Responses to anonymous Referee #1

1. The Lyu et al. manuscript reports on a combined measurement-modeling analysis of a sustained ozone (O_3) pollution event over the North China Plain. Continuous online measurements of O_3, NO, and NO_2 were made in the city of Ji'nan, from the Shandon University campus. For a subset of the measurement period, samples were collected for offline analysis of oxygenated/volatile organic compounds (O/VOCs). Additional chemical and meteorological data were obtained from nearby monitoring stations. Positive matrix factorization (PMF) was used to identify sources of O_3 precursors, using the chemical data as input parameters (VOCs, CO, NO, and NO_2). In addition, the WRF-CMAQ chemical transport model was used to evaluate processes contributing to O_3 formation and depletion, and an MCM-based box model was used to evaluate localized O_3 chemistry. HYSPLIT back trajectory analysis was also performed to identify origins of air masses. Collectively, the research presented represents a significant effort to identify the primary drivers of the sustained O_3 event. No major weaknesses are identified in the approach, the quality of the data, or the simulation results. The major weaknesses are in the presentation of the results and the synthesis of the findings.

We appreciate the referee's time and positive comments. The presentation of the results and the synthesis of the findings in the paper have been improved according to the referee's comments.

2. The introduction starts with a list of publications that have addressed O_3 formation over the North China Plain (NCP). As written, it isn't clear whether there are major discrepancies between studies and/or whether there are gaps in understanding/model representation that are unaddressed by existing studies.

Many thanks for the good comment. The introduction has been reorganized and the knowledge gaps are more clearly presented. In the revised manuscript, the first paragraph in the introduction focuses on the severity and aggravation of O_3 pollution in the NCP. Six publications are cited to illustrate this point, and we summarize the O_3 pollution in the NCP with the sentence "Overall, the NCP suffers from severe O_3 pollution, which is even aggravating." The second and third paragraphs introduce the chemical and meteorological processes influencing O_3 pollution. The knowledge gaps are summarized in the last paragraph as follows.

Despite many previous studies, the evolutions of the synoptic and photochemical processes in O_3 pollution events, and their contributions to the non-attainment of O_3 have been seldom looked into in the NCP. Besides, the local and regional contributions to the elevated O_3 in the NCP are not unambiguously quantified, limited by the deficiencies in model representation of either physical or local chemical processes. The situation was even much worse for Ji'nan, the capital of Shandong province. As early as 2000s, studies (Shan et al., 2008; Yin et al., 2009) reported the maximum hourly O_3 of 143.8 ppbv and 147.8 ppbv in June 2004 and 2005, respectively. Even higher O_3 (198 ppbv) was observed at a rural site downwind of Ji'nan in June 2013 (Zong et al., 2018). However, almost no study was carried out to explore the mechanisms responsible for high O_3 there, though it has been confirmed that air pollution in the NCP cities like Ji'nan influenced air quality in Beijing (Lin et al., 2008; Wang et al., 2010).

For details, please refer to lines 116 – 127, pages 4 – 5.

3. Further, it isn't clear (based on the abstract or implications) how the current work advances the current state of the science (understanding, prediction capabilities, etc.). As written, the implications section highlights that this work confirms O_3 levels are high in the NCP and the NCP may serve as a source region, which do not represent a substantial contribution. However, elucidation of the shifts in regime (from VOC-limited to transition) during the O_3 episodes appears to be a new finding, and therefore should be highlighted and expanded upon.

The valuable comment and suggestion are highly appreciated. Although Ding et al (2009) indicated the transport of O_3 from the NCP to the free troposphere and the downwind areas, their study was based on the aircraft measurement in northeast China and the simulation of the lifting processes of ground-level air masses. To our knowledge, no other study defined the NCP to be a source region of O_3. The present study confirmed that the NCP was an O_3 source, through the ground-level measurement and simulation of in-situ photochemistry. Therefore, we still think that this finding advanced our understanding on the role of the NCP in O_3 pollution in the downwind regions and even whole China. We clarify the differences between this study and Ding et al (2009) in the implications, though the studies corroborated each other in term of the finding that the NCP is a source region of O_3.

Another important finding in this study was that the NCP served as an O_3 source. This was ever proposed by Ding et al. (2009), based on the aircraft measurement and simulation of atmospheric

dynamics. We confirmed it through the ground-level observation and the simulation of in-situ photochemistry.

For details, please refer to lines 663 – 667, pages 27-28.

In addition, we accept the excellent suggestion on highlighting the change of O_3 formation mechanisms from VOC-limited regime to the transitional regime.

The finding that O_3 formation shifted from VOC-limited regime on relatively low O_3 days to the transitional regime on O_3 non-attainment days may elucidate the cause of the increase in O_3, because O_3 productions in the transitional regime are even higher, despite decreases in NO_x emissions. It is unrealistic to expect a continuously linear reduction in NO_x emissions in the NCP, after the substantial decreases of NO_x emissions from power plants and industries in recent years. In other words, restraining on VOC emissions is urgent for O_3 abatement in the NCP.

For details, please refer to lines 657 – 663, page 27.

Revisions have also been made in the abstract to highlight the two findings.

The NCP has been confirmed as a source region of tropospheric O_3, where the widespread shift of regimes controlling O_3 formation like the case presented in this study can be expected, due to the substantial reductions of NO_x emissions in recent years.

For details, please refer to lines 33 – 35, page 2.

4. Further, though significant effort was clearly made and the quality of the work is high, the results are relatively unorganized and presented as speculative. Regarding the latter, the word "might" is used 30 times in the paper; in many places it seems the authors have sufficient information to make more conclusive statements and the contribution of the work is minimized by presenting it as speculative. Regarding organization, in several places within the results and discussion, individual paragraphs are more than one page long (lines 335-378, 733-762, 795-832).

Thanks for the comments. All the conclusions and inferences have been checked throughout the paper and the wordings have been changed to be more definite wherever it is possible based on our confidence on the conclusions and the inferences. Besides, the whole paper has been reorganized to improve the readability. The long paragraphs pointed out by the referee have been

significantly shortened, while the contents are not changed much. For details, please refer to lines 327 – 344, 587 – 605 and 628 – 648.

5. Additionally, there is a lot of repetition in the results and the modeling doesn't clearly build on the measurements (or vice versa). Each section is almost presented as a separate study of processes. Because of these weaknesses, it is difficult to assess the overall importance of the paper and the likely contribution to the field. It is recommended that the paper undergo significant revision before publication in ACP. Specific comments are provided below.

We thank for the comments. The repetitions in the manuscript have been double checked and avoided. For example, the contribution of BVOCs to OH reactivity was discussed in lines 330 – 334 and lines 362 – 367 in the original manuscript, which is now only presented in lines 315 – 318 in the revised manuscript. The low O_3 on July 30 and August 1 were elaborated in the original manuscript in both section 3.1 and section 3.2. However, we only discuss it in section 3.1, with reference to the discussion in section 3.2 – "The low O_3 values on July 30 and August 1 were mainly attributable to the weak solar radiation and low temperature as discussed above." (lines 419-420, page 16). More revisions on the repetition have been made throughout the manuscript.

In fact, the modeling and measurement were built on each other and the results supported each other. In the revised manuscript, the relationships between them are clarified.

The observations indicated the likely different regimes controlling local O_3 formation and the potential impacts of regional transport. To understand the atmospheric chemistry and dynamics, as well as their roles in this O_3 pollution event, the WRF-CMAQ was applied.

For details, please refer to lines 442 – 444, page 18.

The IPR analyses showed that chemical reactions served as an important source of O_3 on episode days in Ji'nan, particularly during 09:00-15:00 LT when O_3 was at high levels. This process was further studied through the simulation of the in-situ photochemistry by PBM-MCM. It should be noted that the simulations were based on the observed concentrations of O_3 precursors, which could be influenced by both local and regional air. It required cautions to extend the results to all the situations in Ji'nan, because the regional effect was not always consistent.

For details, please refer to lines 493 – 498, page 21.

Despite these discrepancies, overall the observed O_3 at the sampling site was well reproduced. In addition, the spatial distribution of the simulated O_3 was highly consistent with the observed O_3 distribution, as shown in Figure S10.

For details, please refer to Text S1 and Figure S10.

Noticeably, the change of regimes controlling O_3 formation is consistent with that predicted by the $\frac{OH\ reactivity_{VOCs^{\#}}}{OH\ reactivity_{NOx}}$ ratio and the ratio of the reaction rates between "HO_2+RO_2" and "OH+NO_2".

For details, please refer to lines 625 – 627, page 26.

The connections between the sections are also rewritten to make the whole paper more coherent. For details, please refer to lines 368 – 369, lines 442 – 444, lines 493 – 495 and lines 587 – 589.

Specific comments:

1. Technical and Editorial: Abstract, line 23: It would be useful to see the fractional contribution to O_3, as well as the given production rates.

Thanks for the suggestion. The process analysis module in CMAQ did not calculate the contributions of different processes to O_3 (ppbv), but the contributions to the total variation rate of O_3 (ppbv/h). During 9:00 – 15:00 on O_3 episode days, the regional transport and chemical reactions elevated O_3 by 18.7 and 14.0 ppbv/h, respectively, which were most offset by dry deposition (-25.6 ppbv/h) and cloud processes (-0.1 ppbv/h). If the percentage contributions to the total variation rate of O_3 were calculated, they were 268%, 200%, -366% and -1% by regional transport, chemical reactions, dry deposition and cloud processes, respectively. To avoid confusion, we do not provide these seemly strange percentages.

2. Abstract, lines 34-37: On line 34, the use of "great" implies something that is positive; suggestions to replace with "major" or "large" or something similar. On line 23, a local photochemical production rate of 14 ppbv/hr is reported for Aug. 9-10 (I believe that is the associated time period) and on line 32, a simulated local photochemical production rate (maximum) of 21.3 ppbv/hr is reported. With these large production rates, the ~1 ppbv/hr decrease in O_3 formation with a hypothetical 10% decrease in diesel and gasoline exhaust seems

insignificant. Even during non-episode periods, a simulated local maximum production rate of 16.9 ppbv/hr is reported. Thus the suggestion that constraining vehicle emissions is the most effective strategy to control O_3 production is not well supported by the numbers presented, and needs further explanation and/or clarification.

Thanks for the valuable suggestion and comment. The word "great" has been replaced with "large". With regard to the seemingly low sensitivity of O_3 production to gasoline and diesel exhaust, it was because that the gasoline and diesel exhausts were assumed to be reduced by 10%. As shown in Figure S14 (Figure S12 in the original Supplement), the source of gasoline exhaust, diesel exhaust, BVOC, LPG usage, solvent usage and petrochemical industry accounted for 4.7, 5.8, 3.3, 1.4, 2.1 and 2.4 ppbv/hr of the maximum O_3 production, respectively. These O_3 productions added up to 19.6 ppbv/hr, comparable to the 21.3 ppbv/hr during O_3 episodes. The difference was explained by the O_3 production attributable to carbonyls, which were not included in the source apportionment. The statement that constraining vehicle emissions was the most effective strategy to control O_3 was supported by the highest O_3 reduction per 10% decrease in source emission for gasoline exhaust (0.47 ppbv/10% reduction in source emission) and diesel exhaust (0.58 ppbv/10% reduction in source emission). On one hand, we would like to inform the readers that the seemingly insignificant O_3 decrease resulted from 10% emission reduction of gasoline and diesel exhausts was due to the fact that many sources contributed to O_3 production and high reduction percentages were required if actions were only taken against one or two sources. On the other hand, the contributions of vehicle exhausts to O_3 production might be underestimated, without the inclusion of the primarily emitted carbonyls from vehicles. Clarifications have been added in the main text of the revised manuscript as follows, but we do not want to repeat them in the abstract.

In fact, the sensitivity of O_3 production rate to the vehicle exhausts might be somewhat underestimated, due to the exclusion of carbonyls in the source apportionment. However, the reductions of O_3 production rate by cutting 10% of vehicle exhausts were still insignificant, compared to the overall maximum O_3 production rate of 21.3 ppbv/hr during O_3 episodes. This indicated that by only restraining emissions from one to two sources, high percentages of emission reductions were required to sufficiently reduce the O_3 production rate. Otherwise, the combined efforts should be made to control the emissions of O_3 precursors from the diverse

sources. In particular, it is essential to get rid of the transitional regime featuring high O_3 production rates and low sensitivities of O_3 production to the precursors.

For details, please refer to lines 640 – 648, page 27.

3. Line 45: Suggestion to remove "of researchers".

Accepted with thanks.

4. Line 52: May to August of which year?

Thanks for the question. The sampling year (2013) is specified (see lines 47-48).

5. Line 80: Can the authors please clarify what is meant by "air profiles"? Chemical composition?

Exactly. To avoid confusion. The term "air profiles" has been changed to "chemical composition of air pollutants". For details, please refer to line 68, page 3.

6. Lines 92-95: The authors state that sources with a large fraction of alkenes, aromatics and carbonyls are significant contributors to photochemical O_3 production. As an example, they cite a paper by Ling and Guo that shows O_3 was most sensitive to xylenes from solvent usage, but this alone does not require a major contribution of xylenes from solvents.

Thanks for the comment. To better support the statement "Therefore, the sources with a bulk emission of these VOCs generally make considerable contributions to the photochemical production of ground-level O_3", we cite another study and the sentence has been revised as follows.

For example, Cheng et al. (2010) pointed out that carbonyls increased the peak O_3 production rates at a rural site and a suburban site in South China by 64% and 47%, respectively.

For details, please refer to lines 89 – 91, page 4.

7. Lines 122-123: This sentence starting with "contradictory" is confusing as written. What is contradictory?

Since this paragraph has been revised substantially, the sentence starting with "contradictory" has been deleted.

8. Line 183: Where is the "widely used" weather station in relation to the measurement site?

We thank for the question. The automatic weather station was deployed at the same site where we collected samples. The Model CAWS600-B weather stations produced by China Huayun group are used in ~2/3 of more than 1500 meteorological stations across China. Therefore, we defined it as a "widely used" weather station.

In addition, the meteorological parameters, including wind speed, wind direction, pressure, temperature and relative humidity, were monitored at the sampling site by a widely used weather station (China Huayun group, Model CAWS600-B).

For details, please refer to lines 194 – 196, page 7.

9. Lines 344-346: The authors discuss the potential interferences and overestimation of NO_2, particularly on episode days. Do the authors mean that the OH reactivity during episodes might be overestimated? Or lower than during non-episodes as stated? Is there a way to approximate or bound the potential overestimation?

Thanks for the questions. Yes, the chemiluminescence NO-NO_2-NO_x analyzer generally overestimates NO_2 due to the reason discussed in section 2.2.1.

Studies indicated that NO_2 monitored with chemiluminescence was generally overestimated due to the conversion of the total odd nitrogen (NO_y) to NO by molybdenum oxide catalysts (McClenny et al., 2002; Dunlea et al., 2007; Xu et al., 2013). The positive bias was more significant in more aged air masses, resulting from higher levels of NO_z (NO_z = NO_y - NO_x) (Dunlea et al., 2007).

For details, please refer to lines 165 – 169, pages 6-7.

Since OH reacts with NO_2 at a much higher rate than with NO_z, the overestimate of NO_2 leads to overestimate of OH reactivity. NO_z is often expected to be higher on O_3 episode days, because the sources of most NO_z species are dominated by secondary formation. Therefore, we speculated that the OH reactivity was overestimated in this study and more overestimated on O_3 episode days than during non-episodes. Here, we adopted 30% and 10% as the upper limits of NO_2 overestimate during episodes and non-episodes, respectively. The rationality is given in the manuscript as follows.

The average overestimation of NO_2 was 22% in Mexico City, which even increased to 50% in the afternoon (Dunlea et al., 2007). Xu et al. (2013) suggested that the chemiluminescence monitors overestimated NO_2 by less than 10% in urban areas with fresh emission of NO_x, but the positive bias went up to 30-50% at the suburban sites. As described in section 2.1, our sampling site was located in the urban area of Ji'nan and was only ~50 m to a main road. Therefore, we infer that NO_2 might not be significantly overestimated in this study. However, the larger overestimations could be expected during O_3 episodes, because the stronger photochemical reactions enhanced the productions of many NO_z species. We adopted 30% (minimum bias in suburban area) and 10% (maximum bias in urban area) as the maximum fraction of NO_2 overestimation during episodes and non-episodes at this urban site, respectively. The influences of the NO_2 measurement interferences on the results were discussed where necessary.

For details, please refer to lines 169 – 180, page 7.

The OH reactivity of NO_x was 4.7±0.8 s^{-1} and 6.9±1.9 s^{-1} during episodes and non-episodes, respectively. Taking 30% and 10% overestimate of NO_2 during episodes and non-episodes into account, we found that the OH reactivity of NO_x during episodes (4.0±0.7 s^{-1}) was indeed lower (p<0.05) than during non-episodes (6.6±1.9 s^{-1}). It should be noted that the OH reactivity of VOCs was not influenced by the overestimate of NO_2, which therefore was still comparable between episodes and non-episodes. Since NO accounted for a considerable part of OH reactivity of NO_x, the maximum of 30% and 10% overestimate of NO_2 only led to 17.5±1.1% and 5.4±0.7% overestimate of OH reactivity of NO_x during O_3 episodes and non-episodes, respectively. Discussions are given in the manuscript as follows.

Taking the positive biases of NO_2 measurement into account (section 2.2.1), we found that the OH reactivity of NO_x was overestimated by the maximum of 17.5±1.1% and 5.4±0.7% during O_3 episodes and non-episodes, respectively. In the case of maximum overestimations, the actual OH reactivity of NO_x during episodes (4.0±0.7 s^{-1}) might be lower (p<0.05) than that during non-episodes (6.6±1.9 s^{-1}).

For details, please refer to lines 331 – 335, page 12.

10. Line 350: "More importantly" than what? High pressures?

Sorry for the confusion. The sentence has been revised to be more concise, and the term "More importantly" was deleted.

The high OH reactivity during non-episodes mainly occurred on July 30 and August 1, due to the high pressure, weak solar radiation and low temperature.

For details, please refer to lines 335 – 337, page 12.

11. Section 3.3: The authors spend a significant time discussing the quality of the O_3 modeling. Since matching observations is not the primary goal of the modeling component, much of that discussion could be moved to the supplement.

The good suggestion is accepted with thanks.

Discussions on the discrepancies and the detailed model validation are provided in Text S1, Figures S9-S11 and Table S4.

For details, please refer to lines 448-449, page 18, and Text S1, Figures S9-S11 and Table S4.

Responses to anonymous Referee #2

General Comments This paper presented a comprehensive diagnostic study of the Ozone-NO_x-VOCs sensitivity in urban Ji'nan. The analysis is trying to synthesize the analysis tools from both observational constrained box model and regional model. This study is on the good way for the exploration of the ozone chemistry in urban China. Nevertheless, there are still trivial problems on the issues like site representation, measurement quality of key parameters like NO, ways to compare box model and regional model, the use and interpretation of PMF on VOCs source apportionment, etc which I provided detailed comments as follows. I suggest publication after addressing the following comments.

We sincerely thank for the positive and valuable comments. Revisions have been made accordingly, and the responses are given below item by item.

Specific Comments 1. Introduction: the review of the current O_3 studies in the part of the introduction was not as comprehensive as it normally required. Recently, there were several papers about the Ozone-NO_x-VOCs sensitivity issues in Chinese megacities been published. It may be useful to include as a comparison.

We thank for the good comment. The review of the current O_3 studies, particularly on the O_3-VOC-NO_x sensitivity in the introduction has been updated.

Xue et al. (2014) indicated that the summer O_3 formation was limited by NO_x in Lanzhou, consistent with Liu et al. (2010) who identified the NO_x-limited regime in most areas of northwest China. In the southwest, O_3 formation was diagnosed as VOC-limited in Chengdu, but NO_x-limited in Pengzhou due to the large quantities of emissions from petrochemical industry (Tan et al., 2018a). Lyu et al. (2016) reported the VOC-limited regime in Wuhan, central China. The VOC-limited regime has also been repeatedly confirmed for O_3 formation in Shanghai (Xue et al., 2014; Xing et al., 2017) and Nanjing (Ding et al., 2013), eastern China. In the Pearl River Delta of southern China, it was found that O_3 formation was generally limited by VOCs in the southwest, while limited by NO_x in the northeast (Ye et al., 2016). In the NCP, both Han et al. (2018) and Xing et al. (2018) summarized that VOCs limited O_3 formation in most urban areas. However, in the suburban and rural areas, O_3 formation was generally in the transitional regime, *e.g.* Yucheng (Zong et al., 2018), or limited by NO_x, *e.g.* Wangdu (Tan et al., 2018b). From a historical perspective, Jin et al. (2017) pointed out that the sensitivity of O_3 formation to VOCs increased in most Chinese cities, however decreased in some megacities (such as Beijing and Shanghai) due to the stringent control of NO_x emissions in recent years. Different VOCs play non-equivalent roles in O_3 formation.

For details, please refer to lines 70 – 86, page 3.

2. Methodology: as shown by previous studies (e.g. Lu et al., JGR, 2010, 115, D07303; Cardelino and Chameides, AE, 2000, 34, 2325), the measurement quality of NO is of crucial importance for the diagnosis of the Ozone-NOx-VOCs sensitivity, sometimes this may lead to totally different results. The important point is that the detection limit of NO shall be on the level of 100 ppt so that sub-ppb NO can be accurately captured. The use of Mo-converter for the NO_2

measurement is another weakness of the current paper. The interference is really variable case by case.

The excellent and professional comment is highly appreciated. We agree that the accurate diagnosis of O_3-VOC-NO_x sensitivity strongly depends upon the measurement quality of NO and NO_2. In this study, the NO_x analyzer used had the detection limit of 0.4 ppbv for NO, higher than the 50 pptv achievable by Lu et al. (2010) and Cardelino and Chameides (2000). However, the lowest mixing ratio of NO during the sampling period was recorded as 2.4 ppbv, which was also much higher than the lowest mixing ratios (lower than 50 pptv in many afternoons) reported by Lu et al. (2010) and Cardelino and Chameides (2000). Moreover, the lowest value of 2.4 ppbv was 6 times (600% of) the lower detection limit of the instrument. Taking the measurement accuracy of <15% into consideration, we believe that the NO measurement was basically reliable in this study. The reliability of NO measurement is justified in the revised manuscript.

