Responses to the reviewer's comments point by point

We thank the reviewer for his/her comments, and we do think the comments and suggestions improved our manuscript considerably. Our point-by-point replies to the comments are given below. The replies are in blue font, the revisions in the revised manuscript and the responses with red font, and important statements are of bold.

Major comments:

1. Now that the grid of Era-interim is fine, thus why only 16-point grid were selected to classify the circulation. Furthermore, if there are some scientific considerations, the authors should clearly illustrate and connected to the O_3 pollution.

Reply:

Thanks for the comment. The description of the method was not sufficient, so we have added more details about the reason for using the Lamb-Jenkinson weather type scheme and the description of this method in the revised paper and Text S1 (lines 21-76 of supplementary material).

In synoptic climatology, along with subjective or manual approaches, objective or automated approaches are widely used synoptic weather typing procedures to identify recurring map patterns or variable groups that typify significant modes of circulation and to classify each case into one of these modes (Yarnal, 1993; Huth et al., 2008). There are many objective methods, such as correlation-based map-pattern technique, sums-of-squares method, rotated principal component analysis, hierarchical clustering (average linkage or Ward's clustering), and K-means clustering. As suggested by Yarnal (1993) and Huth (1996), all the methods proved to be capable of yielding meaningful classifications and none of them can be thought of as the best in all aspects. Which method to use will depend mainly on the aim of the classification. Notably, the final number of synoptic types using these algorithms is associated with a given period and region, statistical algorithms, prior knowledge of the synoptic climatology of the region, and experimentation with various statistical procedures; finally, a subjective decision as to how many clusters are appropriate for the study period is made by investigator. Thus, the results of a synoptic-type analysis are quite subjective.

The noted British climatologist Lamb developed a synoptic-scale, daily weather-map classification for use over the British Isles, and seven basic types were identified manually (Lamb, 1972). . Based on Lamb's study, Jenkinson (1977) improved the subjective approach to an objective approach, called the Lamb-Jenkinson method (Jones et al., 1993; Trigo and Dacamara, 2000). According to the sea level pressure (SLP) of these 16 grids, a set of indices related to the direction and vorticity of geostrophic flow are calculated to determine the weather type. The indices used are the following: southerly flow component of the geostrophic surface wind (SF), westerly flow component of the geostrophic surface wind (WF), resultant flow (FF), southerly shear vorticity (ZS), westerly shear vorticity (ZW) and total shear vorticity (Z). These indices were computed using SLP values obtained for the retained number of grid points and are both for the flow units and for the geostrophic vorticity expressed in hPa. As shown in 1a, the research area is located in the central position, which refers to the area connecting with P4, P8, P12, P13, P9 and P5. The SLP of 16 grids can be used to characterize the distance of between the study region and high-/low-pressure system; therefore, the method is available to classify the weather pattern for each day and has been successfully applied in many areas (Lamb, 1972; Jenkinson, 1977; Trigo and Dacamara, 2000; Demuzere et al., 2009; Santurtún et al., 2015; Pope et al., 2016; Liao et al., 2017). The following presents the calculation methods for each index:

SF=1.035×[0.25×(P5+2×P9+P13)-0.25×(P4+2×P8+P12)]

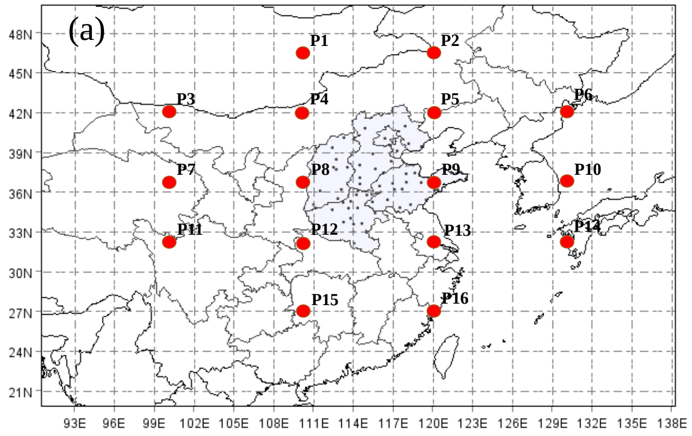
WF=[0.5×(P12+P13)-0.5×(P4+P5)]

ZS=0.85×[0.25(P6+2×P10+P14)-0.25×(P5+2×P9+P13)-0.25×(P4+2×P8+P12)+0.25×(P3+2×P7+P11)]

ZW=1.12×[0.5×(P15+P16)-0.5×(P8+P9)]-0.91×[0.5×(P8+P9)-0.5×(P1+P2)]

F=(SF2+WF2)1/2

Z=ZS+ZW



P represents the SLP at the grid point. The positions of 16 grid points are shown in Fig. 1a; for example, P1 is the SLP at the 1st grid point.

