of the first EOF modes of MDA8 (21.5% and 15.5%) **were enough to determine the dominant patterns, whether basing on the significance test or the above-mentioned comparison.**

As expected, the variance contributions here were not as large as surface air temperature in eastern China. Possible reasons might related to the complexity of generative mechanism of surface O_3 and the urban property of the monitoring sites, which was not the topic of this study.

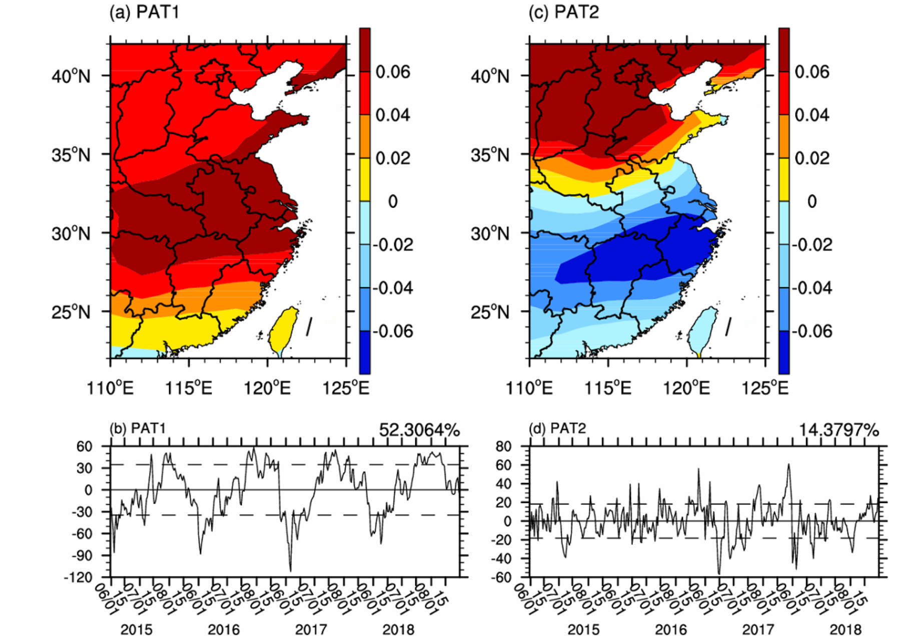

Figure R3. The first EOF pattern (a, b) and second EOF pattern (c, d) of surface air temperature in summer from 2015 to 2018, including the spatial pattern (a, c) and the time coefficient (b, d). The EOF analysis were applied to the daily temperature anomalies at 868 stations to extract the relatively change features of the original data on the daily time-scale. The percentages on panel b and d were the variance contributions of the first and second EOF mode.

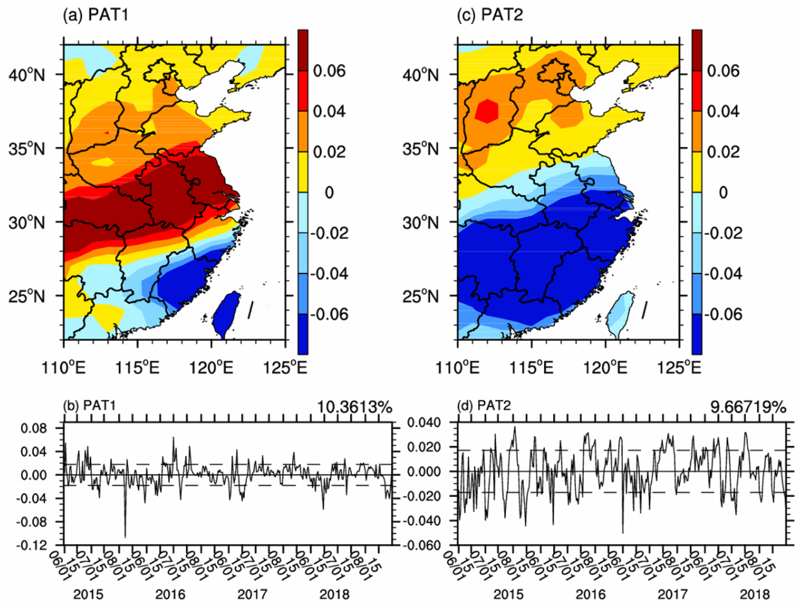

Figure R4. The first EOF pattern (a, b) and second EOF pattern (c, d) of **precipitation** in summer from 2015 to 2018, including the spatial pattern (a, c) and the time coefficient (b, d). The EOF analysis were applied to the daily precipitation anomalies at 868 stations to extract the relatively change features of the original data on the daily time-scale. The percentages on panel b and d were the variance contributions of the first and second EOF mode.