The lowest NO observed during the sampling period was 2.4 ppbv, 6 times (600% of) the lower detection of the NO_x analyzer (0.4 ppbv). Taking the measurement accuracy of <15% into consideration, we believe that the NO measurements were basically reliable.

For details, please refer to lines 160 – 163, page 6.

The potential biases of NO_2 measurements and its influences on the results, including the O_3-VOC-NO_x sensitivity, have been fully discussed in the manuscript.

Studies indicated that NO_2 monitored with chemiluminescence was generally overestimated due to the conversion of the total odd nitrogen (NO_y) to NO by molybdenum oxide catalysts (McClenny et al., 2002; Dunlea et al., 2007; Xu et al., 2013). The positive bias was more significant in more aged air masses, resulting from higher levels of NO_z ($NO_z = NO_y - NO_x$) (Dunlea et al., 2007). The average overestimation of NO_2 was 22% in Mexico City, which even increased to 50% in the afternoon (Dunlea et al., 2007). Xu et al. (2013) suggested that the chemiluminescence monitors overestimated NO_2 by less than 10% in urban areas with fresh emission of NO_x, but the positive bias went up to 30-50% at the suburban sites. As described in section 2.1, our sampling site was located in the urban area of Ji'nan and was only ~50 m to a main road. Therefore, we infer that NO_2 might not be significantly overestimated in this study. However, the larger overestimations could be expected during O_3 episodes, because the stronger photochemical reactions enhanced the productions of many NO_z species. We adopted 30% (minimum bias in suburban area) and 10% (maximum bias in urban area) as the maximum fraction of NO_2 overestimation during episodes and non-episodes at this urban site, respectively. The influences of the NO_2 measurement interferences on the results were discussed where necessary.

For details, please refer to lines 165 – 180, pages 6 – 7.

Taking the positive biases of NO_2 measurement into account (section 2.2.1), we found that the OH reactivity of NO_x was overestimated by the maximum of 17.5±1.1% and 5.4±0.7% during O_3 episodes and non-episodes, respectively. In the case of maximum overestimations, the actual OH

reactivity of NO_x during episodes (4.0±0.7 s^{-1}) might be lower (p<0.05) than that during non-episodes (6.6±1.9 s^{-1}).

For details, please refer to lines 331 – 335, page 12.

In reality, the sensitivity of O_3 formation to NO_x might be underemphasized due to the positive biases of NO_2 measurement (Lu et al., 2010). This effect was expected to be more significant during episodes when the overestimates of NO_2 were higher. However, O_3 formation was not likely only limited by NO_x even during O_3 episodes, which should be still sensitive to VOCs, as NO_2 could not be much overestimated in the urban areas (see section 2.2.1).

For details, please refer to lines 618 – 622, page 26.

3. Methodology: as described the sampling site is very close (~50 m) to a main road which would be a problem for a regional (city scale) perspective.

Thanks for the comment. Though the sampling site was very close to a main road, we still believe that the observations at this site to some extent represented the regional O_3 pollution characteristics, in view of the comparable O_3 at this site to those observed at the air quality monitoring stations in the NCP, and the strong influences of regional transport on O_3 variations at this site. Justifications have been added in the revised manuscript.

The high O_3 at almost all the AQMSs in the NCP (Figure 1 (a)) indicated a regional O_3 pollution event in this period. The regional-wide homogeneity was to some extent represented by the observations at the sampling site, in view of the comparable O_3 levels. This was confirmed by the strong influences of regional transport on O_3 variations at the site, as discussed in section 3.3.

For details, please refer to lines 144 – 148, pages 5-6.

At the same time, O_3 was also elevated by transport at an average rate of 18.7±4.0 ppbv/hr, as a combined effect of vertical transport (-40.8±20.2 ppbv/hr) and horizontal transport (59.5±19.8 ppbv/hr).

For details, please refer to lines 466 – 469, page 19.

4. Section 3.3, Figure 7: it is shown the ozone in Ji'an were actually come from the vertical and horizontal transport processes while removed through chemical reactions for most of time. Even during the O_3 pollution episodes, the chemical production of O_3 were much smaller than that from vertical transport. The diagnosed results again showed that this site is not ideal for the study of the Ozone-NO_x-VOCs sensitivity and significantly reduced the value of current study.

Thanks for the comment. It is true that regional transport made considerable contributions to O_3 variation rate in Ji'nan, though the regional O_3 was still originated from the NCP. However, during 9:00 – 15:00 on O_3 episode days, the contributions of chemical reactions (14.0±2.3 ppbv/hr) and transport (18.7±4.0 ppbv/hr) to O_3 variation rate were comparable.

During O_3 episodes, chemical reactions made positive contributions to O_3 production between 09:00 LT and 15:00 LT, with the average hourly O_3 production rate of 14.0±2.3 ppbv/hr. At the same time, O_3 was also elevated by transport at an average rate of 18.7±4.0 ppbv/hr, as a

combined effect of vertical transport (-40.8±20.2 ppbv/hr) and horizontal transport (59.5±19.8 ppbv/hr).

For details, please refer to lines 465 – 469, page 19.

Besides, the O_3-NO_x-VOC sensitivity identified in this study was not necessary to represent the completely local or completely regional photochemistry. In fact, the observation based model simulated the in-situ photochemistry, where the observed concentrations of O_3 precursors could be influenced by both local and regional air. It requires caution to extend the results to all the situations, but it is also hard to negate the possible representativeness of the results. Therefore, we emphasize the in-situ photochemical modeling and acknowledge the limitation of the results in the revised manuscript as follows.

This process was further studied through the simulation of the in-situ photochemistry by PBM-MCM. It should be noted that the simulations were based on the observed concentrations of O_3 precursors, which could be influenced by both local and regional air. It required cautions to extend the results to all the situations in Ji'nan, because the regional effect was not always consistent.

For details, please refer to lines 494 – 498, page 21.

5. Figure 8 and Figure 9, et al.: there is a general problem related to the PMF analysis of the observed VOCs samples. As the observed VOCs concentration were quite different from the emitted values, the PMF analysis is not applicable for the observed VOCs concentrations. To consider the VOCs consumption after emission through an estimation of the photochemical age is also not very helpful. The photochemical ages from different sources would be quite different for this site and also for different compounds. I suggest to remove this part and the following related discussions.

Many thanks for the comment. We agree that the ambient concentrations of VOCs were most likely different from those immediately emitted from the sources, because the VOCs were subject to complicated atmospheric processes (such as dispersion, deposition and chemical reactions). Also due to this, the source apportionment of VOCs using PMF sometimes did not represent the real source emission characteristics and contributions to VOCs. However, as one of the most commonly used receptor models, PMF has been extensively employed to resolve the sources of VOCs with the ambient concentrations as input. We think that this application had some rationalities, if the source apportionment results were explained with caution. What we would like to emphasize is that PMF identified the source contributions to the steady – state concentrations of VOCs in the atmosphere. In fact, the observation – based model to simulate O_3 was also constrained by the steady – state concentrations of VOCs and the other O_3 precursors. That was why PMF was applied in combination with the PBM-MCM model (an observation – based model) in this study. Explanations to the source apportionment results are added as follows.

Since the source apportionment was performed for the ambient O_3 precursors which were already subject to atmospheric processes, such as dispersion, deposition and chemical reactions,

the results represented the source contributions to the steady – state concentrations of O_3 precursors and the corresponding O_3 productions.

For details, please refer to lines 552 – 555, page 23.

On one hand, the source apportionment of VOCs was not the main objective of this study. On the other hand, we agree that uncertainties existed in the results due to the reasons raised by the referee and the limited number of samples. Therefore, the source apportionment has been moved to the Supplement. For details, please refer to Text S2.

6. Figure 9: the ozone production rates from the box model and that from the regional model are not directly comparable. The box model results assumed a well-mixed condition of the PBL. And it is better compared with the PBL averaged value of the ozone production rates from the regional model.

Thanks for the comment. It is true that the box model simulations assumed the well-mix of air pollutants within the boundary layer. However, the model was constrained by the concentrations of O_3 precursors near the surface (~ 22 m a.g.l.) in this study. Therefore, we believe that the results from the box model should be compared with those simulated on the ground-level layer by the regional model. The justifications are provided in the revised manuscript.

Since the field observations were conducted near the surface (~ 22 m a.g.l.), and the box model introduced below was constrained by the observations, the modeling results on the ground-level layer were extracted from WRF-CMAQ for analyses in this study.

For details, please refer to lines 260 – 263, page 10.

7. Figure 10: the solid lines #1 - #6 from different retrieved sources were not so meaningful as discussed above.

Thanks for the comment. We keep the solid lines #1 - #6 in Figure 8 (Figure 10 in the original manuscript) and the corresponding discussions in the main text due to the reasons illustrated in the response to comment #5.

For details, please refer to the response to comment #5.

Causes of a continuous summertime O_3 pollution event in Ji'nan, a central city in the North China Plain

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Abstract: In summer 2017, measurements of ozone (O_3) and its precursors were carried out at an urban site in Ji'nan, a central city in the North China Plain (NCP). A continuous O_3 pollution event was captured during August 4-11, with the maximum hourly O_3 reaching 154.1 ppbv. Model simulation indicated that local photochemical formation and regional transport contributed 14.0±2.3 and 18.7±4.0 ppbv/hr to O_3 increase during 09:00-15:00 local time (LT) in this event, respectively. For local O_3 formation, the calculated OH reactivity of volatile organic compounds (VOCs) and carbon monoxide (CO) was comparable between O_3 episodes and non-episodes (p>0.05), so was the OH reactivity of nitrogen oxides (NO_x). However, the ratio of OH reactivity of VOCs and CO to that of NO_x increased from 2.0±0.4 s^{-1}/s^{-1} during non-episodes to 3.7±0.7 s^{-1}/s^{-1} during O_3 episodes, which resulted in the change of O_3 formation mechanism from

the VOC-limited regime before the O_3 pollution event to the transitional regime during the event. Correspondingly, the simulated local O_3 production rate during the event (maximum: 21.3 ppbv/hr) was markedly higher than that before the event (p<0.05) (maximum: 16.9 ppbv/hr). Given that gasoline and diesel exhaust made large contributions to O_3 precursors and O_3 production rate, constraint on vehicular emissions is the most effective strategy to control O_3 pollution in Ji'nan. The NCP has been confirmed as a source region of tropospheric O_3, where the widespread shift of regimes controlling O_3 formation like the case presented in this study can be expected, due to the substantial reductions of NO_x emissions in recent years.

Keywords: Ozone, local formation, regional transport, volatile organic compound, North China Plain

1 Introduction

Air pollution in the North China Plain (NCP), the largest alluvial plain of China consisting of Beijing, Tianjin and many cities in Hebei, Shandong, and Henan provinces, has attracted much attention in recent years. While the annual average concentration of $PM_{2.5}$ (particulate matters with aerodynamic diameter less than or equal to 2.5 μm) has been reduced under concerted efforts on emission restrictions (Zhang et al., 2015; Lang et al., 2017), the tropospheric ozone (O_3) pollution, which is less visible than haze but may be equivalently harmful to human health, is still severe. At a regional receptor site of the NCP in a mountainous area north of Beijing, Wang et al. (2006) reported the maximum hourly O_3 of 286 ppbv. A year-round observation of O_3 at 10 urban sites in Beijing also revealed high O_3 concentrations through May to August of 2013 (Wang et al., 2015a). Hourly O_3 mixing ratios of up to 120 ppbv were reported on Mt. Tai, the highest mountain in the NCP (1534 m a.s.l.) (Gao et al., 2005). This indicates the significant photochemical O_3 pollution over the entire NCP. Moreover, O_3 has been increasing in the NCP during the last decades (Zhang et al., 2014; Zhang et al., 2015). The increase rate of O_3 at an urban site in Beijing from 2005 to 2011 was quantified as 2.6 ppbv/year (Zhang et al., 2014), comparable to that (1.7-2.1 ppbv/year) at Mt. Tai in the summer between 2003 and 2015 (Sun et al., 2016). Overall, the NCP suffers from severe O_3 pollution, which is even aggravating.

Apart from the intrusion of stratospheric O_3 in some places with high elevations (Cooper et al., 2005; Lin et al., 2015), photochemical formation is the main source of the ground-level O_3. Volatile organic compounds (VOCs), carbon monoxide (CO) and nitrogen oxides (NO_x) are key

precursors of tropospheric O_3 (Crutzen, 1973; Chameides and Walker, 1973; Carter, 1994; Carter et al., 1995). The general chemical reactions R(1) - R(5) show the production of O_3 from the OH initiated oxidation of hydrocarbons (RH) (Jenkin et al., 1997; Atkinson, 2000; Jenkin and Clemitshaw, 2000).

$$RH + OH + O_2 \rightarrow RO_2 + H_2O \quad (R1)$$

$$RO_2 + NO \rightarrow RO + NO_2 \quad (R2)$$

$$RO + O_2 \rightarrow Carbonyls + HO_2 \quad (R3)$$

$$HO_2 + NO \rightarrow OH + NO_2 \quad (R4)$$

$$NO_2 + O_2 + h\nu \rightarrow O_3 + NO \quad (R5)$$

The production of O_3 is generally limited by VOCs or NO_x or co-limited by both VOCs and NO_x, depending upon the chemical composition of air pollutants, particularly the relative OH reactivity of VOCs and NO_x (OH reactivity is the sum of the products of O_3 precursors concentrations and the reaction rate constants between O_3 precursors and OH). Xue et al. (2014) indicated that the summer O_3 formation was limited by NO_x in Lanzhou, consistent with Liu et al. (2010) who identified the NO_x-limited regime in most areas of northwest China. In the southwest, O_3 formation was diagnosed as VOC-limited in Chengdu, but NO_x-limited in Pengzhou due to the large quantities of emissions from petrochemical industry (Tan et al., 2018a). Lyu et al. (2016) reported the VOC-limited regime in Wuhan, central China. The VOC-limited regime has also been repeatedly confirmed for O_3 formation in Shanghai (Xue et al., 2014; Xing et al., 2017) and Nanjing (Ding et al., 2013), eastern China. In the Pearl River Delta of southern China, it was found that O_3 formation was generally limited by VOCs in the southwest, while limited by NO_x in the northeast (Ye et al., 2016). In the NCP, both Han et al. (2018) and Xing et al. (2018) summarized that VOCs limited O_3 formation in most urban areas. However, in the suburban and rural areas, O_3 formation was generally in the transitional regime, *e.g.* Yucheng (Zong et al., 2018), or limited by NO_x, *e.g.* Wangdu (Tan et al., 2018b). From a historical perspective, Jin et al. (2017) pointed out that the sensitivity of O_3 formation to VOCs increased in most Chinese cities, however decreased in some megacities (such as Beijing and Shanghai) due to the stringent control of NO_x emissions in recent years. Different VOCs play non-equivalent roles in O_3 formation. Alkenes, aromatics and carbonyls can be readily oxidized by oxidative radicals (*e.g.* OH) or photolyzed (applicable for carbonyls), leading to O_3 formation (Cheng et al., 2010; Guo

et al., 2013). Therefore, the sources with a bulk emission of these VOCs generally make considerable contributions to the photochemical production of ground-level O_3. For example, Cheng et al. (2010) pointed out that carbonyls increased the peak O_3 production rates at a rural site and a suburban site in South China by 64% and 47%, respectively. Solvent based industry and paint solvent usage with high emissions of aromatics were responsible for more than half of O_3 formation potential in Shanghai (Cai et al., 2010). Carbonyls and alkenes accounted for 71-85% of the total OH reactivity of VOCs in Beijing (Shao et al., 2009).

In addition to the chemical processes, O_3 pollution is also closely associated with meteorological conditions, which influence the formation, transport and accumulation of O_3. Studies (Chan and Chan, 2000; Huang et al., 2005) indicated that tropical cyclone (typhoon) and continental anticyclone are the most common synoptic systems conducive of O_3 pollution in coastal cities of southern China. Many O_3 episodes in eastern China occurred under the control of the west Pacific subtropical high pressure (He et al., 2012; Shu et al., 2016). In the NCP, the summertime O_3 pollution is generally accompanied with a weak high pressure system (Wang et al., 2010). Furthermore, the terrain also plays a role in O_3 pollution. For example, the mountains in north and west of Beijing lead to upslope winds (valley breeze) in daytime, transporting polluted air masses laden with O_3 from the NCP to Beijing (Lin et al., 2008). Overall, the causes of O_3 pollution are generally complicated and need to be analyzed case by case.

The NCP is the region with the largest emission amount of air pollutants in China (Gu et al., 2014; Li et al., 2017), partially accounting for the severe O_3 pollution there. In addition, O_3 pollution in the NCP is closely related to the synoptic systems and topographic features (Chen et al., 2009; Zhang et al., 2016). For example, the strong photochemical production of O_3 in urban plumes of Beijing was found by Wang et al. (2006), while the contribution of regional transport was revealed by the enhanced O_3 production at a rural site in the NCP under southerly winds (Lin et al., 2008). Through the review of synoptic systems in the NCP from 1980 to 2013, Zhang et al. (2016) concluded that the air quality was generally unhealthy under weak East Asian Monsoons. Moreover, a decadal statistical analysis indicated that meteorological factors explained ~50% of the O_3 variations in Beijing (Zhang et al., 2015). Despite many previous studies, the evolutions of the synoptic and photochemical processes in O_3 pollution events, and their contributions to the non-attainment of O_3 have been seldom looked into in the NCP.

Besides, the local and regional contributions to the elevated O_3 in the NCP are not unambiguously quantified, limited by the deficiencies in model representation of either physical or local chemical processes. The situation was even much worse for Ji'nan, the capital of Shandong province. As early as 2000s, studies (Shan et al., 2008; Yin et al., 2009) reported the maximum hourly O_3 of 143.8 ppbv and 147.8 ppbv in June 2004 and 2005, respectively. Even higher O_3 (198 ppbv) was observed at a rural site downwind of Ji'nan in June 2013 (Zong et al., 2018). However, almost no study was carried out to explore the mechanisms responsible for high O_3 there, though it has been confirmed that air pollution in the NCP cities like Ji'nan influenced air quality in Beijing (Lin et al., 2008; Wang et al., 2010). To better understand O_3 pollution in the NCP, this study investigated the causes of an O_3 episode lasting for eight days in Ji'nan in the summer of 2017. The analyses presented here focus on the synoptic systems dominating Shandong Peninsula during this event; the chemical profiles of O_3 and O_3 precursors; and the simulation of factors contributing to O_3 in Ji'nan with the aid of a chemical transport model and a photochemical box model. In addition, we propose feasible O_3 control measures based on the source-resolved OH reactivity of VOCs and NO_x.

2 Methodology

2.1 Site description

The air quality monitoring and sample collection were carried out on the rooftop of a 7-story building on the campus of Shandong University from July 15 to August 14, 2017. The campus is located in the urban area of Ji'nan, and the site is about 50 m from a main road (Shanda South Road) outside the campus. Figure 1 shows the locations of the sampling site (36.68 °N, 117.07 °E, 22 m a.g.l.) and some surrounding urban air quality monitoring stations (AQMSs) set up by China National Environmental Monitoring Center (CNEMC). Also shown are the observed O_3 and monitored rainfall averaged over August 4-11, 2017 when O_3 episodes occurred in Ji'nan. It is noteworthy that the days with maximum hourly O_3 exceeding 100 ppbv (Grade II of National Ambient Air Quality Standard) were defined as O_3 episode days. O_3 data in hourly resolution at the AQMSs were obtained from the website of CNEMC (http://www.cnemc.cn/). The high O_3 at almost all the AQMSs in the NCP (Figure 1 (a)) indicated a regional O_3 pollution event in this period. The regional-wide homogeneity was to some extent represented by the observations at

the sampling site, in view of the comparable O_3 levels. This was confirmed by the strong influences of regional transport on O_3 variations at the site, as discussed in section 3.3.

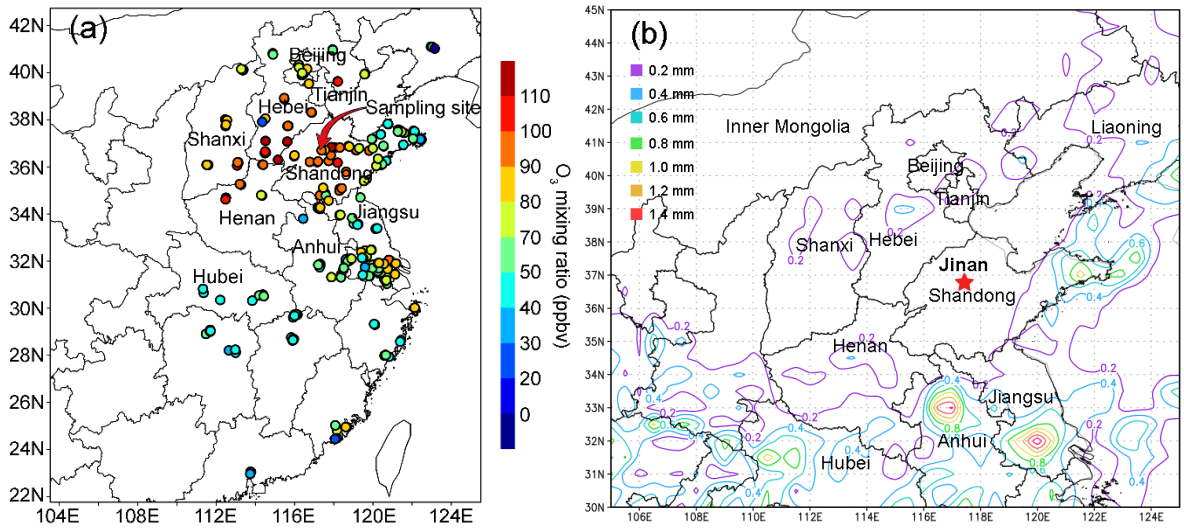


Figure 1 (a) Locations of the sampling site and the CNEMC AQMSs, and the average observed O_3 at 14:00 LT on August 4-11, 2017 (colored circles). The sampling site is overlapped with the nearest AQMS in Ji'nan. (b) Rainfall distribution, in millimeters (mm), averaged over August 4-11, 2017.