The weather types are defined by comparing values of FF and Z:

(1) Direction of flow (in degrees) is given by tan−1(WF/SF), 180° being added if WF is positive. The appropriate wind direction is computed using an eight-point compass, allowing 45° per sector.

(2) If |Z| < FF, flow is essentially straight and considered to be of a pure directional type (eight different possibilities according to the compass directions).

(3) If |Z| > 2FF, the pattern is considered to be of a pure cyclonic type if Z > 0 or of a pure anticyclonic type if Z < 0.

(4) If FF < |Z| < 2FF, flow is considered to be of a hybrid type and is therefore characterized by both direction and circulation (16 different types).

Thus, compared with other objective synoptic classification approaches, the advantage of Lamb-Jenkinson method is that the number of synoptic types and the weather type that is present each day in the specific region is robust and fixed. In addition, the method clearly gives the typical pressure fields (anticyclone, cyclone, directional types and hybrid types), which can well reflect the wind fields over the study region. Particularly, directional types can represent the prevailing wind direction in this area under the control of the specific weather pattern. Many studies have shown that the high/low concentrations of ozone are always associated with the southerly/northerly winds in North China (Han et al., 2019; Li et al., 2019) . Consequently, the Lamb-

Jenkinson weather type scheme is a better method for exploring the O_3 pollution in North China.

2. Closely to comment 1, the synoptic circulation classification must be connected to the features of MDA8 O_3. In the manuscript, firstly 26 types were separated, and then 5 weather categories were summarized. I think better solution is to consider the MDA8 O_3 in the first step. In other words, in the authors' scheme, the 26 types might be already diagnosed by many previous studies, even not related to the surface O_3 pollution.

Reply:

There are two ways to discuss the relationship between synoptic circulation patterns and air pollution: the environmental-to-circulation approach and **the circulation-to-environmental approach (Yarnal, 1993; Demuzere et al., 2009).**

For the **environmental-to-circulation** approach, the circulation data are based on the criteria defined by the environmental variable (e.g., O_3), so it can be of use in a descriptive way to obtain more insight in those patterns involved in regulating the magnitude of surface environmental variables. However, unlike circulation-to-environmental approach, it lacks any capability to quantify the impact of meteorological factors on air pollutant and prediction. Conversely, **the circulation-to-environmental approach classifies the circulation patterns based on standard pressure fields (e.g., SLP or 500 hPa geopotential height) prior to seeking the links between the environmental variable and the circulation data. This approach follows the hypothesis that circulation conditions have a distinctive effect on a certain environmental variable.** In this study, we adopt the latter. **Firstly, circulation classification can typically represent the complete range of the atmospheric circulation over the area and the entire period for which data are available. In addition, the classification of circulation data is independent of the environmental response (Yarnal, 1993). Therefore, it has been widely used for discussing the relationship between synoptic weather patterns and atmospheric pollutants, such as ozone, $PM_{2.5}$, and PM_{10} (Demuzere et al., 2009; Demuzere and van Lipzig, 2010; Santurtún et al., 2015; Pope et al., 2016; Liao et al., 2017).** Above all, the approach provides a basis for quantifying the relationship between O_3 concentration and different circulation patterns and reconstructing and predicting the O_3 concentration caused by synoptic and local meteorological influence, **allowing the effects of the weather type changes on the inter-annual and day-to-day ozone variability to be evaluated.**

The weather types are developed using Era-interim mean sea level pressure data, and for a given day, they describe the location of high- and low-pressure centers that determine the direction of the geostrophic flow. First, the relations between synoptic patterns and O_3 concentration vary over different regions. For example, anticyclonic conditions and easterly flows have been shown to significantly enhance ozone concentrations over the UK in summer (Pope et al., 2016) , but in Spain, the median concentrations were statistically significantly lower on days with anticyclonic weather conditions than in the rest of meteorological situations, with the maximum values found on days with northern and eastern components (Querol et al., 2014). In addition, **due to the differences in the topography, pollution source, local circulation, etc., the relations between these factors and O_3 concentration vary over different regions as well. Demuzere et al. (2009) demonstrated higher surface O_3 concentrations in summer in an easterly weather type at a rural site in Cabauw, Netherlands, whereas an opposite result was obtained by Liao et al. (2017) in the Yangtze River Delta region in eastern China. Therefore, Lamb-Jenkinson synoptic classification and its relationship with O3 needs to be explored separately in different regions, especially in North China.**

3. Only the sea level pressure was considered when synoptic circulation classification, it is better to add some variables in the mid-high troposphere. As you know, the atmospheric circulations in the mid-high troposphere were more representativeness.