Revision:

The empirical orthogonal function (EOF) analysis is a widely used statistical method in meteorology to reconstruct the original variables into several irrelevant patterns (Wilks, 2011). The EOF analysis, applied to the daily anomalies (MDA8 anomalies at 868 stations in this study), extracted the relatively change features of the original data on the daily time-scale. The orthogonal modes included spatial and temporal coefficients, and contained information of some proportion (variance contributions) from the original fields. Significance test must be execute to confirm whether the decomposed patterns had physical meanings. In this study, we used the test method form North et al., (1982). That is, if the eigenvalue (λ) satisfied the condition as $\lambda_i - \lambda_{i+1} \geq \lambda_i (2/n)^{1/2}$, the eigenvalue λ_i was significantly separated. We performed this significance test on the selected patterns from EOF decompositions, and confirmed that these dominant patterns in this study were all significant. The aforementioned EOF analysis programs were finished by the NCAR Command Language.

4. (1) The authors included a lot of figures, but some seem to be redundant. For example, Figures 2 and 3 seem to be repetitive. Most of the figures are not very clear, yet the authors only spend one or two sentences explaining these figures.
(2) None of these figures is labeled clearly. There is even no unit for the numbers presented, which is unacceptable to me.
(3) I'd recommend the authors only keep those most important figures (e.g Figures 7 and 8), and expand their discussions on these figures.

Reply:

(1) In the revised version, we almost rewrite the texts and decrease the number of Figures from 14 to 11. Some necessary information, e.g., the distribution of sites and cities, were added in the supplementary. An important Figure S2 was moved to the main texts as Figure 8.

(2) Most of the Figures were replotted to show the information in a clearer way.

(3) The incorrect figure references and statements were revised throughout the manuscript. The units were added throughout the manuscript.

Minor Comments:

1. **Line 70: It’s not clear what 'sub-daily' means here. If it’s four-hour data, which composites did you select?**

   Reply:

It is **6-hourly** for the Z, wind, relative humidity, vertical velocity, air temperature and cloud cover, while **3-hourly** for the precipitation and downward solar radiation. We directly downloaded the 6-hourly data form the ECWMF website. Due to different representative period of each element, thus we performed distinguishing composites. The 'time' and 'steps' of ERA-Interim can be found on the website of https://confluence.ecmwf.int/pages/viewpage.action?pageId=56658233.

Finally, the daytime atmospheric circulations are the geopotential height, wind, air pressure, cloud cover and relative humidity from 05 a.m. to 05 p.m (Beijing Time)., and the precipitation and downward solar radiation from 08 a.m. to 08 p.m. (Beijing Time).

Revision:

…… the daytime data were calculated by the **6-hourly reanalysis** (including Z, wind, relative humidity, vertical velocity, air temperature and cloud cover) and **3-hourly reanalysis** (precipitation and downward solar radiation) to composite the daytime atmospheric circulations and daytime meteorological conditions. Due to the different representative period of each element in ERA-Interim data, the daytime for Z, wind, relative humidity, vertical velocity, air temperature and cloud cover was from *05 a.m. to 05 p.m (Beijing Time; 21 p.m.–09 a. m. UTC), while it is from 08 a.m. to 08 p.m. (Beijing Time; 00 a.m. to 00 p.m. UTC) f*or precipitation and downward solar radiation……

2. **Please double check the subscripts and superscripts of units and chemical names.**

Reply:

The subscripts and superscripts were checked throughout the manuscript, and the errors were corrected.