2.2 Air quality monitoring and sample collection

2.2.1 Continuous monitoring of air pollutants and meteorological parameters

O_3, NO and NO_2 were continuously monitored at the sampling site between July 15 and August 14, 2017. The air was drawn through a 4 m Teflon tube by the pumps in the trace gas analyzers with the total flow rate of 2 L/min (1.4 L/min for O_3 analyzer and 0.6 L/min for NO_x analyzer). The inlet was located ~1 m above the rooftop of the 7-story building (~22 m a.g.l.). O_3 and NO/NO_x were detected with a UV photometric based analyzer and a chemiluminescence NO-NO_2-NO_x analyzer, respectively (see Table S1 for the specifications). The lowest NO observed during the sampling period was 2.4 ppbv, 6 times (600% of) the lower detection of the NO_x analyzer (0.4 ppbv). Taking the measurement accuracy of <15% into consideration, we believe that the NO measurements were basically reliable. NO_2 was calculated from the difference between NO and NO_x. Studies indicated that NO_2 monitored with chemiluminescence was generally overestimated due to the conversion of the total odd nitrogen (NO_y) to NO by

molybdenum oxide catalysts (McClenny et al., 2002; Dunlea et al., 2007; Xu et al., 2013). The positive bias was more significant in more aged air masses, resulting from higher levels of NO_z (NO_z = NO_y - NO_x) (Dunlea et al., 2007). The average overestimation of NO_2 was 22% in Mexico City, which even increased to 50% in the afternoon (Dunlea et al., 2007). Xu et al. (2013) suggested that the chemiluminescence monitors overestimated NO_2 by less than 10% in urban areas with fresh emission of NO_x, but the positive bias went up to 30-50% at the suburban sites. As described in section 2.1, our sampling site was located in the urban area of Ji'nan and was only ~50 m to a main road. Therefore, we infer that NO_2 might not be significantly overestimated in this study. However, the larger overestimations could be expected during O_3 episodes, because the stronger photochemical reactions enhanced the productions of many NO_z species. We adopted 30% (minimum bias in suburban area) and 10% (maximum bias in urban area) as the maximum fraction of NO_2 overestimation during episodes and non-episodes at this urban site, respectively. The influences of the NO_2 measurement interferences on the results were discussed where necessary.

The hourly concentrations of sulfur dioxide (SO_2) and CO were acquired from a nearest AQMS of CNEMC which is ~1 km from our sampling site. Year-round monitoring of inorganic trace gases was conducted at this AQMS, where the air was drawn into the analytical instruments at a flow rate of 3 L/min through an inlet, ~1 m above the rooftop of a 5-story building (~ 16 m a.g.l.). The specifications of the instruments deployed at the AQMS are also provided in Table S1. The hourly concentrations of O_3 and NO_2 measured at our sampling site agreed well with those reported at the AQMS (NO data was not available on CNEMC website), with the slope of 1.04 (R^2 = 0.82) and 1.13 (R^2 = 0.71) for O_3 and NO_2 in the linear least square regressions, respectively (Figure S1). Due to the instrumental differences and/or differences in sources and sinks of air pollutants at the two sites, the agreements were worse at low mixing ratios for both O_3 and NO_2. Therefore, we only used SO_2 and CO monitored at the nearest AQMS in this study, which had lower photochemical reactivity than O_3 and NO_2, and were more homogeneous at a larger scale.

In addition, the meteorological parameters, including wind speed, wind direction, pressure, temperature and relative humidity, were monitored at the sampling site by a widely used weather station (China Huayun group, Model CAWS600-B). The daily total solar radiation was obtained

from the observations at a meteorological station in Ji'nan (36.6 °N, 117.05 °E, 170.3 m a.s.l), 9 km to our sampling site.

2.2.2 Sample collection and chemical analysis

The VOC and oxygenated VOC (OVOC) samples were collected on 9 selective days (*i.e.*, July 20 and 30, August 1, 4-7 and 10-11), referred to as VOC sampling days hereafter. The days were selected to cover the periods with relatively high and low levels of O_3. The high O_3 days were forecasted prior to sampling based on the numerical simulations of meteorological conditions and air quality. In total, 6 out of 9 VOC sampling days were O_3 episode days with the maximum hourly O_3 ranging from 100.4 to 154.1 ppbv. On each day (regardless of episode or non-episode), 6 VOC/OVOC samples were collected between 08:00 and 18:00 LT every 2 hours with the duration of 1 hour for VOC and 2 hours for OVOC samples. VOC samples were collected with 2 L stainless steel canisters which were cleaned and evacuated before sampling. A flow restrictor was connected to the inlet of the canister to guarantee 1 hour sampling. OVOC were sampled with the 2,4-dinitrophenylhydrazine (DNPH) cartridge, in front of which an O_3 scrubber was interfaced to remove O_3 in the air. A pump behind the DNPH cartridge drew the air at a flow of 500 L/min. After sampling, all the DNPH cartridges were stored in a refrigerator at 4 °C until chemical analysis.

VOC samples were analyzed with a gas chromatograph-mass selective detector/flame ion detector/electron capture detector system (Colman et al., 2001). In total, 85 VOCs, including 59 hydrocarbons, 19 halocarbons and 7 alkyl nitrates, were quantified. The overall ranges of the detection limit (DL), accuracy and precision for VOCs analysis were 1-154 pptv, 1.2-19.8% and 0.1-17.9%, respectively. The analysis results given by this system have been compared with those analyzed by UCI and good agreements were achieved (Figure S2). OVOC samples were eluted with 5 mL acetonitrile, followed by analysis with the high performance liquid chromatography. The DL, accuracy and precision for all OVOCs analysis were within the range of 3-11 pptv, 0.32-0.98% and 0.01-1.03%, respectively.

2.3 Model configuration

2.3.1 Chemical transport model

To analyze the processes contributing to high O_3 in Ji'nan, a chemical transport model, the Weather Research Forecast-Community Multi-scale Air Quality (WRF-CMAQ), was utilized to simulate O_3 in this study. WRF v3.6.1 was run to provide the offline meteorological field for CMAQ v5.0.2. A two-nested domain was adopted with the resolution of 36 km (outer domain) and 12 km (inner domain), respectively. As shown in Figure S3, the outer domain covered the entire continental area of China aiming to provide sufficient boundary conditions for the inner domain, which specifically focused on eastern China.

We used the 2012-based Multi-resolution Emission Inventory for China (MEIC) to provide anthropogenic emissions of air pollutants, which was developed by Tsinghua University specific for China, with the grid resolution of 0.25 °×0.25 ° (Zhang et al., 2007; He, 2012). Five emission sectors, namely transportation, agriculture, power plant, industry and residence were included in MEIC. The emission inventory was linearly interpolated to the domains with consideration of the earth curvature effect. For grids outside China, the air pollutant emissions were derived from INTEX-B (Intercontinental Chemical Transport Experiment-Phase B) Asian emission inventory (Zhang et al., 2009). Consistent with many previous studies (Jiang et al., 2010; Wang et al., 2015b), the Model of Emissions of Gases and Aerosols from Nature (MEGAN) was used to calculate the biogenic emissions. The physical and chemical parameterizations for WRF-CMAQ were generally identical to those described in Wang et al. (2015b), with some improvements. Firstly, the carbon bond v5 with updated toluene chemistry (CB05-TU) was chosen as the gas phase chemical mechanism (Whitten et al., 2010). Secondly, a single-layer urban canopy model (Kusaka and Kimura, 2004) was used to model the urban surface-atmosphere interactions. Thirdly, the default 1990s U.S. Geological Survey data in WRF was replaced by adopting the 2012-based moderate resolution imaging spectroradiometer (MODIS) land cover data for eastern China. The substitution was performed to update the simulation of boundary meteorological conditions (Wang et al., 2007).

An integrated process rate (IPR) module incorporated in CMAQ was used to analyze the processes influencing O_3 concentration. Through solving the mass continuity equation established between the overall change of O_3 concentration with time and the change of O_3 concentration caused by individual processes, including horizontal diffusion (HDIF), horizontal advection (HADV), vertical diffusion (VDIF), vertical advection (VADV), dry deposition

(DDEP), net effect of chemistry (CHEM) and cloud processes (CLD), the contributions of the processes to O_3 variation rate were determined. Note that the estimate of CHEM is influenced by the estimate of O_3 precursor emissions, the simulation of meteorological conditions and the chemical mechanism, all the three aspects should be taken into account wherever CHEM is discussed. The IPR analysis has been widely applied in process diagnosis of O_3 pollution (Huang et al., 2005; Wang et al., 2015b). Since the field observations were conducted near the surface (~ 22 m a.g.l.), and the box model introduced below was constrained by the observations, the modeling results on the ground-level layer were extracted from WRF-CMAQ for analyses in this study.

2.3.2 Photochemical box model

A Photochemical Box Model incorporating the Master Chemical Mechanism (PBM-MCM) was used to study the in situ O_3 chemistry, in view of the detailed (species-based) descriptions of VOC degradations in the MCM (Saunders et al., 2003; Lam et al., 2013). The PBM model was localized to be applicable in Ji'nan, with the settings of geographic coordinates, sunlight duration and photolysis rates. The photolysis rates were calculated by the TUV model (Madronich and Floke, 1997). Specifically, the geographical coordinates, date and time were input into the TUV model, initializing the calculation of solar radiation with the default aerosol optical depth (AOD), cloud optical depth (COD), surface albedo and other parameters. Then, COD was adjusted to make the calculated daily total solar radiation progressively closer to the observed value. When the difference between the calculated and observed solar radiation were less than 1%, the input parameters with the adjusted COD were accepted. Based on the settings, the hourly solar radiations and the photolysis rates of O_3 ($J(O^1D)$) and NO_2 (JNO_2) were calculated by the TUV model, and applied to PBM-MCM for O_3 chemistry modelling. Table S2 shows the daily maximum $J(O^1D)$ and JNO_2 on the VOC sampling days. The MCM v3.2 (http://mcm.leeds.ac.uk/MCM/) used in the present model consists of 17,242 reactions among 5,836 species. The measurements of O_3 and its precursors at 00:00 on each day were used as the initial conditions for each day's modelling. The initial O_3, as the O_3 left over from the days before the modelling day, accounted for a part of the primary OH production. Hourly concentrations of 46 VOCs, 4 OVOCs and 4 trace gases (SO_2, CO, NO and NO_2), as well as hourly meteorological parameters (temperature and relative humidity) were input into the model,

so that the model was constrained to observations. The hourly observed O_3 were not input, as it was the species to be modeled. The Freon, cycloalkanes and methyl cycloalkanes with low O_3 formation potentials were not included in model input. Also omitted were the species whose concentrations were lower than the detection limits in more than 20% of the samples, such as the methyl hexane and methyl heptane isomers. For the hours when measurement data were not available, the concentrations were obtained with linear interpolation. Some secondary species, such as formaldehyde (HCHO), acetaldehyde and acetone, were input into the model to constrain the simulation. Since other secondary species, *e.g.*, PAN and HNO_3 were not observed in this study, their concentrations were calculated by the model. Dry deposition was considered for all the chemicals by setting the deposition velocities identical to those in Lam et al. (2013). Since NO and NO_2 were separately measured and input into the model, they experienced different reactions as described by the species-based chemical mechanisms.

The simulations were separately carried out on all the VOC sampling days. To spin-up the model, the concentrations of air pollutants and meteorological conditions which were the same as those on the day of interest were input into the model for 72-h simulation before the modelling on that day. The model treated the air pollutants to be well-mixed in the boundary layer, without consideration of dilution and transport. O_3 in the free troposphere was not considered either, due to the lack of O_3 observations above the boundary layer over Ji'nan. This might hinder the accurate reproduction of the observed O_3, particularly on the days when advection and diffusion were strong. Since the model mainly described the in situ photochemistry, it was validated through comparison with the CHEM process simulated by WRF-CMAQ. The simulated O_3 production rates were output every hour, which were integrated values over every 3600 s (model resolution: 1 s). More details about the model configuration can be found in Lam et al. (2003) and Lyu et al. (2017).

3. Results and discussion

3.1 Overall characteristics of O_3 pollution in Ji'nan

Figure 2 shows the time series of trace gases, the OH reactivity of VOCs, CO and NO_x, and meteorological conditions on the VOC sampling days in Ji'nan (Trace gases in the whole sampling period are shown in Figure S4). All the OH reactivity values discussed in this study were calculated rather than observed. The OH reactivity values of VOCs are grouped into those

of carbonyls, biogenic VOCs (BVOCs), aromatics, alkenes and alkanes (Table S3 lists the VOCs included in each group). The reaction rate constants between O_3 precursors and OH in calculation of OH reactivity were adopted from the MCM v3.2 (http://mcm.leeds.ac.uk/MCM/). The average total OH reactivity on all the VOC sampling days (19.4±2.1 s^{-1}) was comparable to that reported in New York (19±3 s^{-1}, Ren et al., 2003), Houston (9-22 s^{-1}, Mao et al., 2010) and Beijing (15-27 s^{-1}, Williams et al., 2016). Consistent with the previous studies in urban areas (Ren et al., 2003; Yang et al., 2016 and references therein), NO_x was the largest contributor (28.9±1.9%) to the total OH reactivity. Noticeably, 20.5±4.1% of the total OH reactivity was attributable to BVOCs, which was much higher than the contributions in urban areas (<10%) reviewed by Yang et al. (2016). The elevated isoprene levels (2.2±0.6 ppbv during episodes and 0.9±0.3 ppbv during non-episodes) under high temperature (mean: 31 ℃) explained the considerable contribution of BVOCs to the total OH reactivity in this study.

O_3 episodes were captured on 6 out of the 9 VOC sampling days, with the highest O_3 of 154.1 ppbv at 13:00 LT on August 10. It was found that the total OH reactivity of VOCs and CO ($OH\ reactivity_{VOCs+CO}$) was comparable between O_3 episodes (14.8±2.0 s^{-1}) and non-episodes (12.2±3.0 s^{-1}), so was the OH reactivity of NO_x (4.7±0.8 s^{-1} and 6.9±1.9 s^{-1} during episodes and non-episodes, respectively). Taking the positive biases of NO_2 measurement into account (section 2.2.1), we found that the OH reactivity of NO_x was overestimated by the maximum of 17.5±1.1% and 5.4±0.7% during O_3 episodes and non-episodes, respectively. In the case of maximum overestimations, the actual OH reactivity of NO_x during episodes (4.0±0.7 s^{-1}) might be lower (p<0.05) than that during non-episodes (6.6±1.9 s^{-1}). The high OH reactivity during non-episodes mainly occurred on July 30 and August 1, due to the high pressure, weak solar radiation and low temperature. Despite the comparable OH reactivity, we found that the ratio of $\frac{OH\ reactivity_{VOCs+CO}}{OH\ reactivity_{NOx}}$ during O_3 episodes (3.7±0.7 s^{-1}/s^{-1}) was higher (p<0.05) than during non-episodes (2.0±0.4 s^{-1}/s^{-1}). It was likely that the difference was even larger, due to the more significant overestimation of NO_2 during episodes. This indicated that O_3 formation was more limited by VOCs during non-episodes than during episodes. In fact, O_3 formation in Ji'nan switched to the transitional regime during episodes from the VOC-limited regime during non-episodes (see section 3.4.2). This partially explained the building-up of O_3 on episode days, as O_3 productions were generally the highest in the transitional regime.

From the perspective of meteorological conditions, O_3 episodes had relatively stronger solar radiation, higher temperature, lower relative humidity and weaker winds (p<0.05). This is reasonable as O_3 formation and accumulation are generally enhanced under these weather conditions. As aforementioned, the solar radiation on July 30 was much weaker than those during O_3 episodes, which was probably the most critical factor leading to low O_3 on this day. Figure S5 shows the COD retrieved from the terra/MODIS (https://ladsweb.modaps.eosdis.nasa.gov/search/imageViewer/1/MOD06_L2--61/2017-08-06/DB/Site:142/2873994172--3) at 10:00 – 12:00 LT of the VOC sampling days. The terra/MODIS image revealed thick cloud cover with high COD over Ji'nan on July 30, explaining the weak solar radiation. In fact, obvious anti-correlation existed between solar radiation and the COD. The influences of cloud cover/ COD and solar radiation on O_3 pollution during the study period in Ji'nan are discussed in section 3.2. Unlike many previous findings that O_3 pollution was aggravated by high pressure (Chan and Chan, 2000; Zhao et al., 2009), the sea-level pressure during O_3 episodes (993.4±0.2 hPa) was significantly lower than during non-episodes (996.1±0.4 hPa) in this study (p<0.05). When O_3 reached its hourly maximum on August 10 (154.1 ppbv), the pressure was at its lowest value (990.2 hPa). The continuously severe O_3 pollution event under low pressure is further investigated below.

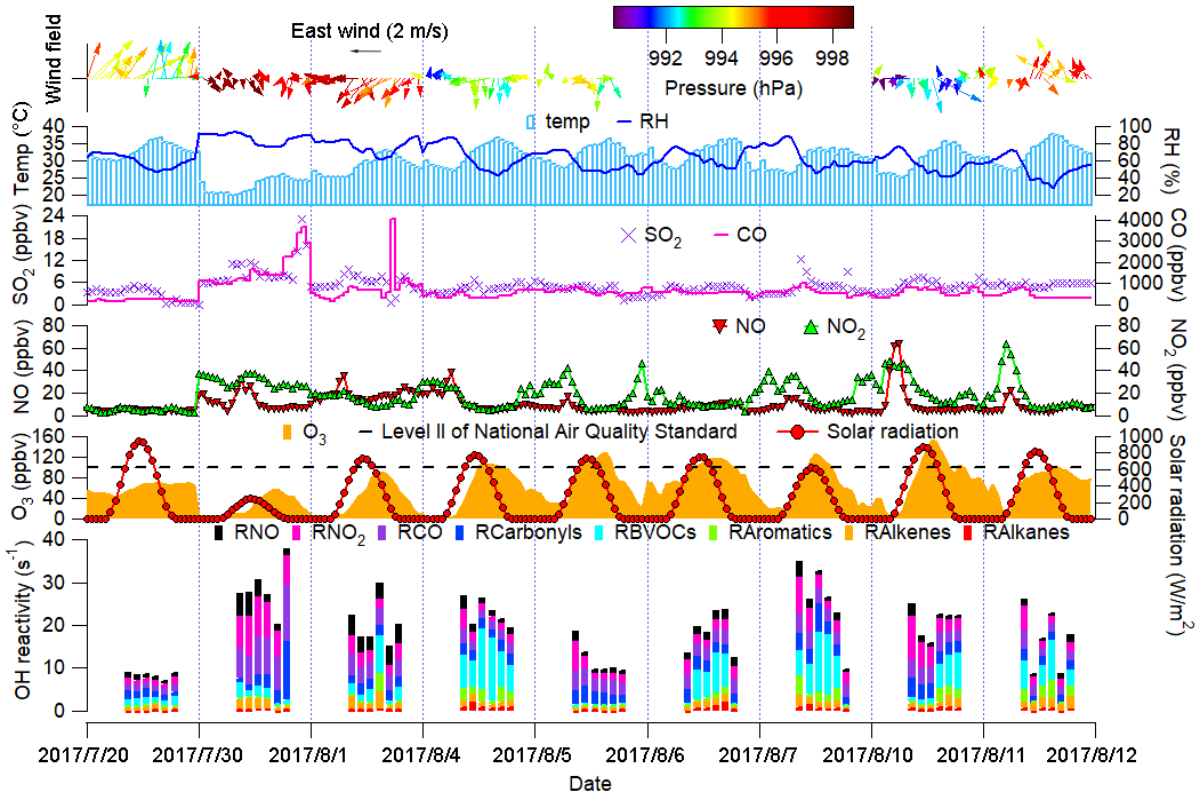


Figure 2 Time series of trace gases, OH reactivity of O_3 precursors and meteorological parameters. Wind speed and wind direction were not monitored from 17:00 LT on August 5 to 23:00 LT on August 7 due to malfunction of the weather station. RX in the bottom panel is the OH reactivity of species/group X.

3.2 Synoptic processes and relationship with O_3 pollution

Obviously, this O_3 pollution event was accompanied by unique weather conditions (*e.g.* low pressure on high O_3 days), which needed to be further studied. Figure 3 displays the average weather charts at 14:00 LT during O_3 episodes and non-episodes (weather charts on individual VOC sampling days are shown in Figure S6). Clearly, the temperature over Shandong Peninsula was much higher during O_3 episodes than non-episodes, which favored O_3 formation on episode days. Additionally, southerly and southwesterly winds originating from the inland areas (Hubei, Henan, and Anhui provinces) prevailed in central and western Shandong province during O_3 episodes. In contrast, the winds were generally from the sea or coastal region in Jiangsu province during non-episodes. O_3 and O_3 precursors might be transported to Ji'nan in the former cases. Though the winds were from the relatively clean sea and coastal regions during non-episodes,

the concentrations of O_3 precursors on July 30 and August 1 were still high, which were mainly caused by weather conditions (high pressure, low temperature and low solar radiation), as discussed in section 3.1. Further, we also noted that the winds changed direction from southwest to northwest around Ji'nan during O_3 episodes. This meant that there might be a local circulation hampering the dispersion of air pollutants during episodes. It seems that the turning-round of the winds around Ji'nan was associated with the sea breeze from Bohai Bay. This was very similar to the convergence of continental air and sea breeze (from South China Sea) in Pearl River Delta (Fung et al., 2005; Lo et al., 2006). Overall, the wind fields were more favorable for regional transport and accumulation of air pollutants in Ji'nan during O_3 episodes. In addition, Shandong Peninsula was under a uniform pressure field with the sea-level pressure of 1000-1001 hPa during O_3 episodes, implying the relatively stagnant weather conditions unfavorable for the dispersion of air pollutants.