Reply:

Thanks for your suggestion. **A method to classify daily circulation patterns was originally developed by Lamb (1972), which is a subjective classification method. The method used surface pressure synoptic charts describing the flow in the 500-hPa level in the atmosphere.** To avoid dependency of the daily weather maps on experience and consistency of the researcher, this method was objectified by Jenkinson (1977); as a result, this method has been upgraded to objective classification method. Moreover, as shown by Conway and Jones (1998), **circulation patterns fundamentally control meteorological characteristics on the surface, whereby the use of surface level pressure has several advantages.** The study done by Mckendry et al. (2006) showed that **upper pressure level patterns are less variable than surface pressure patterns and that particular upper level patterns may be associated with a large range of sea-level pressure synoptic types.** The surface pressure field can better represent the local meteorological factors. Therefore, sea level pressure is more appropriate for the classification of circulation patterns (Demuzere et al., 2010).

4. The authors illustrated that "39.2% of the inter-annual domain-averaged O3 increase from 2013 to 2017 was 28 attributed to synoptic changes". I wonder how to discuss the interannual variations only using 5 years data.

Reply:

The quantifying work was reported by Hegarty et al. (2007). She indicated that 46% of the inter-annual variability in summertime O_3 was caused by synoptic changes with intensity being the dominant factor based on 5 years (2000-2004) of ozone data in the northeastern USA. The basic principle of the method is to find out the relevance of the change in the synoptic intensity to ozone inter-annual variability. We upgraded this method by using six intensity factors that reflect the changes in the synoptic intensity and found the strongest correlation intensity index with ΔO3 under each weather type in each city. Then, we reconstructed the inter-annual ozone levels by taking into account either frequency-only or both frequency and intensity variations of synoptic circulations as introduced in Section 2.4. After reconstructing the O_3 concentration ($\overline{\overline{O_{3\,m}}}(\mathrm{fre}+\mathrm{int})$), $\Delta\overline{\overline{O_{3m}}}(\mathrm{fre}+\mathrm{int})$ is the difference between maximum and minimum annual reconstructed ozone values by considering the effects of both frequency and intensity of synoptic weather patterns; ΔO_3_obs indicated the maximum and minimum difference of annual observed ozone concentration. Therefore, $\boldsymbol{\Delta\overline{\overline{O_{3m}}}(\mathrm{fre}+\mathrm{int})/}$

ΔO_3_obs indicates the inter-annual oscillations in ozone levels caused by synoptic variability, introduced in Section 3.3.2. The ratio of the oscillation of ozone concentration caused by meteorological factors to the oscillation of actual ozone concentration is the impact of meteorological conditions on the interannual variation of ozone concentration. In this paper, inter-annual variability in domain-averaged observed MDA8 O_3 in 14 cities varied from averaged maximum values of 135 μg m^{-3} in 2017 to a minimum 104 μg m^{-3} in 2013. The contributions of circulation patterns variations in inter-annual O_3 increase was 39.2%, and the remaining inter-annual variability was possibly due to nonlinear relationships with recent emission control measures over North China. Therefore, the five spots (years) are sufficient to illustrate the inter-annual variations.

5. To provide the potential of O3 forecast, several models were built for each city and the results were shown in Section 3.4.

(1) How can we pre-determine the type of the synoptic circulations?

One possible way is to use the output of numerical weather model.

Reply:

Yes, we intend to use the forecasting SLP data from numerical weather model (e.g., WRF) to determine day-to-day weather patterns.

(2) The selected predictors in the models were the simultaneous variables, thus the question is how to obtain the predictors? If the answer is the output of NWP, the models should be trained from the achieved NWP output data instead of the observation or reanalysis.

Reply:

First, the relevance of establishing this equation is to quantify the effect of synoptic changes in weather patterns on day-to-day ozone concentration and then to establish the ozone potential forecast model.