Revision:

The O_3 pollution levels in Beijing-Tianjin-Hebei (part of NC) were the most severe in China (Wang et al., 2006; Shi et al., 2015) and this situation has been getting worse. The O_3 concentrations in North China underwent a significant increase in the period of 2005–2015, with an average rate of 1.13±0.01 ppbv yr^{-1} (Ma et al., 2016). Even on the highest mountain over NC, Mount Tai, summer (June-July-August, JJA) O_3 increased significantly by 2.1 ppbv yr^{-1} (Sun et al., 2016). The O_3 levels generally presented increasing trends from 2012 to 2015 in the YRD (Tong et al., 2017), e.g., the O_3 concentrations in Shanghai (a mega-city) increased by 67% from 2006 to 2015 (Gao et al., 2017). In the PRD region, O_3 increased by 0.86 ppbv yr^{-1} from 2006 to 2011 (Li et al., 2014). Severe ozone pollution is projected to increase in the future over eastern China (Wang et al.,

3. Variations and dominant patterns

During 2015–2018, summer surface ozone pollution was severe in China, especially in the economically developed regions. Spatially, the JJA mean MDA8 increased from south to north in eastern China (Figure 1a). To the south of 28°N (i.e., South China), the mean MDA8 was mostly lower than 100 μg/m³ and the ozone pollution was obviously lower than that in North China and in the Huanghuai area (NCH). It is notable that, although the values of MDA8 in the PRD were not as large as those in NCH, they were relatively higher than those in the surrounding areas. The mean MDA8 was above 110 μg/m³ to the north of 32°N (i.e., the NCH area), and thereinto, the large values of MDA8 centred on the Beijing-Tianjin-Hebei region and in western Shandong province exceeded 150 μg/m³. In the transitional zone, i.e., between 28°N and 32°N, the MDA8 varied from

3. Lines 95 - 100: How did you calculate ozone levels in each province? Are the ground-based measurements spatially representative?

Reply:

In the O_3 datasets, there is an attribute indicating the subordinate city, thus we can calculate the ozone levels of certain geographic position.

4. Line 125: How did you compose atmospheric circulations? This is an important step, but there is almost no explanation of the method.

Reply:

In the revised version, the composite steps were detailedly introduced in the first paragraph of Section 4. For convenience, an example was given.

Revision:

……Anomalous daytime atmospheric circulations associated with PAT1 (**PAT1P composite minus PAT1N composite**) and PAT2 (PAT2P composite minus PAT2N composite) were shown Figure 5–6. **For example,** the mean of the atmospheric circulations associated PAT1P (PAT1N) were firstly computed, and then the differences between PAT1P composites and PAT1N composites were calculated as the anomalous daytime atmospheric circulations associated with PAT1……

5. Line 189: 2105 -> 2015

Reply:

These errors were corrected.

Revision:

……The MDA8 anomalies in 2016 were negative in NC, but positive in the YRD and PRD (**Figure 7b**), which was the opposite pattern of PAT2. The interannual anomalies of atmospheric circulations in 2016, **with respect to the mean of 2015–2018** (Figure 10)……

6. Line 200: The conclusion that atmospheric circulation accelerated ozone formation in YRD but weaken in NC is interesting, but this does not agree with ground-based observations, which do not show any enhancement of ozone in YRD in 2016 (nor decreased ozone in NC, Figure 6).

Reply:

According to the comment "too much Figures", the old Figure 6 and the one related sentence was deleted, as no new information were shown.

The "increasing in YRD" and "decrease in NC" was **with respect to the mean status during 2015–2018.** Although the old Figure 6 was deleted, the same information could also be read from the Figure 7b. It is evident there were negative anomalies in the NC region. In the YRD region, particularly in the south of YRD, positive anomalies occurred.

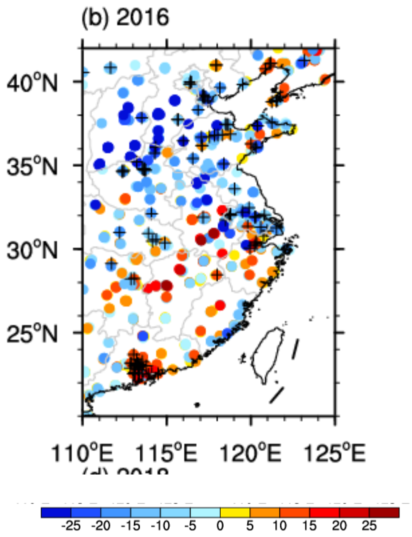

Figure 7. Anomalies in the summer mean MDA8 (Unit: μg/m³) in 2015 (a), 2016 (b), 2017 (c) and 2018(d), ***relative to the mean during 2015–2018.*** The black pluses indicate indicate that the maximum MDA8 was larger than 265 μg/m³.