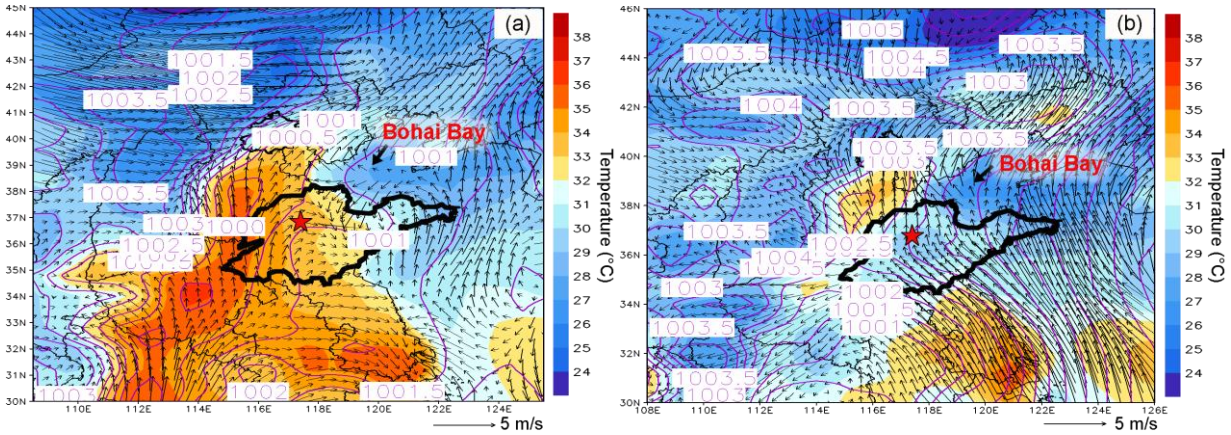


Figure 3 Weather chart at 14:00 LT averaged over (a) O_3 episodes and (b) non-episodes. The red star represents Ji'nan. The dark black line is the boundary of Shandong province. Bohai Bay is located to the northeast of Shandong province. Numbers in the figure are sea-level pressures in unit of hPa.

To better understand the relationship between O_3 pollution and the synoptic systems, Table 1 summarizes the synoptic systems, weather conditions and air mass origins on all the VOC sampling days. The weather charts at surface level and 500 hPa on August 1, 4, 7, 10 and 13 are presented in Figures S7-S8, showing the evolution of the synoptic systems. To identify the origins of air masses, the 48 hour backward trajectories of air masses are shown in Figure 4. The trajectories were computed using the Hybrid Single Particle Lagrangian Integrated Trajectory

(HYSPLIT) Model v 4.9. Each trajectory was calculated for 48 hours and the calculation was done every 6 hours (4 trajectories each day). Our sampling site (36.68 °N, 117.07 °E) was set as the starting point of the backward trajectories with the height of 500 m a.s.l. The discrepancy between the wind direction and origin of air masses, *e.g.* on August 1 and 11, was likely due to the air recirculation at the ground level.

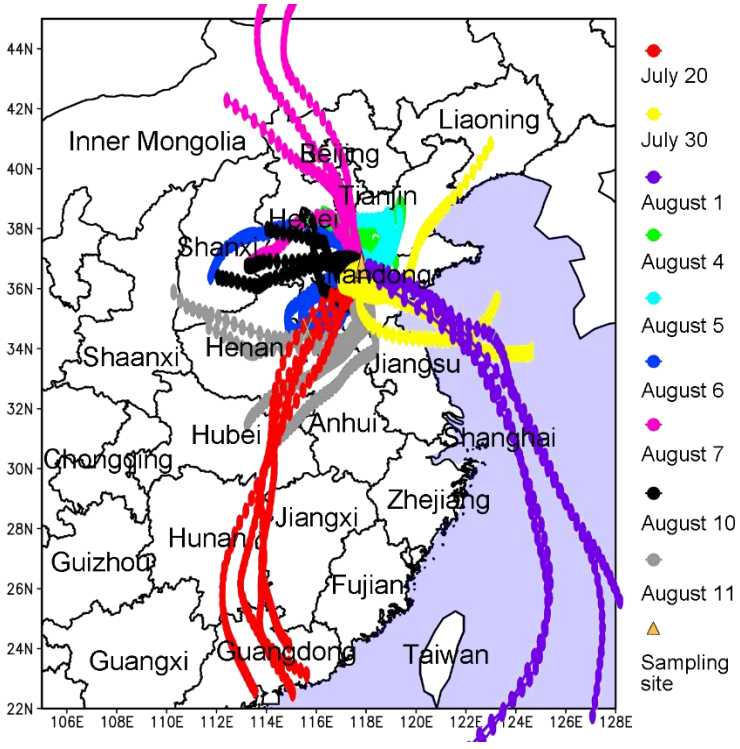
It was found that Ji'nan was under the control of the Western Pacific Subtropical High (WPSH) on July 20 (weather chart on 500 hPa is not shown here), and the air masses arriving in Ji'nan originated from South China 48 hours prior (Figure 4). As anticipated, the WPSH caused high temperatures and the intensive solar radiation during the study period (maximum: 943 W/m^2) in Ji'nan (Figure 2), which was conducive to O_3 formation. However, the winds on July 20 were the strongest in the entire VOC sampling period, with the highest hourly wind speed of 3.9 m/s. The strong winds facilitated the transport and dispersion of O_3 precursors and locally formed O_3 on July 20 (refer to the low levels of O_3, O_3 precursors and OH reactivity in Figure 2). The WPSH moved southward on the following days and Ji'nan was under a uniform pressure field, which was formed in the peripheries of two low pressure systems (two rain belts as shown in Figure 1), *i.e.* one over Central China and another over North China (Figure S7). Thus, the pressure in Ji'nan was relatively high (997.1±0.3 hPa), compared to the south and north regions. This synoptic system lasted for several days until August 7, covering 2 non-episode days and 4 O_3 episode days. The low O_3 values on July 30 and August 1 were mainly attributable to the weak solar radiation and low temperature as discussed above.

In contrast, continuously strong solar radiation with low COD (Figure 2 and Figure S5), high temperature and continental air masses (Figure 4) were observed on August 4-7. This, in addition to the shift of O_3 formation mechanism (see sections 3.1 and 3.4.2), explained the prolonged O_3 pollution event. On August 10, the rain belt over North China moved southward, forming a deep low pressure trough over the NCP and Ji'nan was behind the trough (Figure S8 (d)). The low pressure trough is a typical synoptic system conducive of O_3 pollution, resulting from the intrusion of O_3 in the stratosphere and/or the upper troposphere (Chan and Chan, 2000). Moreover, there was nearly no cloud cover over the entire NCP on August 10 (Figure S5). Consequently, the highest O_3 (154.1 ppbv) in this sampling campaign was observed on August 10. On August 11, the low pressure system continued to extend to the Yellow Sea. O_3 decreased

substantially on this day with the disappearance of the low pressure trough and the weakening of solar radiation, though the hourly maximum O_3 still reached 100.4 ppbv. On the following days, the precipitations relieved the O_3 pollution in Ji'nan.

Table 1 Summary of the synoptic systems, weather conditions and air mass origins on VOC sampling days.

Date	O_3 maximum (ppbv)	Episode/non-episode	Synoptic system Weather condition	Air mass origin
July 20	71.0	Non-episode	WPSH, strong southwesterly winds	Continental air masses from South China
July 30	57.6		Uniform pressure field (weak high pressure), rain, fog, calm winds	Marine air masses
August 1	90.6		Uniform pressure field (weak high pressure), northeasterly winds	
August 4	107.5	Episode	Uniform pressure field (weak high pressure), northeasterly winds	Continental air masses from Shandong province
August 5	128.2		Uniform pressure field (weak high pressure), calm winds	
August 6	116.9		Uniform pressure field (weak high pressure), southwesterly winds	
August 7	126.9		Uniform pressure field (weak high pressure), calm winds	Continental air masses from the north
August 10	154.1		Low-pressure trough, calm winds	Continental air masses from the west
August 11	100.4		Subtropical high, southeasterly winds	Continental air masses from the southwest



437

438 Figure 4 Forty eight hour backward trajectories calculated every 6 hours, with Ji'nan (36.68 ℃N,
439 117.07 ℃E, 500 m a.g.l.) as the starting point. The trajectories are simulated by HYSPLIT v4.9.
440 The water areas are highlighted in blue.

441 **3.3 O_3 simulation and process analysis**

442 The observations indicated the likely different regimes controlling local O_3 formation and the
443 potential impacts of regional transport. To understand the atmospheric chemistry and dynamics,
444 as well as their roles in this O_3 pollution event, the WRF-CMAQ was applied. Figure 5 shows
445 the hourly average simulated and observed O_3 on the VOC sampling days in Ji'nan. Overall, the
446 model well reproduced the magnitudes and diurnal patterns of the observed O_3, except for the
447 higher simulated O_3 on July 20 and the under-prediction of O_3 on August 1, 7 and 10.
448 Discussions on the discrepancies and the detailed model validation are provided in Text S1,
449 Figures S9-S11 and Table S4.

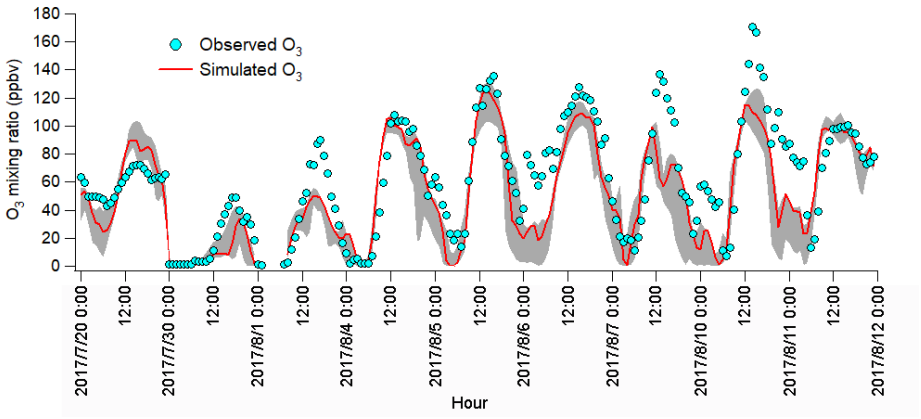


Figure 5 Hourly average mixing ratios of the WRF-CMAQ simulated and observed O_3 in Ji'nan. The grey area shows the minimum and maximum simulated O_3 at the sampling site and 8 adjoining grids (12×12 km^2 for each grid).

The IPR analysis quantifies the contributions of different processes to the O_3 production rate, as shown in Figure 6. HDIF and HADV were summed as horizontal transport (HTRA), and the vertical transport (VTRA) was a total representative of VDIF and VADV. It was found that chemical reactions generally led to O_3 decrease during non-episodes. The negative contributions of chemical reactions on July 20 coincided with the very low concentrations of O_3 precursors and the flat diurnal cycle of O_3 (Figure 2). The chemical destruction of O_3 on July 30 and August 1 was most likely related to the relatively weak solar radiation and low temperature, which inhibited the in situ photochemical reactions. In fact, the negative chemical effect should be considered as the titration of NO to regionally-transported and/or background O_3 and the depletion of O_3 by the freshly emitted NO near the sources (Beck and Grennfelt, 1994; Sillman, 1999). Conversely, the combined effect of horizontal and vertical transport was to increase O_3.

During O_3 episodes, chemical reactions made positive contributions to O_3 production between 09:00 LT and 15:00 LT, with the average hourly O_3 production rate of 14.0±2.3 ppbv/hr. At the same time, O_3 was also elevated by transport at an average rate of 18.7±4.0 ppbv/hr, as a combined effect of vertical transport (-40.8±20.2 ppbv/hr) and horizontal transport (59.5±19.8 ppbv/hr). The negative contribution of vertical transport to O_3 in these hours might be caused by the updraft with the increase of temperature in the city. The O_3 enhancement by horizontal transport could be explained by the westerly to northerly airflows and the high O_3 in the NCP where the airflows originated or passed (Figure 4 and Figure S10). The much higher O_3 over the

NCP than in the surrounding regions indicated that the NCP was an O_3 source in this case. In fact, the transport of O_3 from the lower troposphere over the NCP to the free troposphere and further to northeast China was also presented by Ding et al. (2009).

During 16:00-08:00 LT on O_3 episode days, O_3 was titrated and chemically consumed at the rate of 49.4±6.3 ppbv/hr. This was reasonable in view of the fresh vehicular emissions (particularly NO_x) in the morning and evening rush hours, when the titration of O_3 by NO produced NO_2. The NO_2 was carried over to the other places by air circulation, and/or oxidized to NO_3 and N_2O_5, which could further react with aerosol to form HNO_3 and $ClNO_2$ in the evening. Horizontal and vertical transport dominated O_3 sources, with the average positive contribution of 5.7±7.0 and 54.5±9.6 ppbv/hr during 16:00-08:00 LT on August 4-11, respectively. The strong vertical transport coincided with the downward winds in the evening, which brought the high-altitude O_3 to the ground, as indicated in Figure S9. However, the sources of O_3 in the upper atmosphere were beyond the scope of this study.

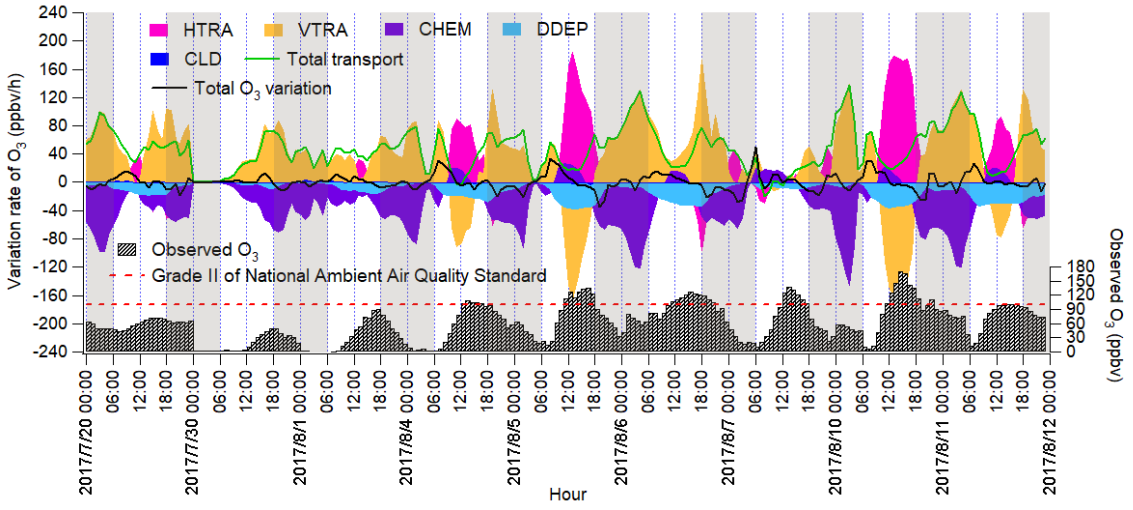


Figure 6 Time series of O_3 variation rate in Ji'nan induced by individual processes calculated based on the change of O_3 per hour. Total transport is the sum of HTRA and VTRA, and the sum of O_3 variation rates attributable to all the processes is represented by total O_3 variation rate. The nighttime (18:00 – 06:00 LT) has been highlighted in grey.

3.4 Local O_3 formation and control

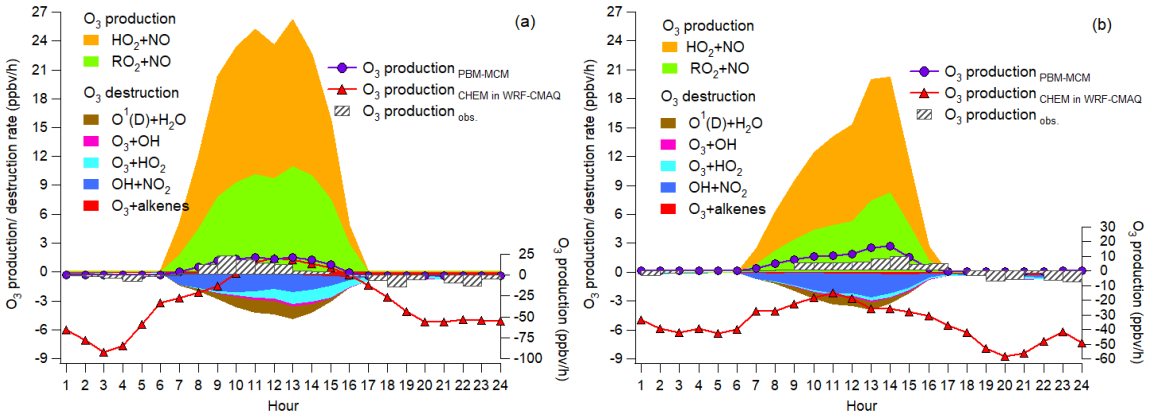
3.4.1 Pathway and source contributions to O_3 production

493 The IPR analyses showed that chemical reactions served as an important source of O_3 on episode
494 days in Ji'nan, particularly during 09:00-15:00 LT when O_3 was at high levels. This process was
495 further studied through the simulation of the in-situ photochemistry by PBM-MCM. It should be
496 noted that the simulations were based on the observed concentrations of O_3 precursors, which
497 could be influenced by both local and regional air. It required cautions to extend the results to all
498 the situations in Ji'nan, because the regional effect was not always consistent. Table S5 lists the
499 production and destruction pathways of O_3 (Thornton et al., 2002; Monks, 2005; Kanaya et al.,
500 2009). Briefly, the oxidation of NO by HO_2 and RO_2 produced NO_2, which led to O_3 formation
501 following NO_2 photolysis (R2 and R4-R5 in introduction). Therefore, the reactions between NO
502 and HO_2/RO_2 were considered as the production pathways of O_3. To account for O_3 destruction,
503 reaction between $O^1(D)$ and H_2O denoted the photolysis of O_3, and reactions of O_3 with OH,
504 HO_2 and alkenes were also included. Furthermore, since HNO_3 was an important sink of NO_2,
505 the reaction between OH and NO_2 was treated to be destructive to O_3. The titration of O_3 by NO
506 was not included in O_3 destruction, because NO_2 produced in this reaction was either not
507 considered as a source of O_3.

508 Figure 7 (a) and (b) show the 24 hour average simulated pathway contributions to O_3 production
509 rate for the 6 O_3 episode days and 3 non-episode days. Also shown are the O_3 production rates
510 simulated by PBM-MCM (O_3 production $_{PBM\text{-}MCM}$), those simulated by WRF-CMAQ simulation
511 (O_3 production $_{CHEM}$), and those calculated from the observed hourly O_3 (O_3 production $_{obs.}$).
512 Overall, O_3 production $_{PBM\text{-}MCM}$ and O_3 production $_{obs.}$ were on the same magnitudes, especially
513 during O_3 episodes with more stagnant weather conditions. This indicated that the PBM-MCM
514 model reasonably reproduced the in situ O_3 photochemistry. Though obvious discrepancies
515 existed between O_3 production $_{CHEM}$ and O_3 production $_{PBM\text{-}MCM}$, they agreed well with each other
516 during 10:00-15:00 LT on episode days, consistent with the finding that chemical reactions made
517 great contributions to O_3 in this period (Figure 6). The lower or even negative O_3 production
518 $_{CHEM}$ resulted from the titration of the regionally transported and/or local background O_3 by NO
519 and the following depletion of NO_2 through reacting with OH and/or transport. Differently,
520 PBM-MCM did not consider the transport of O_3, though the transport effect was partially
521 represented by constraining the model to the observed concentrations of O_3 precursors. In
522 addition, the PBM-MCM was constructed by the observed air pollutants, which were already
523 subject to chemical reactions before being detected by the analytical instruments. This meant that

the reaction between NO and O_3 from the emission to the detection of NO_x was not considered in PBM-MCM. However, as an emission-based model, WRF-CMAQ performed better in describing the reactions immediately after the emissions of air pollutants. Therefore, the chemical destructions of O_3 in the vicinity of NO_x sources also accounted for the aforementioned discrepancy. The obviously higher reaction rate between NO and O_3 simulated by WRF-CMAQ (Figure S12) confirmed our inferences.

During both O_3 episodes and non-episodes, the reaction between HO_2 and NO dominated over "RO_2+NO" in O_3 production, while the O_3 destruction was mainly attributable to the formation of HNO_3, the reaction between O_3 and HO_2 and photolysis of O_3. The net O_3 production rate during O_3 episodes (maximum: 21.3 ppbv/hr) was much (p<0.05) higher than during non-episodes (maximum: 16.9 ppbv/hr), which partially explained the higher O_3 on episode days. In general, "OH+NO_2" serves as the chain terminating reaction in VOC-limited regime of O_3 formation, while the radical-radical reactions take over the role in NO_x-limited regime (Finlayson-Pitts and Pitts, 1993; Kleinman, 2005). Here, we found that the ratio of total reaction rates between "HO_2+RO_2" and "OH+NO_2" substantially increased from 0.2±0.1 during non-episodes to 1.0±0.3 during O_3 episodes (p<0.05). This suggested that O_3 formation during non-episodes was limited by VOCs, while it switched to be co-limited by VOCs and NO_x during O_3 episodes in view of the equivalent role of "HO_2+RO_2" and "OH+NO_2" in terminating the chain reactions.