To better reflect this view, we added the following sentences in lines 86-89 of the revised manuscript: 'Quantifying the contribution of local meteorological factors

to the day-to-day variation in ozone will a provide scientific basis and guidance for reasonable ozone reduction measures, and clarifying and quantifying the relationship between meteorological factors and ozone is vital for daily ozone pollution potential forecasts.'

In order to accurately express the relationship between the actual local meteorological factors and ozone concentration in the atmosphere, we input the measured meteorological factors for building and validating the model. As for the prediction stage, we believe that the meteorological factors simulated by numerical models are credible for the short-term forecasting.

(3) TCC is not a routine observed variable, and also not a reliable NWP output.

Reply:

Thank you very much for your valuable comments. We initially considered the meteorological variables simulated by NWP. TCC can be obtained indirectly from the model; however, considering its complexity and its influence on ozone in the prediction model, **we do not consider TCC anymore and rebuilt the ozone potential prediction model. When TCC is excluded, it has little effect on the results of the model. The corrected results are shown in Section 3.4, Table 2 and Tables S3-S4.**

The following sentences are the result of the revision shown in lines 37-39, 397-398 and 431-433 of the revised manuscript, respectively.

'Overall, 41-63% of the day-to-day variability of MDA8 O_3 concentrations was due to local meteorological variations in most cities over North China, except for two cities: QHD (Qinhuangdao) at 34% and ZZ (Zhengzhou) at 20%.'

'The result of validation shows that R^2 was higher than 0.50 except for QHD, SJZ and ZZ (0.24-0.47), while CV was lower than 40% except for TY and ZZ.'

'Local meteorological parameters could explain 57-63% and 41-52% of the day-to-day MDA8 O_3 concentration variability for the northern cities (except for QHD, 34%) and southern cities (except for ZZ, 20%), respectively.'

6. The English were intensively suggested to be improved by the native speaker.

Reply:

Thanks; we have revised the language problems with the help of native speaker in this revised version. Language modification is not marked in the revised manuscript in red font.

Minor comments:

1. Line 24: what is the S-W-N stand for? cyclone type (C)….

The use of abbreviations should be modified throughout the manuscript, particularly in the Abstract.

Reply:

Thanks for the comment. The revised sentence, as shown in lines 27-29, reads as follows: 'S-W-N directions (geostrophic wind direction diverts from south to north), LP (low-pressure related weather types) and C (cyclone type, controlled by low pressure center)'

2. What is the mean of QHD, ZZ?

Reply:

We have added the description to the article. As shown in lines 37-39 of revised manuscript, the revised sentence is as follows:

'Overall, 41-63% of the day-to-day variability of MDA8 O_3 concentrations was due to local meteorological variations in most cities over North China, except for two cities: QHD **(Qinhuangdao)** at 34% and ZZ **(Zhengzhou)** at 20%.'

3. Line 101-113: the type set is different.

Reply:

Thanks for your suggestion, as shown in lines 111-118 of revised manuscript, the revised sentences are as follows:

"Each city has at least two monitoring sites, and the city MDA8 O_3 levels are the corresponding averages over all sites in that city. MDA8 O_3 values were collected in only 14 cities for the time period 2013-2017 and in an additional 44 cities for the time period 2015-2017, with detailed information shown in Fig. 1 and Table S1. The original unit of the ozone observations is μg m^{-3}, and the converted coefficient from mixing ratios (unit: ppbv) to μg m^{-3} is a constant (e.g., 0.5 at temperature of 25 °C and pressure of 1013.25 hPa). In this study, we will use the original unit. Unless otherwise noted, **the analysis of O_3 refers to MDA8 O_3** during April-October in this paper."

4. Line 164: Why mentioned Figure 7a before Figure 2? Similar problems can be find in the manuscript.

Reply:

We have tried to set the figures in order, but when the complex method is introduced in Section 2, the figure is also needed. Thus, we have to adjust the order based on the main content.

5. Line 182: the definition of "exceedance ratio"?

Reply:

Thanks a lot. We ignored the definition of 'exceedance ratio' in our paper. We added the sentence as shown in lines 193-194 of revised manuscript, as follows: exceedance ratio which means the proportion of days exceeding the standard (160 μg m^{-3}).

6. Line 188: the reason for these 14 cities? That is, why the authors choose these 14 cities?

Reply:

These 14 cities first started monitoring in North China in 2013, and they have 5-year ozone data; additionally, they can represent the pollution situation in North China to a great extent.

7. Line 219: "and and and" is not a good section title.

Reply:

We have revised the section title as 'The meteorological conditions and regional ozone concentrations under different predominant circulation type'.