7. Line 205 - 201: The figure numbers are wrong?

Reply:

The incorrect figure references and statements were revised throughout the manuscript. The units were added throughout the manuscript.

Revision:

The MDA8 anomalies were mostly positive in the east of China in 2018 (Figure ~~10~~7d). "–+–" pattern of Z850 anomalies were located over the Ural Mountains and to the north of Lake Baikal and the Aleutian Islands (Figure 1~~2~~1a), which was consistent with the anomalous patterns in Figure ~~7~~5. The East Asia deep trough shifted northward than the mean status during 2015–2018, and meanwhile, the western ridge point of WPSH also shifted northward, resulting in a higher SAT in the east of China and accelerating the photochemical conversion for elevating the surface ozone concentration. The local anomalous anti-cyclone over the NCH and the Japan Sea also existed in the interannual signals, which induced the divergence of water vapor in southeast China (Figure 1~~2~~1b). Due to the lack of moisture, it was difficult for cloud cover to form, and more solar

8. Line 210: How did you draw the conclusion that positive MDA8 anomalies are observed in 2018? This conclusion seems to be inconuistunt with Figure 6.

Reply:

According to the comment "too much Figures", the old Figure 6 and the one related sentence was deleted, as no new information were shown.

The "positive anomalies in 2018" was **with respect to the mean status during 2015–2018.** Although the old Figure 6 was deleted, the same information could also be read from the Figure 7d. It is evident there were positive anomalies in the eastern China.

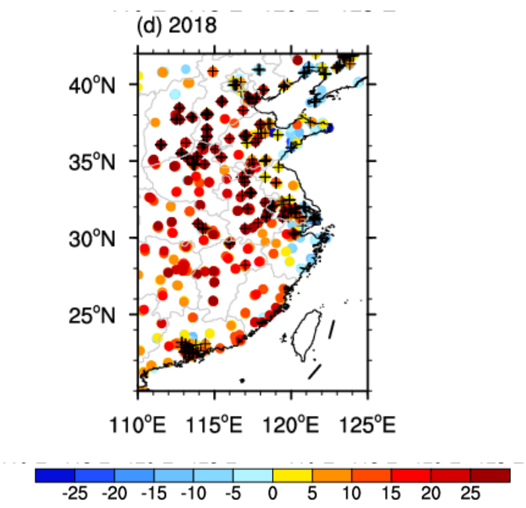

Figure 7. Anomalies in the summer mean MDA8 (Unit: μg/m³) in 2015 (a), 2016 (b), 2017 (c) and 2018(d), ***relative to the mean during 2015–2018.*** The black pluses indicate indicate that the maximum MDA8 was larger than 265 μg/m³.

9. Figure 1,7, 11: missing units.

Reply:

The units were added throughout the manuscript.

Revision:

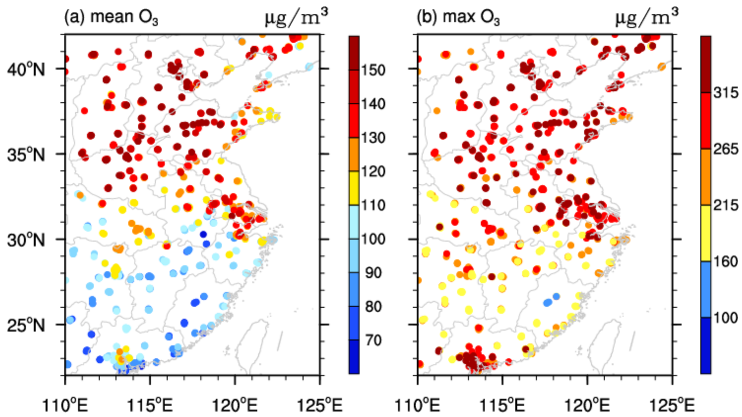

Figure 1. Distribution of the (a) mean values and (b) maximum values of MDA8 **(Unit: μg/m³)** at the observation sites in summer from 2015 to 2018.