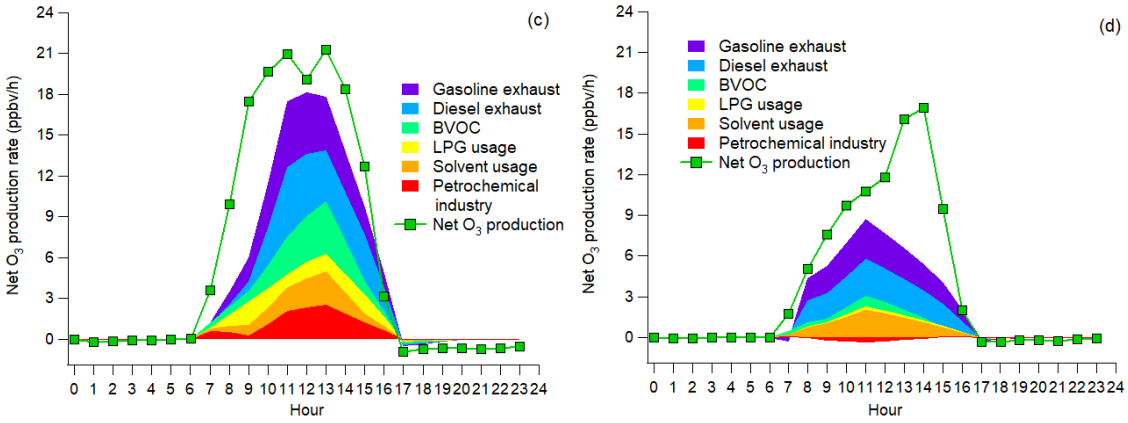


Figure 7 Pathway contributions to O_3 production and destruction rate during episodes (a) and non-episodes (b). Contributions of O_3 precursor sources to net O_3 production rate during episodes (c) and non-episodes (d).

Further, the 24 hour average contributions to net O_3 production rate of different sources of O_3 precursors were identified for the 6 episode days and 3 non-episode days, as presented in Figure 7 (c) and (d). Text S2 and Figure S13 illustrate the source apportionment of O_3 precursors and the simulations of the source-specific contributions to O_3 production rates. The results are presented in Table 2. Since the source apportionment was performed for the ambient O_3 precursors which were already subject to atmospheric processes, such as dispersion, deposition and chemical reactions, the results represented the source contributions to the steady – state concentrations of O_3 precursors and the corresponding O_3 productions. It was found that gasoline exhaust and diesel exhaust were the largest contributors to O_3 production regardless of O_3 episodes or non-episodes. Specifically, the net O_3 production rate was 1.0 ±0.3 ppbv/hr for both gasoline and diesel exhaust during non-episodes, which however increased to 1.8 ±0.6 ppbv/hr for gasoline exhaust and 1.7 ±0.4 ppbv/hr for diesel exhaust during O_3 episodes. This suggested that vehicular emissions played critical roles in building up ground-level O_3 in Ji'nan. If carbonyls were taken into account, the contributions of vehicular emissions to O_3 production rate were even higher than the currently simulated values, due to the dominance of vehicular exhausts in the sources of carbonyls in urban areas (Grosjean et al., 1990; Granby et al., 1997). In addition, the contributions of the other sources to O_3 production rates all increased during O_3 episodes except for solvent usage (p>0.05), as listed in Table 2. It is not surprising to see the coincident increases, in view of the higher simulated and observed overall O_3 production rate during episodes.

Further insight into the percentage contributions (not shown here) found that the contributions of BVOC, LPG usage and petrochemical industry relative to the sum of the O_3 production rates of the 6 sources increased substantially from 9.9±4.2%, 4.3±1.4% and -2.8±1.9% during non-episodes to 19.2±4.3%, 9.1±3.4% and 12.1±3.1% during O_3 episodes, respectively. The increased O_3 production rates by BVOCs could be explained by the increase of isoprene (episodes: 2.2±0.6 ppbv; non-episodes: 0.9±0.3 ppbv), under higher temperature and stronger solar radiation during O_3 episodes. The enhanced O_3 formation from petrochemical industry on episode days was likely associated with the dominance of continental air (Figure 4) and the extensive petrochemical industries in the NCP. For example, the mixing ratio of styrene increased from 54.7±22.0 pptv during non-episodes to 162.3±44.7 pptv during O_3 episodes. The reason for elevated O_3 production rate by LPG usage during episodes was unknown. It is worth noting that the source contributions to O_3 production might have some uncertainty due to the limited number of samples (54 samples) and O_3 precursors (31 VOCs, CO, NO and NO_2) for source apportionment.

Table 2 Contributions to VOCs, CO, NO, NO_2 and O_3 production rate by the sources of O_3 precursors averaged on the VOC sampling days in Ji'nan (Unit: % unless otherwise specified).

Source	VOCs*	CO	NO	NO_2	O_3 production rate (ppbv/hr)	
					O_3 episodes	Non-episodes
GE [1]	25.7±3.6	29.9±2.1	30.9±2.4	22.2±2.4	1.8±0.6	1.0±0.3
DE [2]	17.6±2.4	57.3±5.2	52.0±5.8	54.4±5.8	1.7±0.4	1.0±0.3
BVOC	6.1±2.6	0.0±1.7	0.0±2.8	0.0±2.3	1.2±0.5	0.2±0.1
LPG [3]	14.7±2.0	2.2±1.1	9.1±1.6	4.7±0.9	0.8±0.5	0.1±0.1
Solvent [4]	17.1±3.9	3.1±1.8	5.1±3.8	7.8±3.1	0.8±0.5	0.7±0.3
PI [5]	18.8±3.1	7.4±1.9	2.9±1.8	10.9±2.5	1.0±0.3	-0.1±0.1

VOCs*: VOCs applied in source apportionment (see Text S2).

[1] gasoline exhaust, [2] diesel exhaust, [3] LPG usage, [4] solvent usage and [5] petrochemical industry.

3.4.2 O_3 control measures

Both WRF-CMAQ and PBM-MCM revealed the significant local O_3 production in the O_3 pollution event. The relationships between O_3 and its precursors need to be clarified, so that the science-based control measures can be taken. Throughout the VOC sampling period, the OH

reactivity of VOCs ($OH\ reactivity_{VOCs}$) were within the range of 33-123% of the average $OH\ reactivity_{VOCs}$ during O_3 episodes. For OH reactivity of NO_x ($OH\ reactivity_{NOx}$), the range was 61-242%. The O_3 production rates were simulated in a set of assumed scenarios with different $OH\ reactivity_{VOCs}$ and $OH\ reactivity_{NOx}$. To include the OH reactivity of VOCs and NO_x on all the VOC sampling days, factors from 10% to 140% with the step of 10% were applied to the average diurnal profiles of VOCs and CO during O_3 episodes, while the factors ranged from 10% to 300% with the step of 10% for NO_x. The initial concentrations of all the air pollutants were also scaled by the factors and the model was constrained to these scaled concentrations every hour, except for O_3. It should be noted that the factors applied to CO were exactly the same as those applied to VOCs, therefore we use $VOCs^{\#}$ to represent the sum of VOCs and CO hereafter. The 14 gradients of $OH\ reactivity_{VOCs^{\#}}$ and 30 gradients of $OH\ reactivity_{NOx}$ made up 420 scenarios. Meteorological conditions were exactly the same for all the scenarios and the clear sky was hypothesized. According to the simulations, the maximums of the O_3 production rates occurred at 12:00 LT. Thus, the simulated O_3 production rates at 12:00 LT, as a function of $OH\ reactivity_{VOCs}$ and $OH\ reactivity_{NOx}$, are plotted in Figure 8. Text S3 describes the methods to define the regimes controlling O_3 formation.

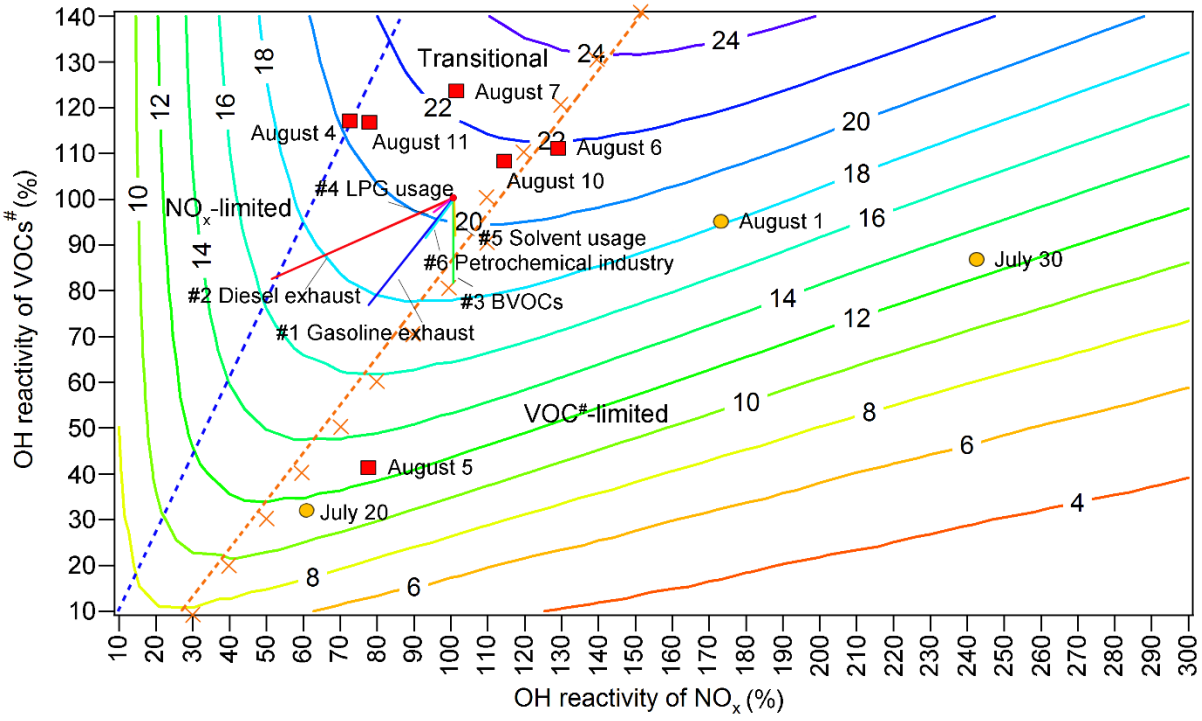


Figure 8 Isopleths of the net O_3 production rate (ppbv/hr) at 12:00 LT as a function of $OH\ reactivity_{VOCs^{\#}}$ and $OH\ reactivity_{NOx}$. The red blocks and orange circles denote the calculated $OH\ reactivity_{VOCs^{\#}}$ and $OH\ reactivity_{NOx}$ at 12:00 LT on O_3 episode and non-episode days, respectively. Each orange cross represents the $OH\ reactivity_{VOCs^{\#}}$ and $OH\ reactivity_{NOx}$ at 12:00 LT in the scenario with highest O_3 production rate at a given $OH\ reactivity_{VOCs^{\#}}$. The orange dashed line and blue dashed line divide O_3 formation into the VOC-limited regime, transitional regime, and NO_x-limited regime.

It was found that O_3 formation was mainly limited by $VOCs^{\#}$ during non-episodes. However, it switched to be co-limited by $VOCs^{\#}$ and NO_x (transitional regime) on episode days with the net O_3 production rate among the highest, except for August 5 when the strong sea breeze diluted air pollutants in Ji'nan and/or intercept the transport of air pollutants from Central China to Ji'nan (Figure S6). In reality, the sensitivity of O_3 formation to NO_x might be underemphasized due to the positive biases of NO_2 measurement (Lu et al., 2010). This effect was expected to be more significant during episodes when the overestimates of NO_2 were higher. However, O_3 formation was not likely only limited by NO_x even during O_3 episodes, which should be still sensitive to VOCs, as NO_2 could not be much overestimated in the urban areas (see section 2.2.1). Therefore, O_3 formation was considered to be in the transitional regime during episodes. This partially explained the increased O_3 during episodes in Ji'nan, given the higher O_3 production rates in transitional regime (Figure 8). Noticeably, the change of regimes controlling O_3 formation is consistent with that predicted by the $\frac{OH\ reactivity_{VOCs^{\#}}}{OH\ reactivity_{NOx}}$ ratio and the ratio of the reaction rates between "HO_2+RO_2" and "OH+NO_2".

The source apportionment of O_3 precursors enabled us to calculate the source-specific $OH\ reactivity_{VOCs^{\#}}$ and $OH\ reactivity_{NOx}$. Accordingly, the variations of O_3 production rates induced by the reductions in source emissions are presented in Figure 8 (straight solid lines #1-#6). The start point of the straight lines corresponded to 100% of the total average $OH\ reactivity_{VOCs^{\#}}$ and $OH\ reactivity_{NOx}$ during O_3 episodes. The end points, however, denoted the $OH\ reactivity_{VOCs^{\#}}$ and $OH\ reactivity_{NOx}$ with the complete elimination of emissions from the individual sources. Therefore, the differences of the O_3 production rate between the start point and end points were the source contributions to the O_3 production rate,

while the lengths of the lines reflected the contributions to the OH reactivity. Further, the simulated O_3 production rates on the lines #1-#6, as a response of reductions in source emissions, are extracted and plotted in Figure S14. Obviously, the highest efficiencies of O_3 reduction could be achieved by cutting diesel exhaust (0.58 ppbv hr^{-1}/10% emission reduction) and gasoline exhaust (0.47 ppbv hr^{-1}/10% emission reduction). In fact, the sensitivity of O_3 production rate to the vehicle exhausts might be somewhat underestimated, due to the exclusion of carbonyls in the source apportionment. However, the reductions of O_3 production rate by cutting 10% of vehicle exhausts were still insignificant, compared to the overall maximum O_3 production rate of 21.3 ppbv/hr during O_3 episodes. This indicated that by only restraining emissions from one to two sources, high percentages of emission reductions were required to sufficiently reduce the O_3 production rate. Otherwise, the combined efforts should be made to control the emissions of O_3 precursors from the diverse sources. In particular, it is essential to get rid of the transitional regime featuring high O_3 production rates and low sensitivities of O_3 production to the precursors.

4 Implications

This study investigates the causes of a severe O_3 pollution event lasting for eight consecutive days in the NCP, one of the most densely populated regions in the world. Photochemical O_3 formation in the lower troposphere of the NCP is demonstrated as the main source, under the synoptic conditions of weak high pressure or low pressure trough. Though NO_x, as an important precursor of O_3, has been significantly reduced in emissions in China since 2013 (Duncan et al., 2016; Liu et al., 2017), O_3 pollution is still severe or even becoming worse in the NCP, as revealed in the present and also previous studies (Zhang et al., 2014; Sun et al., 2016). The finding that O_3 formation shifted from VOC-limited regime on relatively low O_3 days to the transitional regime on O_3 non-attainment days may elucidate the cause of the increase in O_3, because O_3 productions in the transitional regime are even higher, despite decreases in NO_x emissions. It is unrealistic to expect a continuously linear reduction in NO_x emissions in the NCP, after the substantial decreases of NO_x emissions from power plants and industries in recent years. In other words, restraining on VOC emissions is urgent for O_3 abatement in the NCP. Another important finding in this study was that the NCP served as an O_3 source. This was ever proposed by Ding et al. (2009), based on the aircraft measurement and simulation of atmospheric dynamics. We confirmed it through the ground-level observation and the simulation of in-situ

photochemistry. It can be expected that organic nitrates are also intensively formed in the NCP as byproducts in the photochemical cycles of O_3 formation. In combination with the fact that the NCP locates within the mid-latitude band of Northern Hemisphere under the dominance of westerlies, O_3 and organic nitrates formed in this region can be transported over a long distance following uplift processes, which has been confirmed to partially account for the enhancement of background O_3 in North America and even Europe (Derwent et al., 2015; Lin et al., 2017). Therefore, the recent air pollution control measures taken in China (including China's Clean Air Act Plan in force in 2013) are still inadequate to ease the global O_3 burden in a short period. More effective Action Plans should be implemented to achieve an O_3 benefit, with comprehensive thinking of atmospheric dynamics and chemistry.

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Supporting Information for "**Causes of a continuous summertime O_3 pollution event in Ji'nan, a central city in the North China Plain**"

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Text S1 Validation of the WRF-CMAQ modeling

Due to inevitable uncertainties inherent in the chemical transport models, such as the uncertainties in emission inventory, meteorological simulation and chemical mechanisms (Hu et al., 2016), it is difficult to deduce the reasons for the discrepancies between the simulation and observation. However, the observation data revealed extremely high levels of some VOCs on the three days when O_3 was under-predicted. Specifically, 13.5 ppbv of ethene was observed at 14:00 LT on August 1. On August 7, 5.6 ppbv of isoprene, 16.2 ppbv of HCHO and 2.3 ppbv of hexanal were measured during 12:00 – 14:00 LT. On August 10, 22.7 ppbv of propene and 12.7 ppbv of i-butane were recorded at 08:00 and 16:00 LT, respectively. It is noteworthy that these mixing ratios were 5 – 10 times higher than their averages. Further, most of these VOCs are highly reactive in O_3 photochemistry and may make great contributions to local O_3 production. With the setting of constant emissions of O_3 precursors, WRF-CMAQ did not reproduce these extremely high levels of VOCs, which was a plausible reason for the under-prediction of O_3 on August 1, 7 and 10. Ji'nan was behind a low pressure trough on August 9 – 10. However, vertical transport was simulated to make negative contributions to O_3 between 10:00 LT and 18:00 LT on August 10, according to the process analysis. In addition, the simulated O_3 in the upper atmosphere on August 10 was relatively

low compared to that on August 5, 6 and 9 (Figure S9). Namely, the model might fail to reproduce the O_3 enhancement driven by the low pressure trough on August 10.

The process analysis indicated that horizontal and vertical transport dominated the sources of O_3 at noon (10:00-12:00 LT) and the other times of July 20, respectively. While vertical transport explained the high O_3 at night (Figure 2), it was not likely that horizontal transport built up O_3 at noon, because the southwesterly airflow originated from South China and passed central China (Figure 4) where O_3 values were relatively low on that day (high O_3 occurred in Hebei province in the northwest). Therefore, the overestimate of the transport effect led to the higher simulated O_3 on July 20.

Despite these discrepancies, overall the observed O_3 at the sampling site was well reproduced. In addition, the spatial distribution of the simulated O_3 was highly consistent with the observed O_3 distribution, as shown in Figure S10. The average concentrations of the simulated VOCs were also compared with the observations (Figure S11). While the day-to-day and diurnal variations of the observed VOCs were not well reproduced (not shown), which is a proverbial drawback of the WRF-CMAQ, the model reasonably simulated the magnitudes of VOCs. Moreover, the averages of the observations (Avg. Obs.) and simulations (Avg. Sim.), difference between Avg. Obs. and Avg. Sim. (Diff.), root mean square error (RMSE), normalized mean bias (NMB), normalized mean error (NME) and index of agreement (IOA) were calculated to reflect the agreements between the simulated and observed temperature (Temp.), relative humidity (R.H.), wind speed (W.S.), pressure (Press.), NO_2 and O_3, as listed in Table S4. Generally, the lower Diff., RMSE, NMB and NME, but higher IOA indicate better agreement between the simulated and observed values (Willmott et al., 1985). The validation of the simulations of air pollutants was carried out at 8 AQMSs of CNEMC in and around Ji'nan, and at the sampling site, while the meteorological parameters monitored at 6 airports in eastern and northern China and at the sampling site were used to validate the simulated meteorological conditions. The statistics calculated in this study were well within the ranges of those reported in previous studies involving WRF-CMAQ simulations (Table S4) (Jiang et al., 2010; Wang et al., 2015), suggesting good performance of the model in reproducing the meteorological conditions and air pollutants. Thus, the simulated results were accepted for further analyses.

Text S2 Source apportionment of O_3 precursors

The positive matrix factorization (PMF) model was employed to identify the sources of O_3 precursors. Details about the operation principles of PMF can be found in Paatero and Tapper (1994). Briefly, the model treats the matrix of input concentrations as the product of two matrixes (*i.e.*, factor contribution and factor profile). Here, hourly concentrations of 31 VOCs, CO, NO and NO2 in 54 samples were input into the model. The VOCs, which were common tracers of specific sources (*e.g.*, isoprene for biogenic emissions), and had relatively high concentrations (detectable in at least 80% samples), were selected for source apportionment (termed as VOCs* hereafter). On average, VOCs* accounted for 79.5±11.7% of the total quantified VOCs (mean ± 95% confidence interval of the hourly values in the statistical period, same for all the other "a ± b" expressions elsewhere unless otherwise specified). The uncertainties of the input concentrations of O_3 precursors were set as $\frac{5}{6} \times \mathrm{DL}$ and $\sqrt{(10\% \times concentration)^2 + (0.5 \times DL)^2}$ for the concentrations lower than and higher than DL, respectively.

The model was run for 20 times with a random seed and the best resolution automatically given by the model was accepted. A total of 6 sources of O_3 precursors were resolved by PMF in this study. The number of sources was chosen based on the criteria that the tracers indicating different sources were not allocated in the same source, and all the sources were interpretable according to the tracers. The Bootstrap method integrated in PMF was used to estimate the uncertainties of the modelling results.

Figure S13 shows the profiles of the six sources of O_3 precursors extracted from PMF. The first source contained high levels of *n*/*i*-pentanes and aromatics, likely representing gasoline exhaust (Ho et al., 2009; Ling and Guo, 2014). The heavy (C_8-C_{10}) hydrocarbons dominated in the second source accompanied by great abundances of the combustion tracers, such as C_2-C_3 hydrocarbons, CO, NO and NO_2, in line with the features of diesel exhaust (Liu et al., 2008). The third source was assigned as BVOC, due to the exclusively high loading of isoprene (Guenther, 2006). The fourth source was rich in C_4 hydrocarbons, including *n*/*i*-butanes and 1,3-butadiene. It was defined as liquefied petroleum gas (LPG) usage, since butanes and butenes are present in large quantities in China's LPG (Song et al., 2008 and references therein). Solvent usage was represented by the fifth source, in view of the high loadings of hexane isomers (2,3-dimethylbutane, 2-methylpentane and 3-methylpentane) and moderate loadings of *n*-hexane, toluene, ethylbenzene and xylenes (Guo et al., 2011). At last, most of styrene, benzene, toluene, exthylbenzene and xylenes are allocated to the sixth source, which also contained

moderate levels of light (C_2-C_5) hydrocarbons. Since styrene is a common petrochemical product (Jobson et al., 2004; Liu et al., 2008), this source was designated as petrochemical industry.