8. Figure 4 & 6: the panels are too small to read.

Reply:

We have revised the unclear figures in the article, as shown below:

Figure 4:

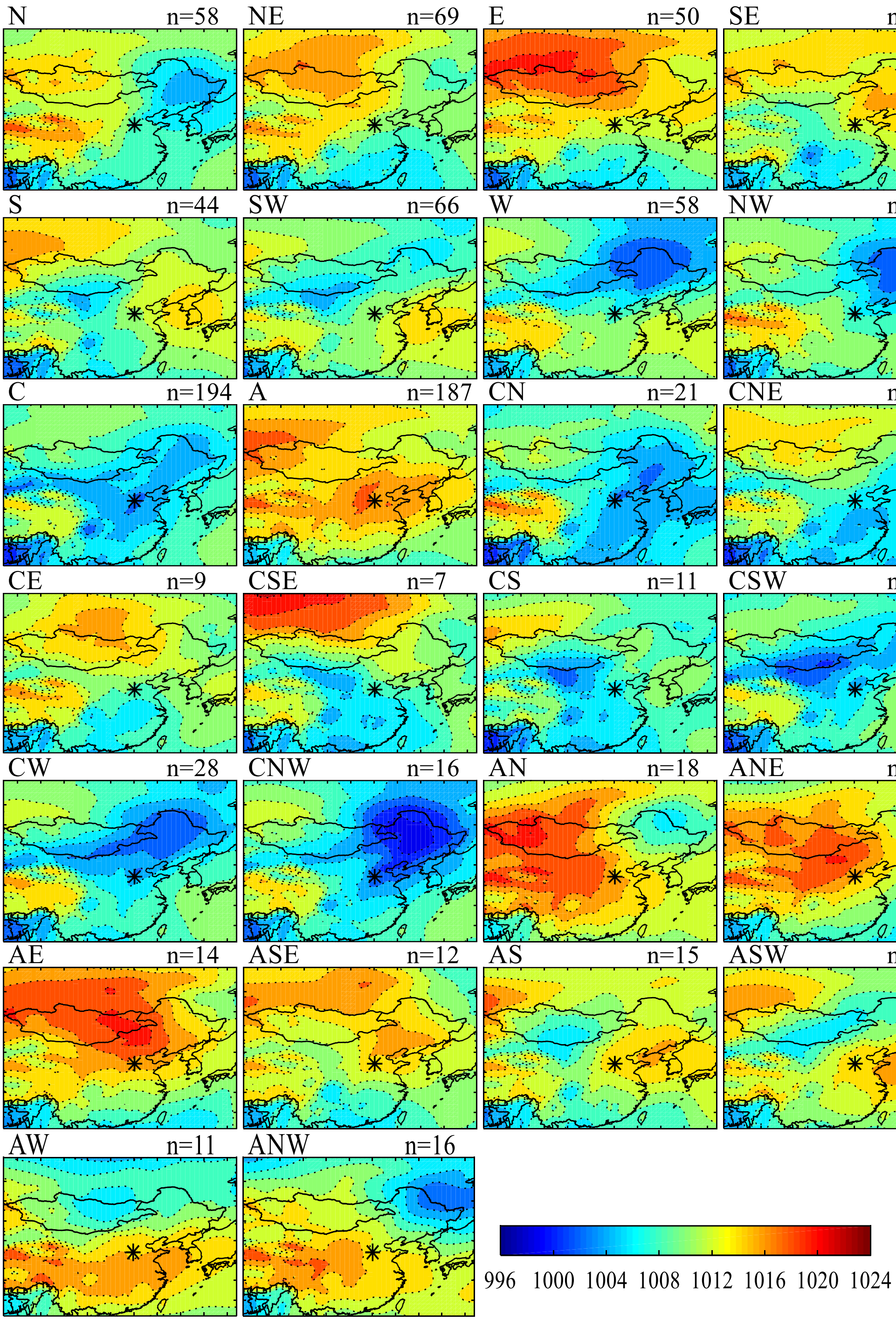


Fig. 4. Mean surface pressure field (unit: hPa) for the 26 weather types during April-October of 2013-2017 and occurrence days (1070 days in total). '*' indicates the center of North China.