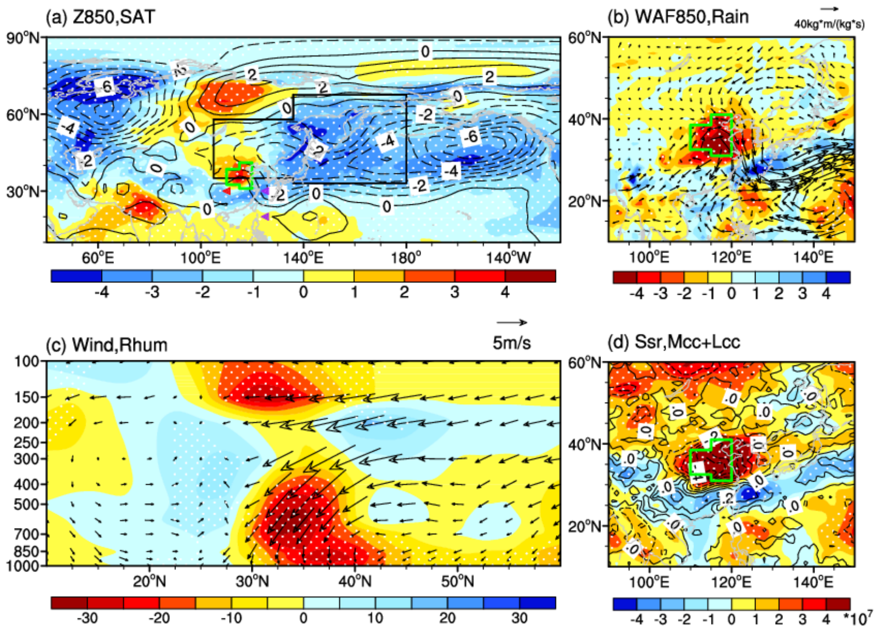

Figure 5. Differences of the daytime atmospheric circulations (i.e., PAT1P minus PAT1N). (a) Geopotential height at 850 hPa (Unit: 10gpm, contours) and surface air temperature (Unit: K, shading), (b) water vapor flux (Unit: kg*m/(kg*s)) at 850 hPa (arrows) and precipitation (Unit: mm, shading), (c) 100 °E–120 °E mean wind (Unit: m/s, arrows) and relative humidity (Unit: %, shading), (d) downward solar radiation at the surface (Unit:10^7 J/m^2, shading) and the sum of low and medium cloud cover (Unit: 1, contours). The white dots indicate that the shading was above the 95% confidence level. The green boxes in panels a, b and d show the NCH region, and the black box in panel a indicates the location of the East Asia trough. The purple triangles indicated the data used to calculate the $WPSH_1$, while the red triangle represented the west ridge point of WPSH.