The source contributions to the O_3 production rates were obtained from the differences in simulated O_3 production rates between a base run and a constrained run. In the base run, the O_3 production rate was simulated with the observed concentrations of air pollutants except for the carbonyls, while the concentrations of air pollutants attributable to a specific source were deducted from the observed concentrations in the input of the constrained run. To account for the influence of primary hydrocarbons on the formation of carbonyls, and the subsequent impact on O_3 production, carbonyls were not constrained to observations in either the base run or the constrained runs. However, the source-specific primary emissions of carbonyls and their contributions to O_3 production were not considered in this approach. Therefore, the source-specific contributions to net O_3 production rates were expected to be underestimated, as carbonyls are generally of high O_3 formation potentials (Cheng et al., 2010; Dong et al., 2014). The method was applied to each of the six sources, derived from the PMF analysis, thereby acquiring the contribution to O_3 production rates of each source.

Text S3 Definitions of the O_3 formation regimes

As shown in Figure 8, O_3 formation can be divided into VOC$^{\#}$-limited regime and NO_x-limited regime with the method used in Lyu et al. (2017). Briefly, at a given $OH\ reactivity_{VOCs^{\#}}$, O_3 production rate generally reached the maximum at a specific $OH\ reactivity_{NOx}$ due to the dual role of NO_x in O_3 formation. The scenario with this specific $OH\ reactivity_{NOx}$ was treated as dividing point between NO_x-limited regime and VOC$^{\#}$-limited regime. Since 14 gradients of $OH\ reactivity_{VOCs^{\#}}$ (10% - 140% with the step of 10%) were set for all the scenarios, 14 pairs of $OH\ reactivity_{NOx}$ and $OH\ reactivity_{VOCs^{\#}}$ were obtained, as shown by the orange crosses in Figure 8. A dividing line was acquired from the linear regression between $OH\ reactivity_{VOCs^{\#}}$ and $OH\ reactivity_{NOx}$ in these scenarios (orange dashed line in Figure 8). O_3 formation was limited by VOCs$^{\#}$ and NO_x in the lower right and upper left of the dividing line, respectively. Since the horizontal and vertical coordinates were percentages relative to the average $OH\ reactivity_{VOCs^{\#}}$ and $OH\ reactivity_{NOx}$ during O_3 episodes, rather than the actual values of OH reactivity, we did not present the dividing ratio of $\frac{OH\ reactivity_{VOCs^{\#}}}{OH\ reactivity_{NOx}}$ here. Further, it was found that O_3 production rate was also enhanced with the increase of

$OH\ reactivity_{VOCs^{\#}}$ in the upper left area close to the dividing line. We defined it as a transitional regime where the O_3 production rate was comparably sensitive to VOCs# and NO_x. Beyond the transition area in the upper left of the dividing line, the sensitivity of O_3 production rate to NO_x was generally ten times higher than to VOCs#, which was designated as NO_x-limited regime. The transitional regime and the NO_x-limited regime are divided by the blue dashed line in Figure 8.

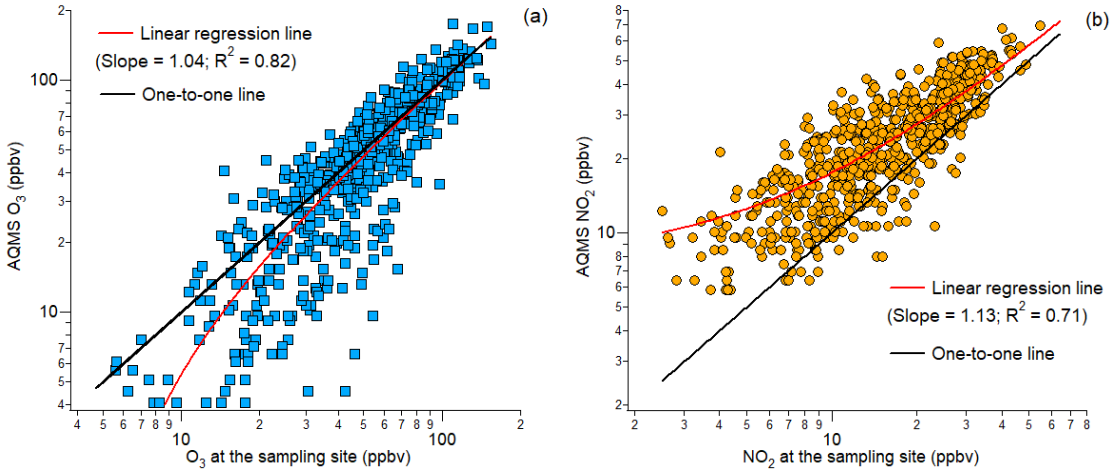
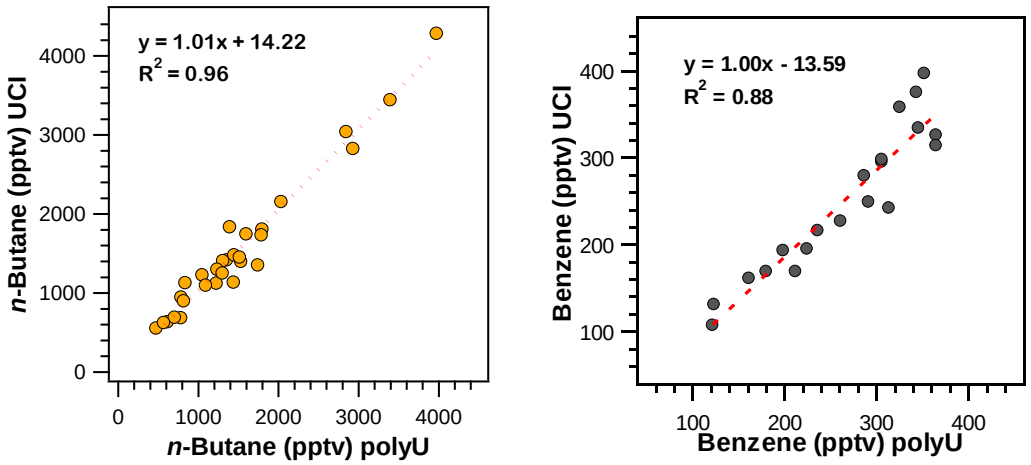


Figure S1. Agreement of the hourly (a) O_3 and (b) NO_2 between our observations on the campus of Shandong University and those monitored at the nearest AQMS by CNEMC.



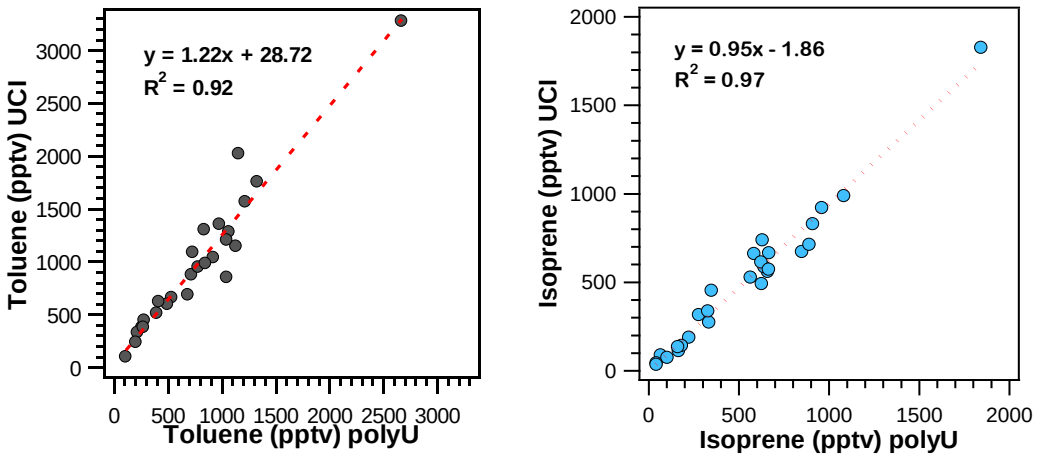


Figure S2. Inter-comparison of VOC analysis results between our laboratory (x axis) and Prof. Donald Blake's group (y axis). *n*-butane, benzene, toluene and isoprene are selected as examples. The red dashed line represents the linear regression between VOCs analyzed in two laboratories.

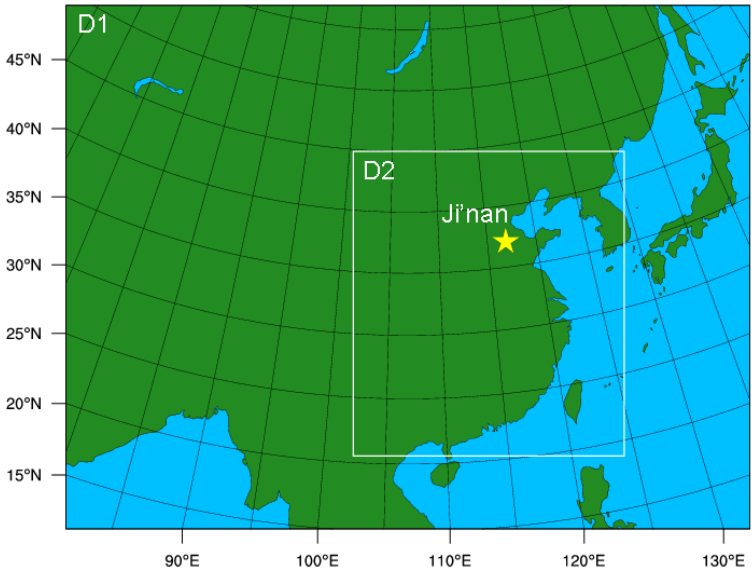


Figure S3. Settings of the two-nested domains for the WRF-CMAQ model. D1 and D2 are the outer and inner domain, covering the entire continental area of China and eastern China, respectively. The yellow star represents Ji'nan.

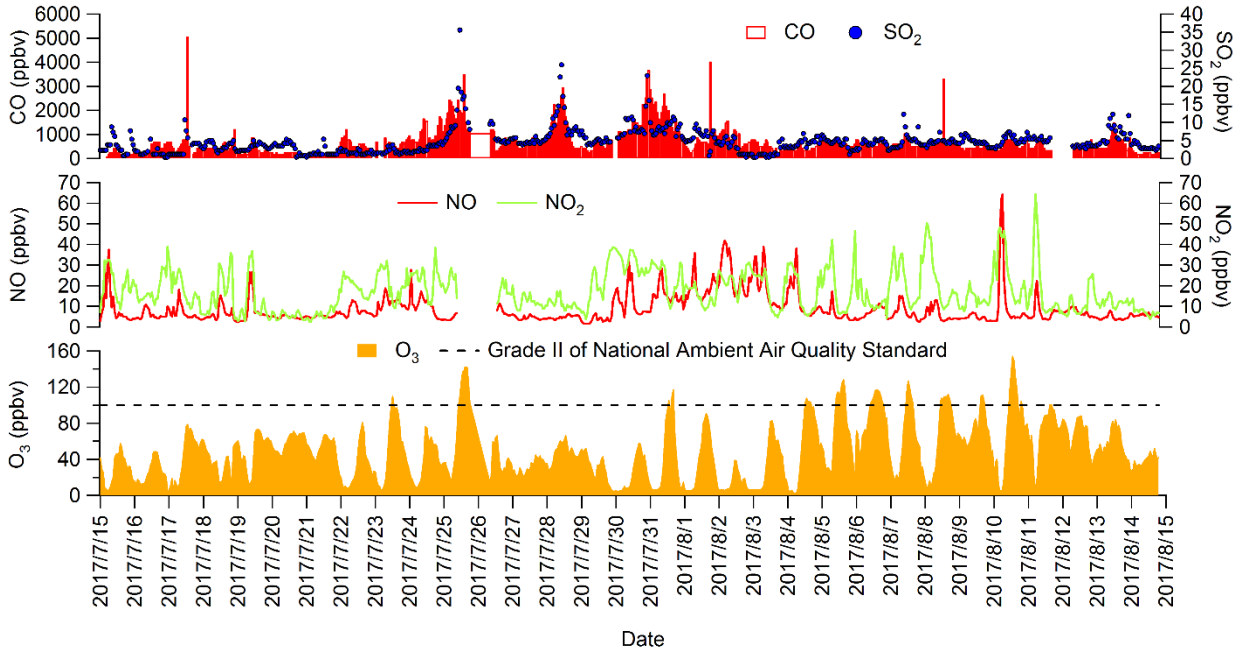
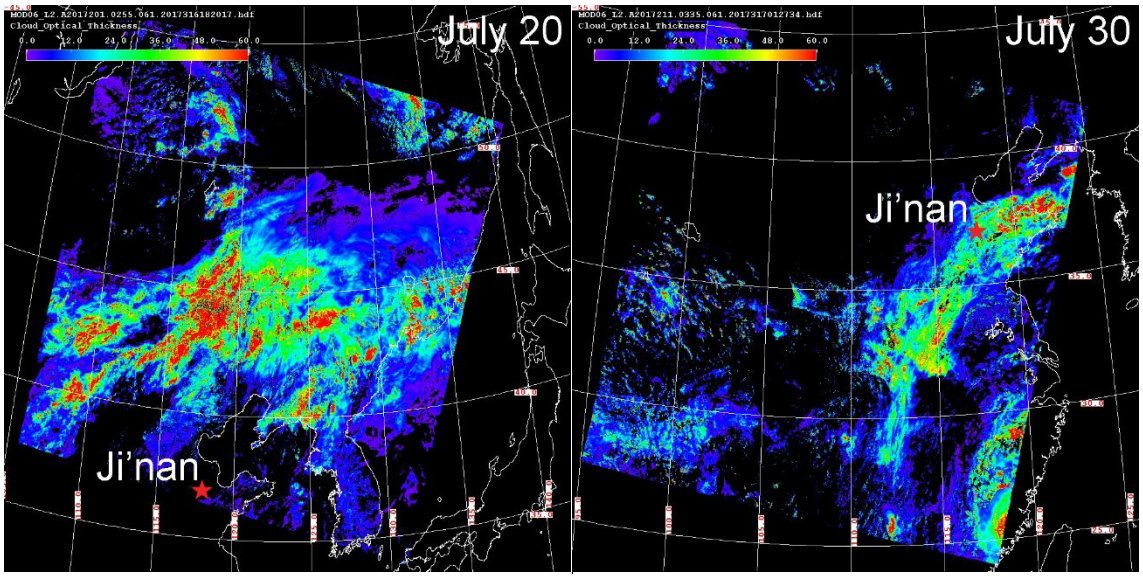
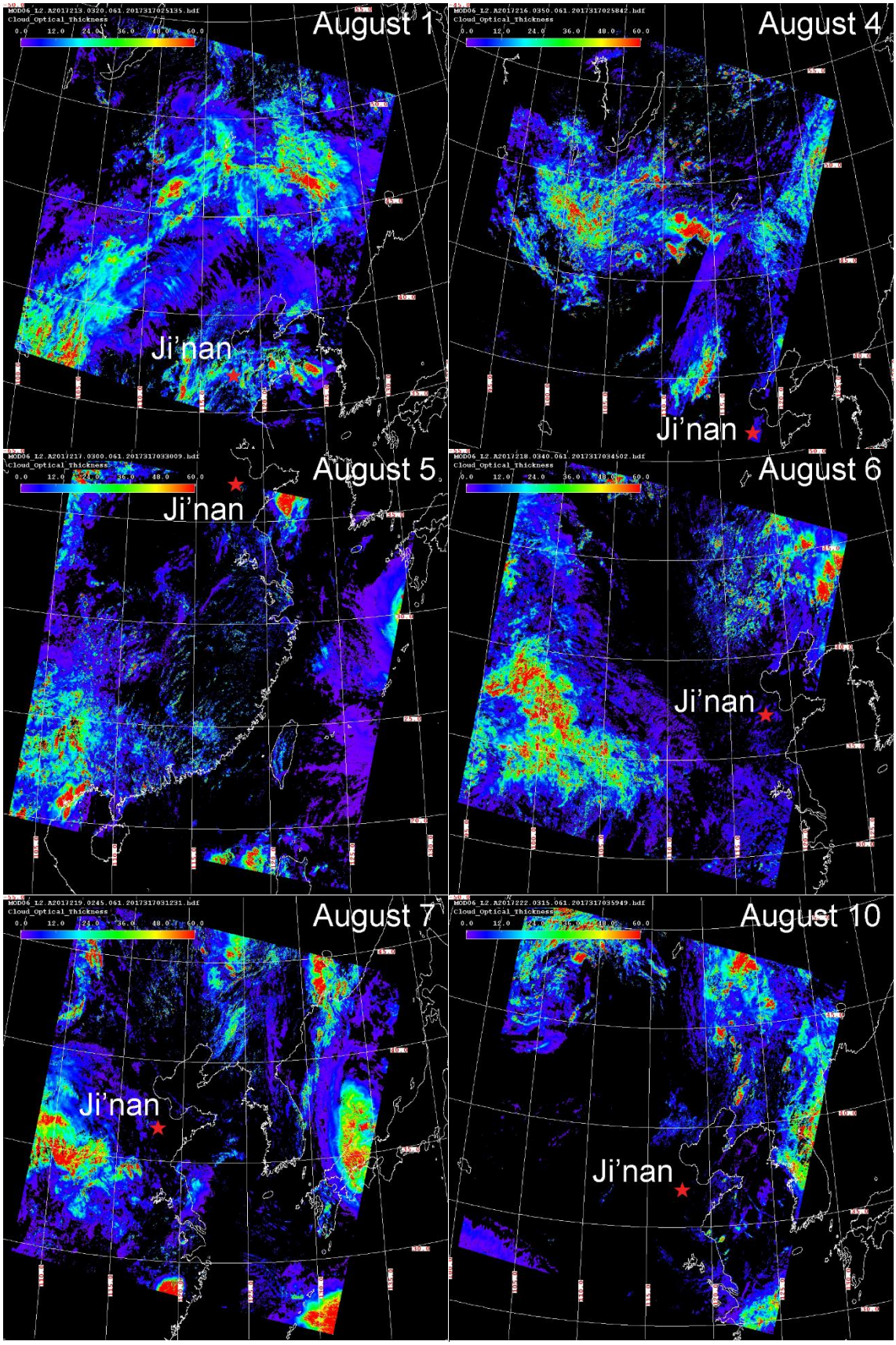


Figure S4. Hourly variations of trace gases monitored at the sampling site (O_3, NO and NO_2) and at the nearest AQMS (CO and SO_2) during July 15-August 14, 2017.




August 1
Ji'nan
August 4
Ji'nan
August 5
Ji'nan
August 6
Ji'nan
August 7
Ji'nan
August 10
Ji'nan

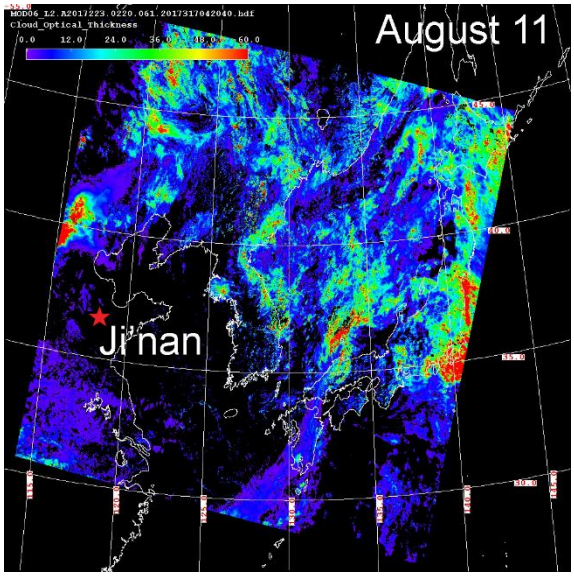
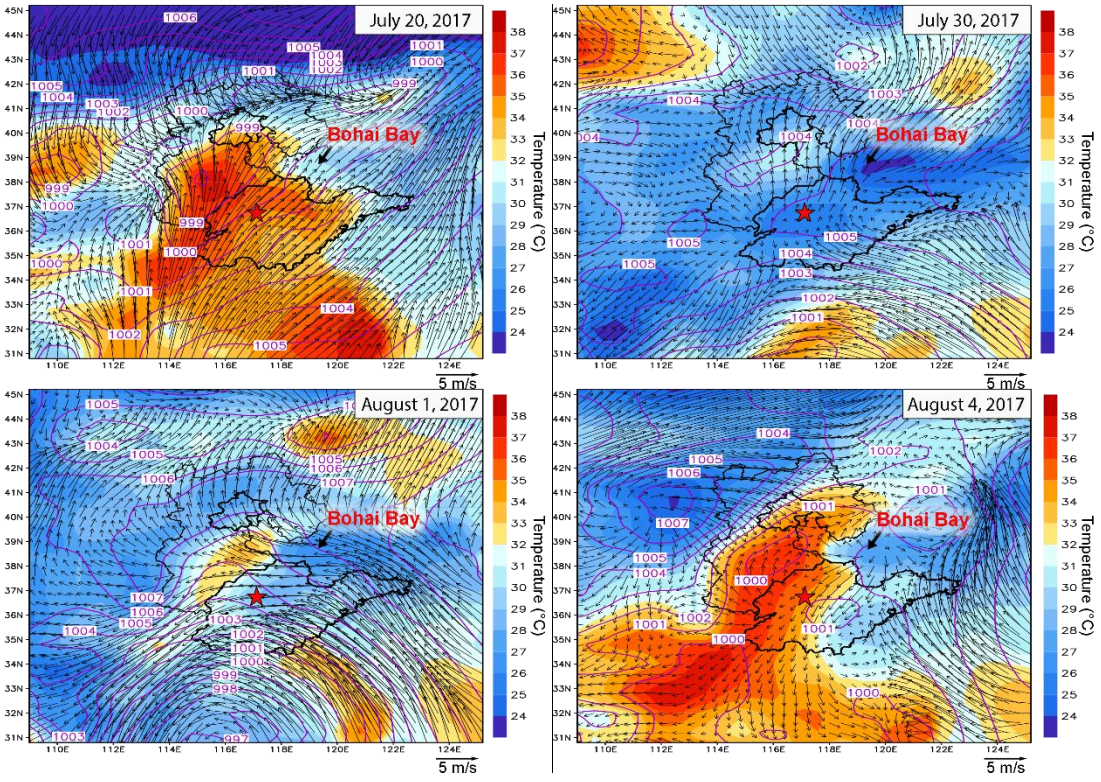


Figure S5. Cloud optical depth (COD) retrieved from terra/MODIS at noon (10:30 – 12:00 LT) of the canister sampling days. The color scale denotes for the COD within the range of 0 (purple) to 60 (red). The red star denotes Ji'nan.