Figure 6:

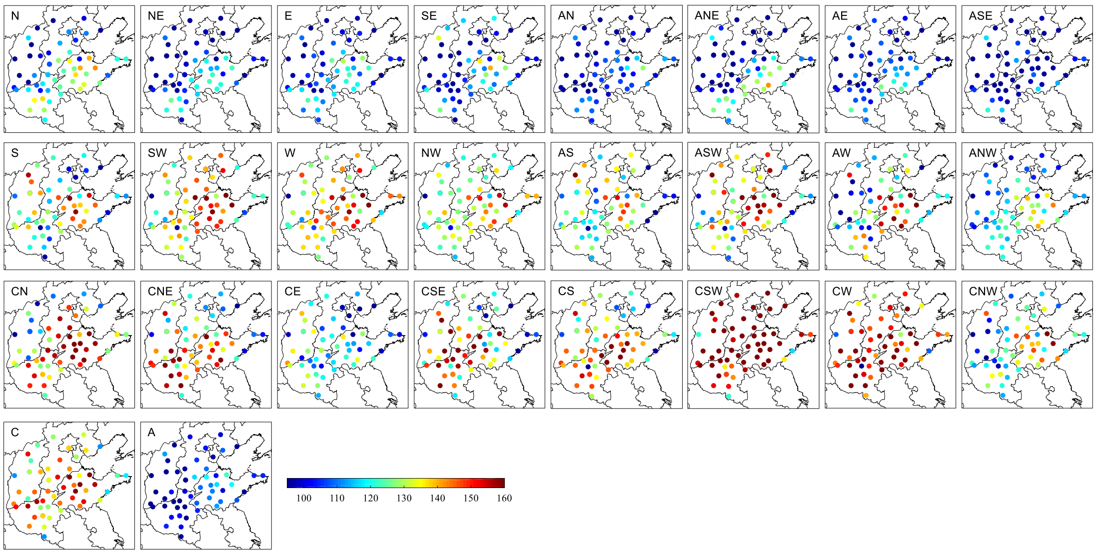


Fig. 6. Spatial distribution of average MDA8 O_3 for the 26 weather types. The first, second, and third rows correspond to the weather categories N-E-S direction, S-W-N direction and LP, respectively, and the fourth row includes both categories C and A.

9.Figure 3: the color bae cannot show the 26 types.

Reply:

We have revised the unclear figure in the article, as shown below:

Figure 3:

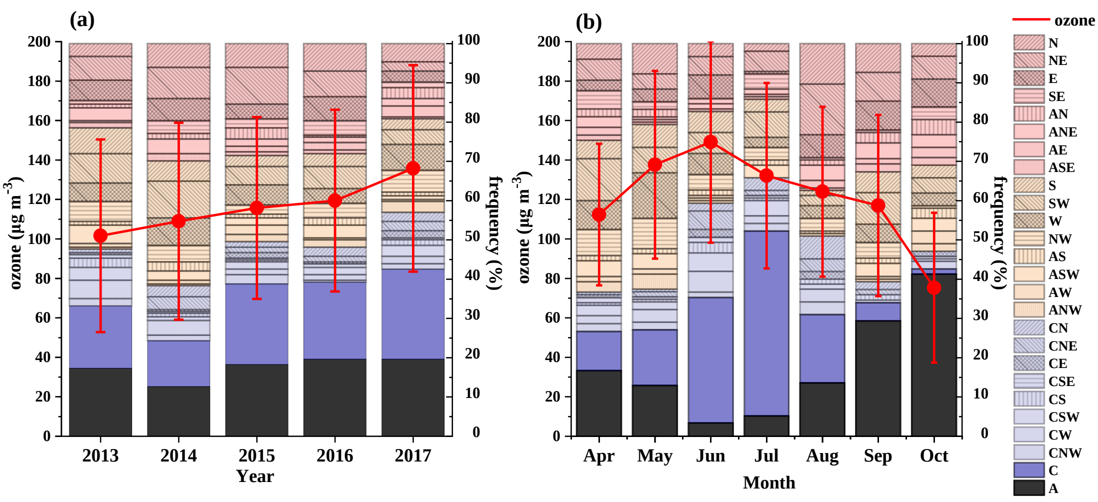


Fig. 3. Interannual (a) and monthly (b) averaged concentrations of ozone and frequencies of 26 weather types from April-October 2013-2017. The red dots represent the mean values, the vertical red lines indicate the standard deviations, and stacked charts represent the percentages of various weather types (2013 and 2014 are averaged for 14 cities; 2015-2017 are averaged for 58 cities). The pink, orange, light blue, dark blue and black areas represent the weather categories N-E-S direction, S-W-N direction, LP, C and A, respectively.

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