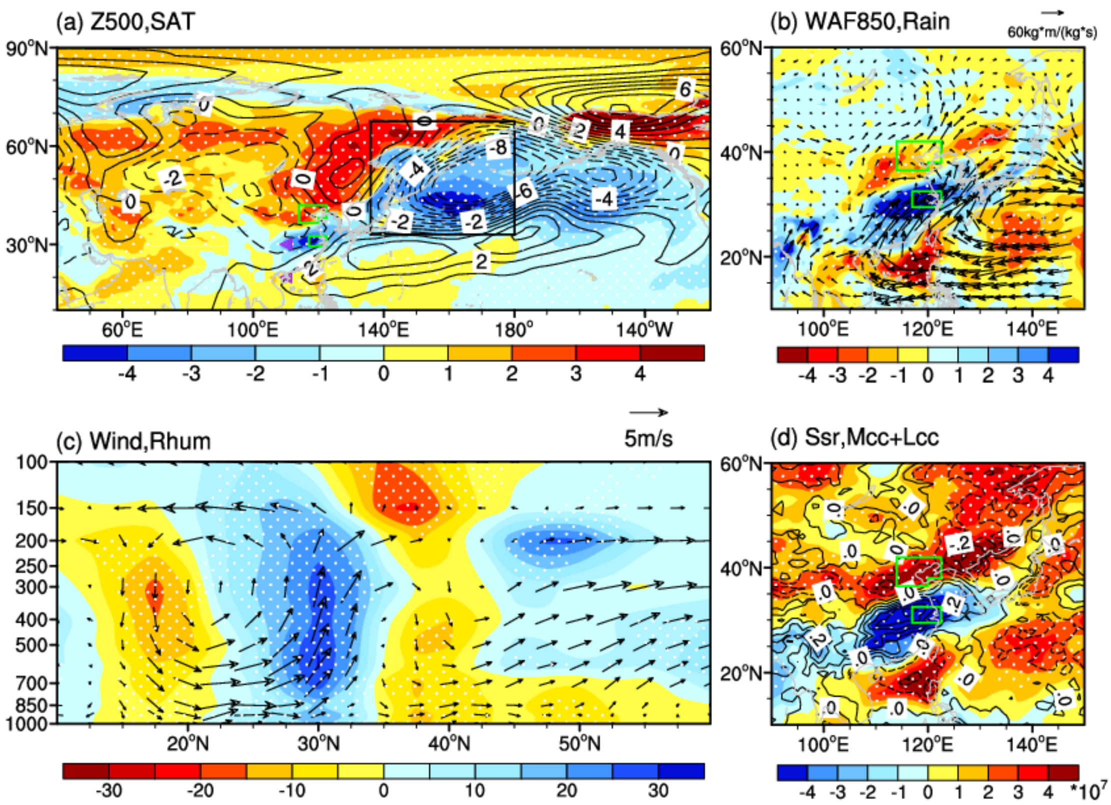

Figure 6. Differences of the daytime atmospheric circulations (i.e., PAT2P minus PAT2N). (a) Geopotential height at 500 hPa (Unit: 10gpm, contours) and surface air temperature (Unit: K, shading), (b) water vapor flux (Unit: kg*m/(kg*s)) at 850 hPa (arrows) and precipitation (Unit: mm, shading), (c) 100 °E–120 °E mean wind (Unit: m/s, arrows) and relative humidity (Unit: %, shading), (d) downward solar radiation at the surface (Unit: $10^7 J/m^2$, shading) and the sum of low and medium cloud cover (Unit: 1, contours). The white dots indicate that the shading was above the 95% confidence level. The green boxes in panel a, b and d are the NC and YRD regions, and the black box in panel a indicates the location of the East Asia trough. The purple triangles indicated the data used to calculate the $WPSH_2$.

10.Figures 2, 3, 8, 12: Missing y label.
Reply:

The y-label of Figure 2 and 9 was added.

The old Figure 8 and 12 presented the variations in standardized indices, thus there was no y-label. Because no new information was showed in these two Figures, the Figure 8 and 12 were deleted.

Revision:

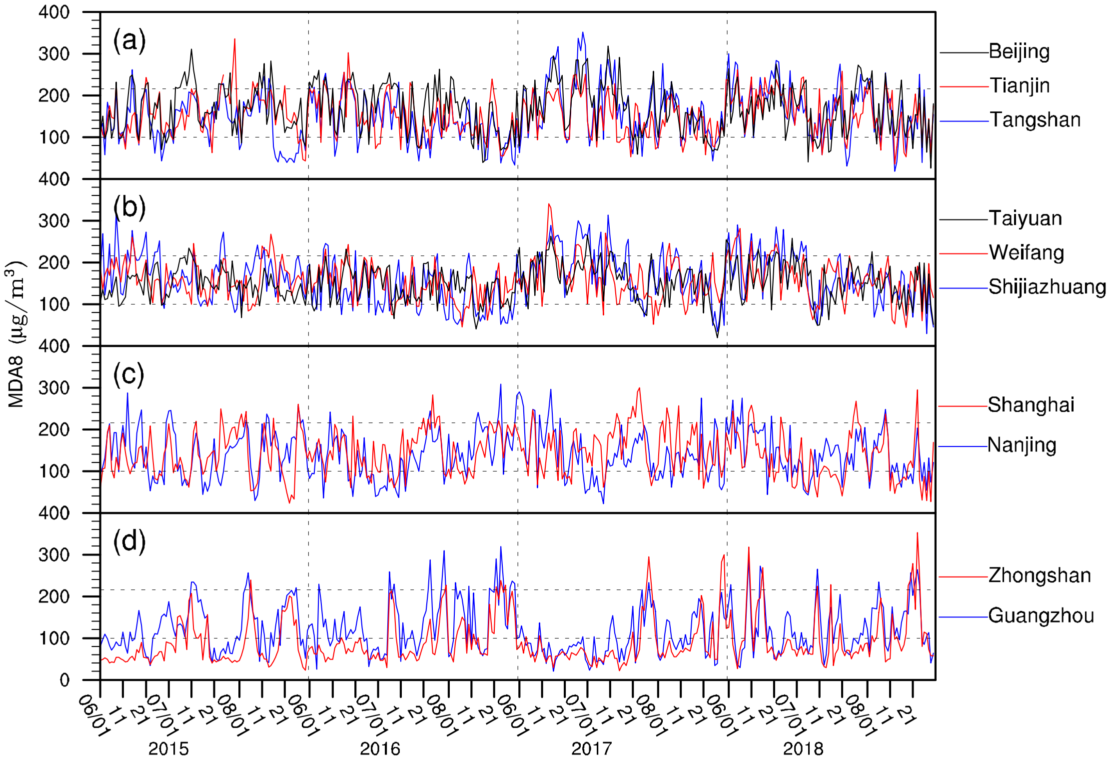

Figure 2. Variations in MDA8 (Unit: μg/m³) of polluted cities from 2015 to 2018, including (a) Beijing, Tianjin and Tangshan; (b) Taiyuan, Weifang and Shijiazhuang; (c) Shanghai and Nanjing; and (d) Zhongshan and Guangzhou. The cites in panels (a)-(d) were located from north to south. The horizontal dash lines indicated the value of 100 μg/m³ and 215 μg/m³.

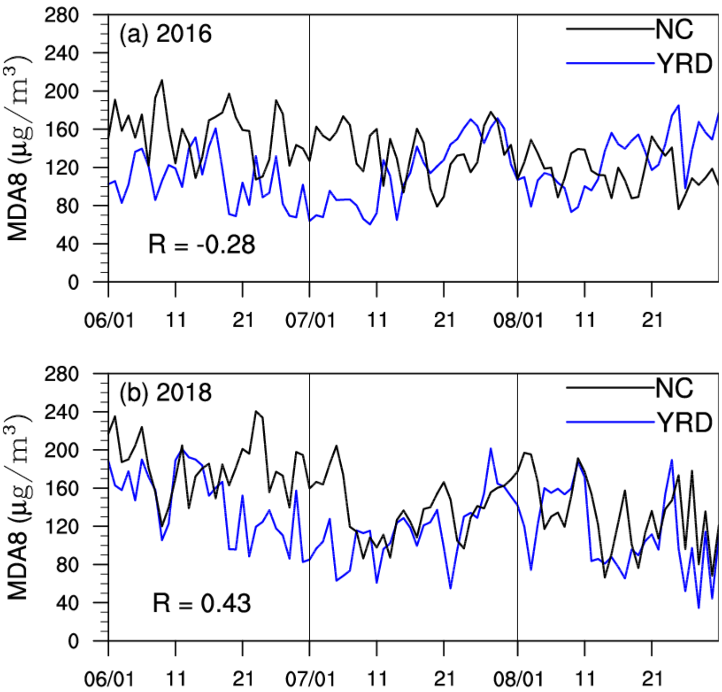

Figure 9. Variations in the MDA8 (Unit: μg/m³) of NC (black) and the YRD (blue) in 2016 (a) and 2018 (b).

11. Figure 4: The authors need to explain how they construct spatial and temporal EOFs, and what the figures show here. What do the numbers represent?

Reply:

This comments were closely **related to the Major comment 3**, thus the information was not repeated here.

In the Figure caption, we clarified the meaning of the percentage number.

Revision:

Figure 3. ……The EOF analysis were applied to the daily MDA8 anomalies at 868 stations to extract the relatively change features of the original data on the daily time-scale. The percentages on panel b and d were the v**ariance contributions of the first and second EOF mode**……

Figure 8….. The **percentages were the variance contributions** of the first and second EOF mode……

12. Figure 5: It's not clear why it is necessary to composite to positive and negative patterns. How does this help explain the results?

Reply:

By composite the MDA8 for PAT1 and PAT2, we can clearly see the meaning of the EOF analysis. The real MDA8 values for PAT1 and PAT2 showed more information than the extracted spatial coefficient of the EOF.

13. Line 202: Where is Figure 10d?

14. Figure 14 not referenced in the manuscript.

Reply:

Most of the Figures were replotted to show the information in a clearer way.

The incorrect figure references and statements were revised throughout the manuscript. The units were added throughout the manuscript.