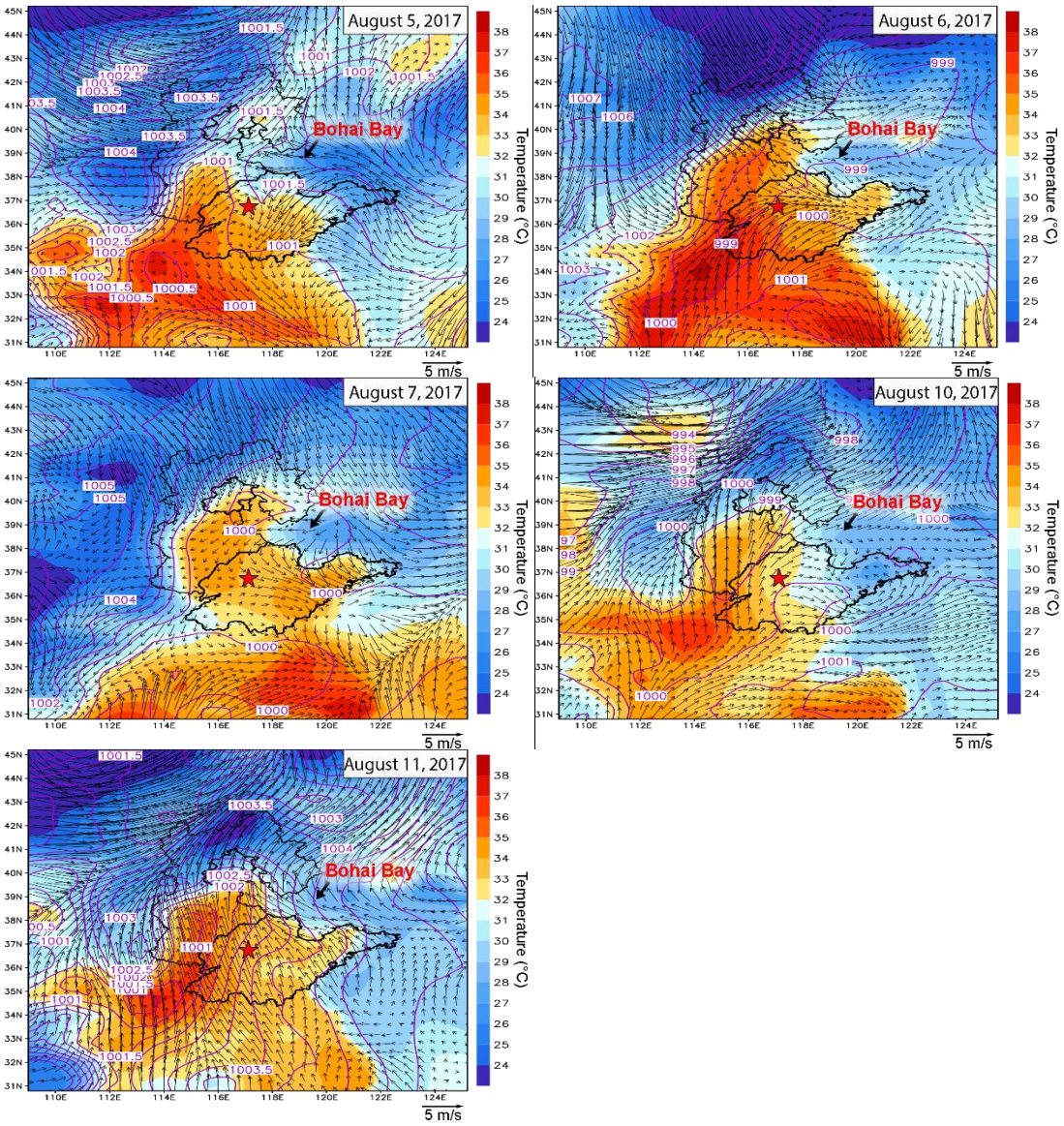
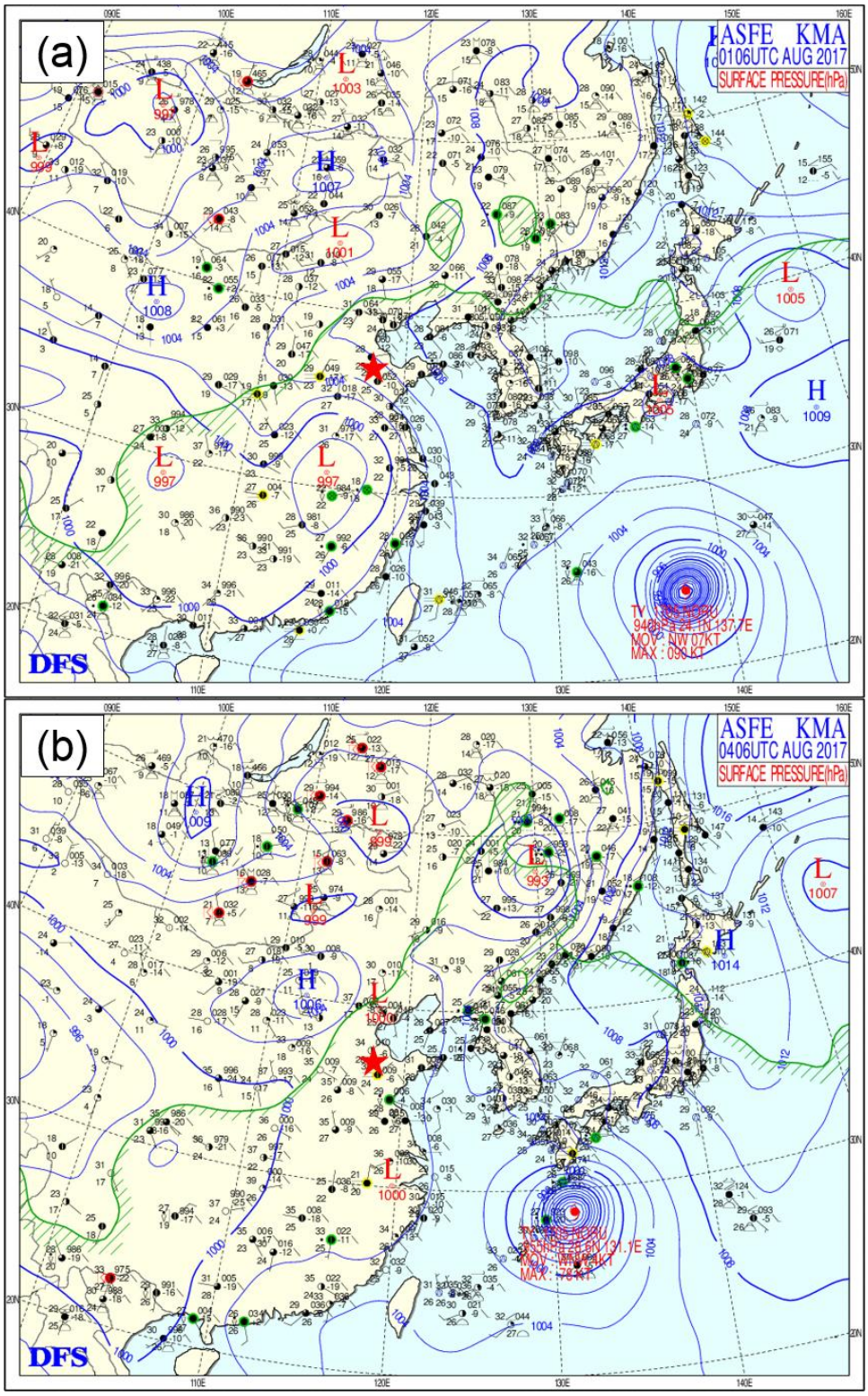
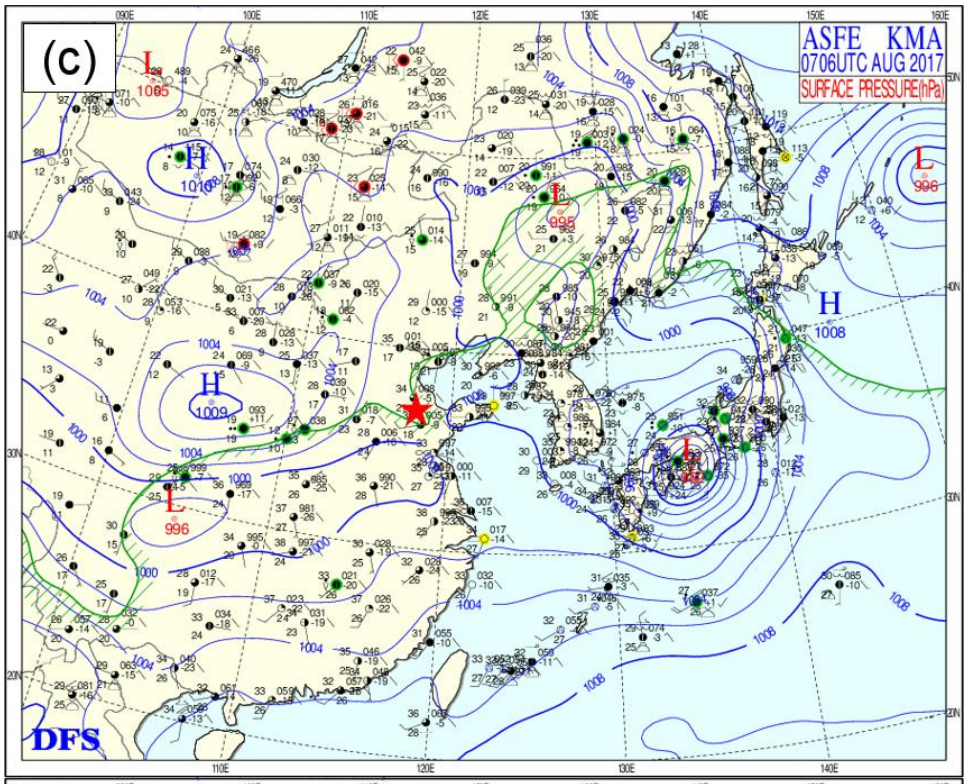
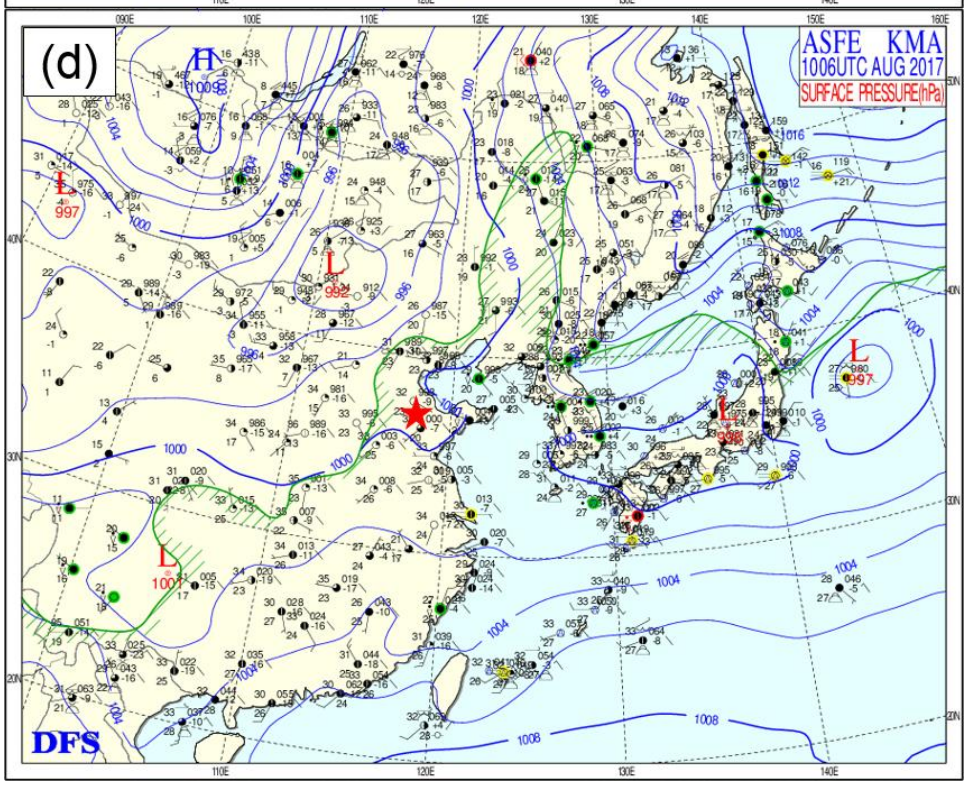


Figure S6. Weather charts at 14:00 LT on individual VOC sampling days. The red star denotes for Ji'nan. The dark black line is the boundary of Shandong province. Bohai Bay is located to the northeast of Shandong province. Numbers in the figure are sea-level pressures in unit of hPa.


(a)
ASFE KMA
0106UTC AUG 2017
SURFACE PRESSURE(hPa)
DFS
(b)
ASFE KMA
0406UTC AUG 2017
SURFACE PRESSURE(hPa)
DFS


(c)
ASFE KMA
0706UTC AUG 2017
SURFACE PRESSURE(hPa)
DFS


(d)
ASFE KMA
1006UTC AUG 2017
SURFACE PRESSURE(hPa)
DFS

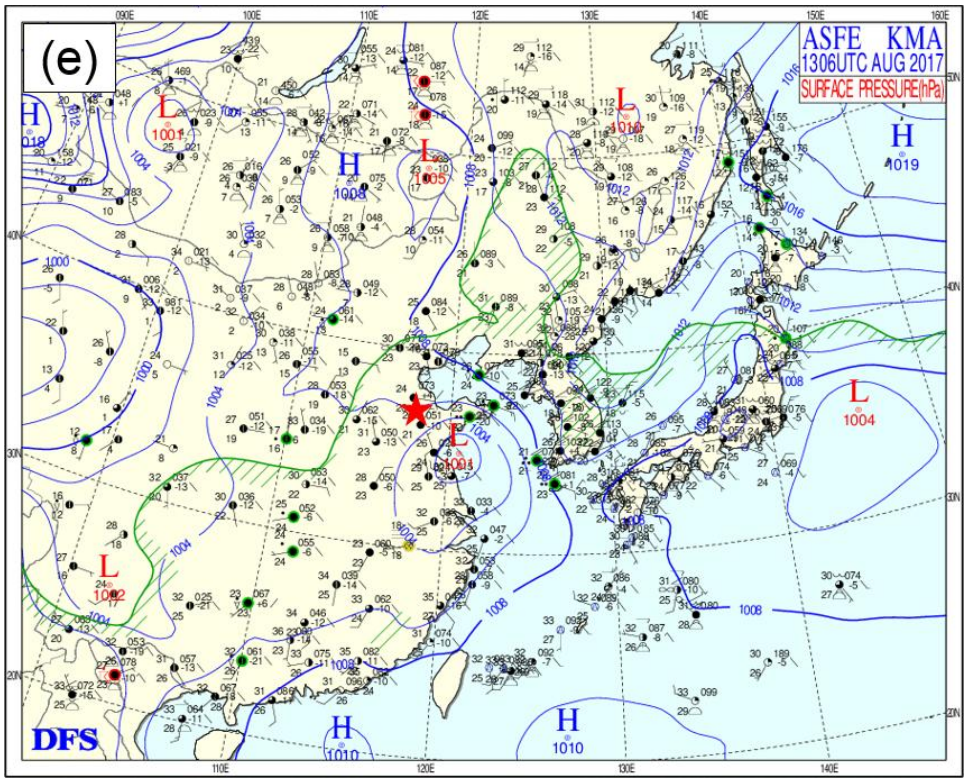
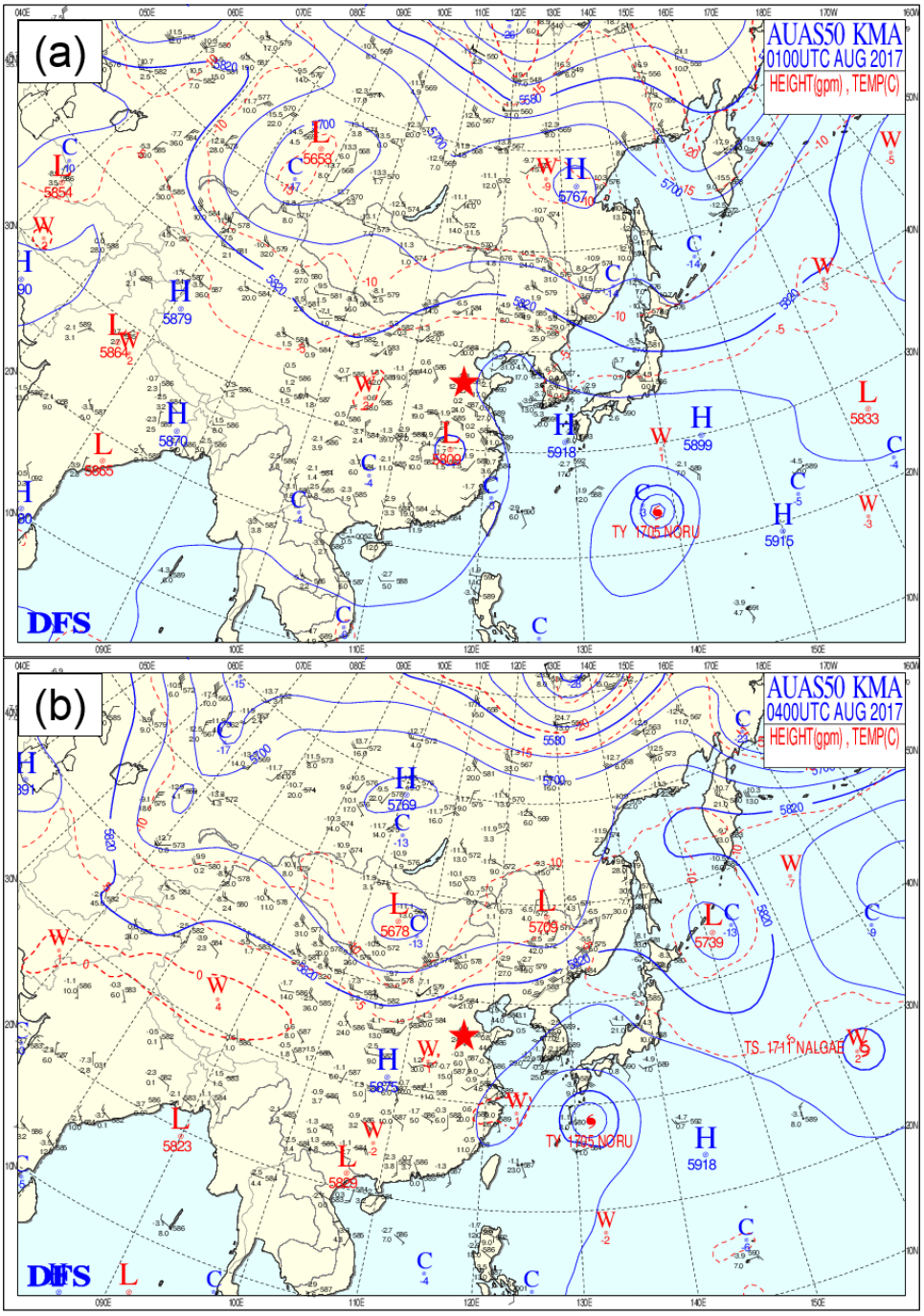
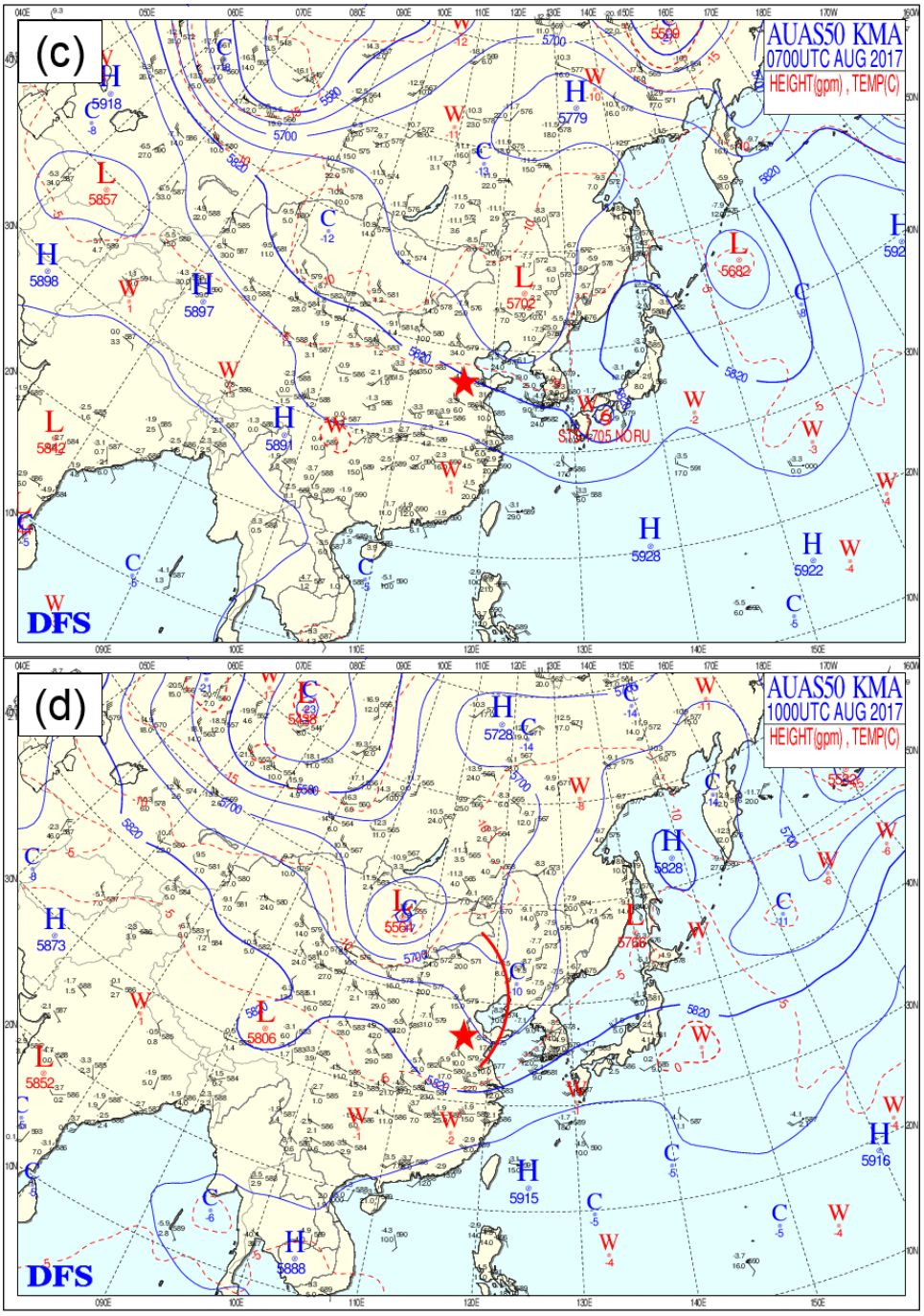


Figure S7. Weather chart over the Northeast Asia on (a) August 01, (b) August 04, (c) August 07, (d) August 10 and (e) August 13 at 06:00 UTC (14:00 LT) at surface level. The red star denotes Ji'nan city. The capital letter "H" and "L" represents high pressure center and low pressure center, respectively. Blue lines are the sea level isobars. Green line is the isometric humidity line with the specific humidity of ≥15g/kg on the grid side. All the charts can be accessed through the link: http://222.195.136.24/forecast.html.


(a)
AUAS50 KMA
0100UTC AUG 2017
HEIGHT(gpm) , TEMP(C)
TY 1705 NORU
DFS
(b)
AUAS50 KMA
0400UTC AUG 2017
HEIGHT(gpm) , TEMP(C)
TS 1711 NALGAE
TY 1705 NORU
DFS


(c)
AUAS50 KMA
0700UTC AUG 2017
HEIGHT(gpm) , TEMP(C)
DFS
(d)
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1000UTC AUG 2017
HEIGHT(gpm) , TEMP(C)
DFS

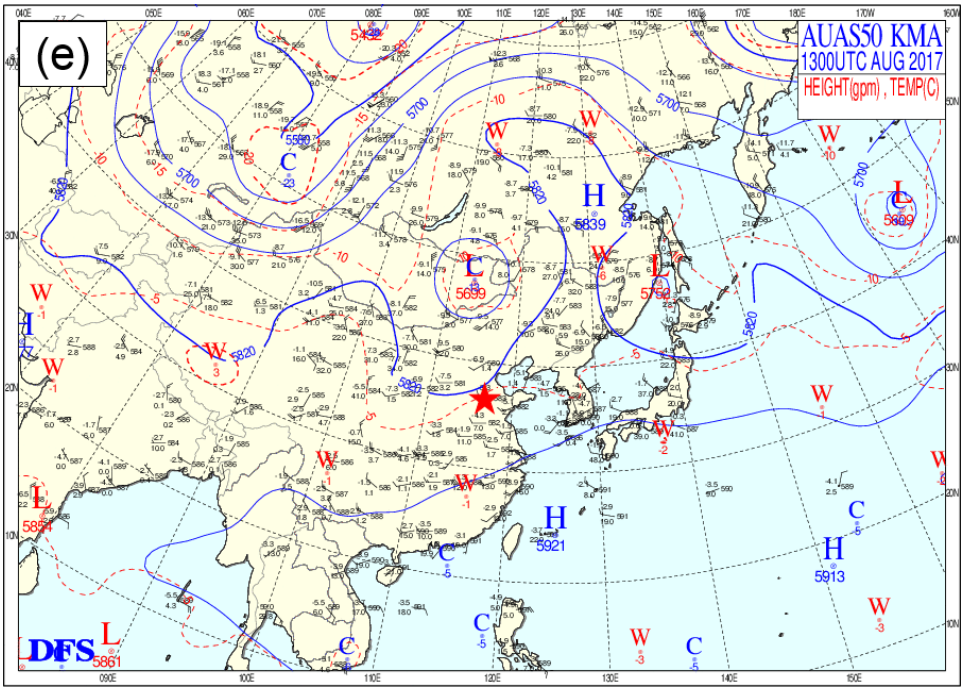

Figure S8. Weather chart over the Northeast Asia on (a) August 01, (b) August 04, (c) August 07, (d) August 10 and (e) August 13 at 00:00 UTC (08:00 LT) at altitude of 500 hPa. The red star denotes Ji'nan city. The capital letter "H" and "L" represents high pressure center and low pressure center, respectively. Blue lines are the 500 hPa geopotential height (gpm) lines. The red curve in panel (d) demonstrates the low pressure trough. All the charts can be accessed through the link: http://222.195.136.24/forecast.html.

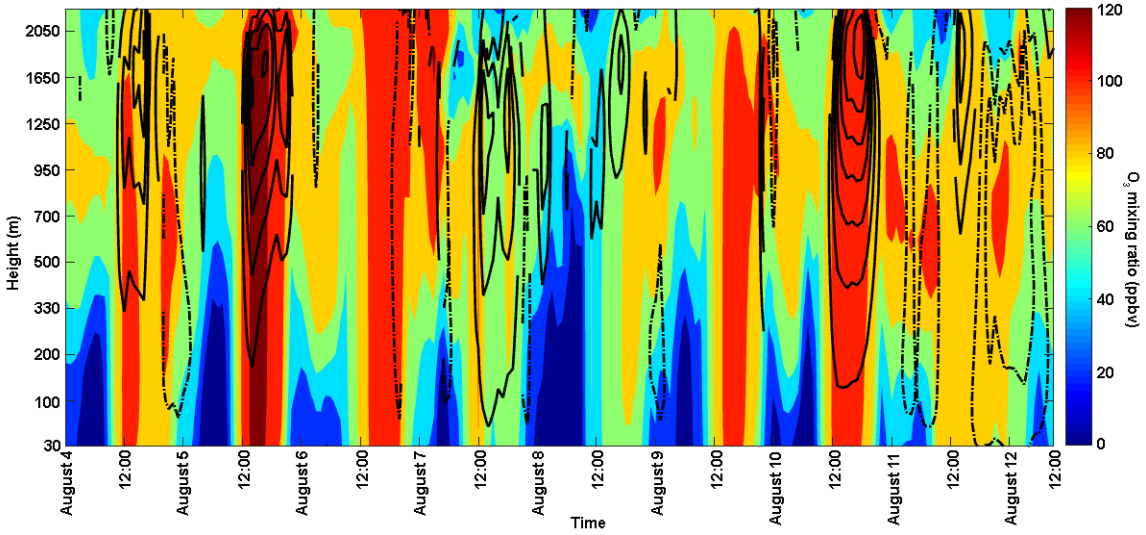

Figure S9. Vertical profile of the simulated O_3 over Ji'nan during August 4-11. The black solid and dotted lines represent the updraft and downdraft simulated by WRF-CMAQ, respectively. The areas with no line indicate that there were no simulated winds in vertical direction.

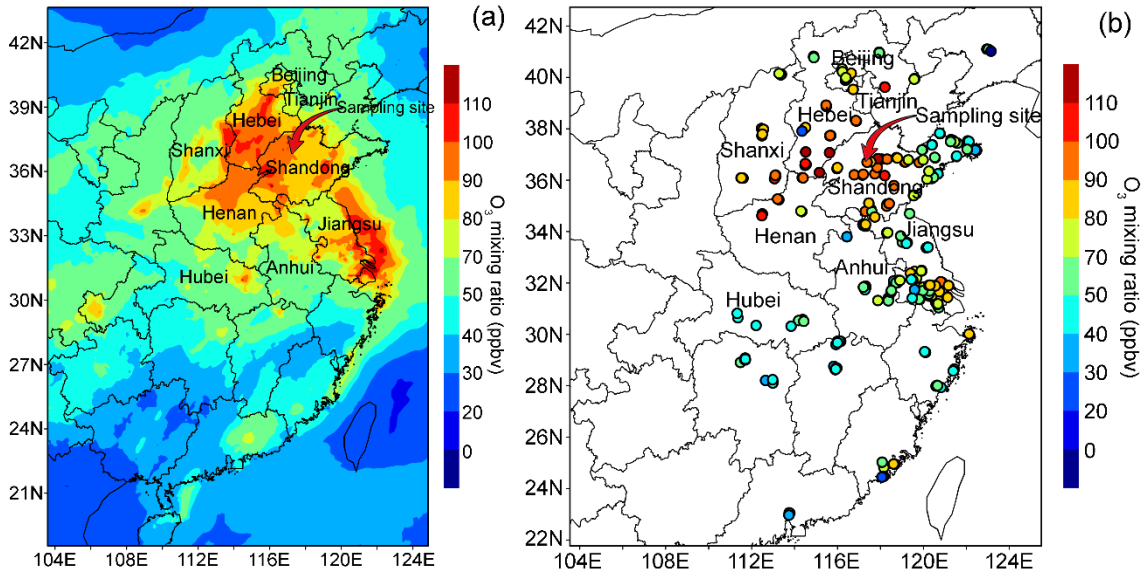

Figure S10. Comparison between the spatial distributions of (a) the WRF-CMAQ simulated O3 and (b) the observed O3 at 14:00 LT averaged over August 4-11. The observed O3 was acquired from the AQMSs of CNEMC.

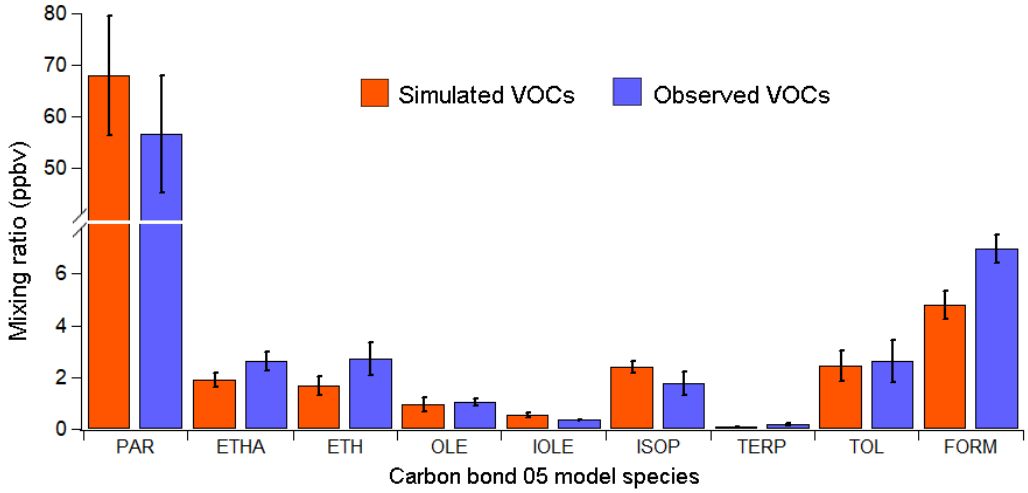

Figure S11. Comparison between the averages of the hourly observed and WRF-CMAQ simulated VOCs. PAR: paraffin carbon bond; ETHA: ethane; ETH: ethene; OLE: terminal olefin carbon bond; IOLE: internal olefin carbon bond; ISOP: isoprene; TERP: terpene; TOL: toluene and other monoalkyl aromatics; FORM: formaldehyde. The matrix of assignments from real compounds to carbon bond 05 model species can be found in Yarwood et al. (2005).

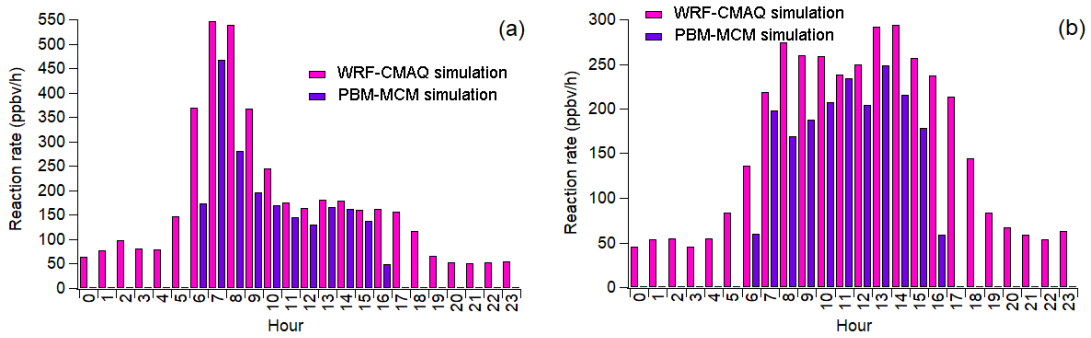

Figure S12. Average diurnal cycle of "$NO+O_3$" reaction rates simulated by WRF-CMAQ and PBM-MCM during (a) O_3 episodes and (b) non-episodes.

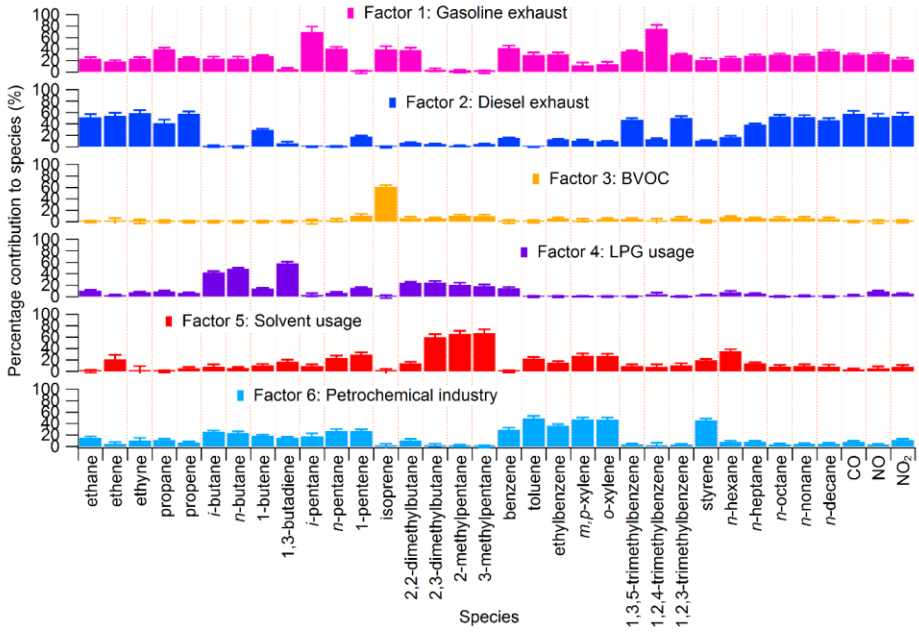

Figure S13. Profiles of the six sources of O_3 precursors identified for the samples collected in daytime of the VOC sampling days in Ji'nan.

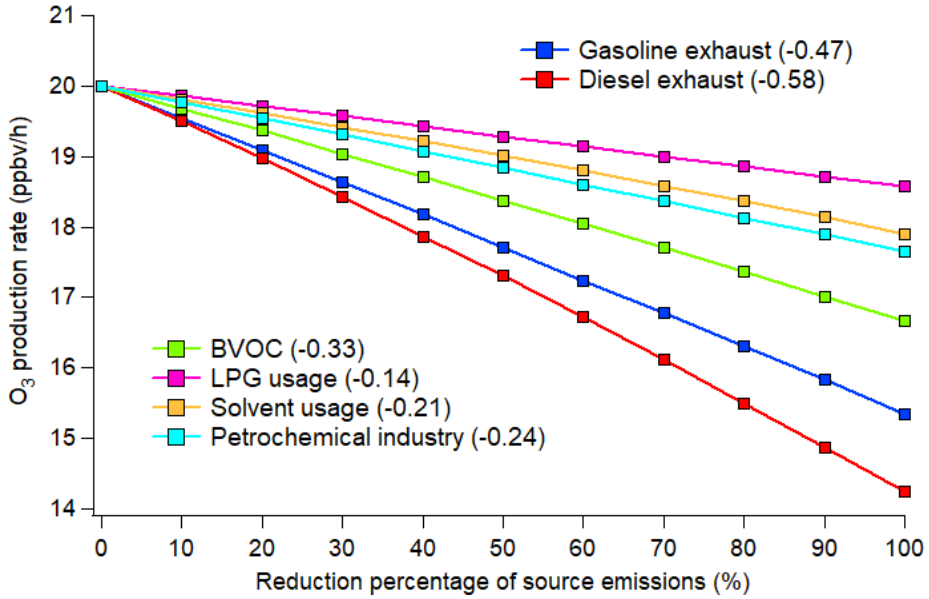

Figure S14. Average O_3 production rate at 12:00 LT during O_3 episodes as a response of the reduction percentages of source emissions. Numbers in the brackets are the average O_3 reduction efficiencies (ppbv/10% reduction in source emissions).

Species	Site	Instrument	Resolution	Accuracy	Precision	Detection limit
SO_2	AQMS*	API, Model 100 E	20 sec	<20%	0.5% of reading above 50 ppbv	0.4 ppbv
CO	AQMS	API, Model 300 E	10 sec	<20%	0.5% of reading	40 ppbv
NO-NO_2-NO_x	AQMS	API, model 200E	20 sec	<20%	0.5% of reading	0.4 ppbv
	Campus site #	Thermo, Model 42C	1 min	<15%	0.4 ppbv	0.4 ppbv
O_3	AQMS	API, model 400E	10 sec	<20%	<0.5% of reading	0.6 ppbv
	Campus site	Thermo, Model 49C	20 sec	<15%	1.0 ppbv	1.0 ppbv

* An air quality monitoring station of China National Environmental Monitoring Center closest to our sampling site in the campus of Shandong University; # Our sampling site on the campus of Shandong University.

Table S1. Descriptions of the trace gas analyzers used in this study.

Date	Episode/Non-episode	$J(O^1D)$ (s^{-1})	JNO_2 (s^{-1})
July 20	Non-episode	3.40×10^{-5}	9.27×10^{-3}
July 30	Non-episode	1.02×10^{-5}	2.73×10^{-3}

August 1	Non-episode	2.71×10^{-5}	7.50×10^{-3}
August 4	Episode	2.85×10^{-5}	7.95×10^{-3}
August 5	Episode	2.69×10^{-5}	7.50×10^{-3}
August 6	Episode	2.75×10^{-5}	7.70×10^{-3}
August 7	Episode	2.34×10^{-5}	6.52×10^{-3}
August 10	Episode	3.07×10^{-5}	8.72×10^{-3}
August 11	Episode	2.90×10^{-5}	8.25×10^{-3}

Table S2. Daily maximum photolysis rates of O_3 and NO_2 on VOC sampling days in Ji'nan.

OH reactivity of species X	Full name of species/VOC groups	Species included
RNO	Nitric oxide	Nitric oxide
RNO2	Nitrogen dioxide	Nitrogen dioxide
RCO	Carbon monoxide	Carbon monoxide
RCarbonyls	Carbonyls	Formaldehyde, acetaldehyde, acetone, hexanal
RBVOCs	Biogenic VOCs	Isoprene, *α*-pinene, *β*-pinene
RAromatics	Aromatics	Benzene, toluene, ethylbenzene, *m*/*p*-xylenes, *o*-xylene
RAlkenes	Alkenes	Ethene, ethyne, propene, 1-/*i*-butene, 1,3-butadiene, *trans*-2-butene, *cis*-2-butene, 1-pentene
RAlkanes	Alkanes	Ethane, propane, *n*/*i*-butanes, *n*/*i*-pentanes

Table S3. Full name of inorganic trace gases and VOC species for the calculation of OH reactivity.

Meteorological parameter/Air pollutant	Avg. Obs.	Avg. Sim.	Diff.	RMSE	NMB	NME	IOA
Temp. (℃)	30.0	30.7	0.7	2.4	0.02	0.06	0.89
R.H. (%)	72.7	67.5	-5.2	14.4	-0.06	0.15	0.82
W.S. (m/s)	2.8	3.3	0.5	1.5	0.38	0.56	0.74
Press. (hPa)	1000.5	998.8	-1.7	4.0	-0.002	0.003	0.56
NO2 (ppbv)	26.7	28.4	1.7	16.7	0.18	0.58	0.73
O3 (ppbv)	62.8	52.4	-10.4	24.0	-0.07	0.48	0.89

Table S4. Statistical comparisons of the WRF-CMAQ simulated and observed meteorological parameters, O_3 and NO_2. The comparisons are made for the hourly data in 24 hours on all the VOC sampling days.

O_3 production pathway	O_3 destruction pathway
$HO_2 + NO$	$OH + NO_2$
$RO_2 + NO$	$O^1(D) + H_2O$
	$O_3 + OH$
	$O_3 + HO_2$
	O_3 + alkenes

Table S5. Production and destruction pathways of O_3.

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