A CMAQ-based Study on Evaluation of Achievements of Measures on Ozone Pollution Prevention and Control in Summer 2017 in Chengdu

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Abstract. Ozone Pollution is one of the major difficulties in improving the air quality of Chengdu. In 2017, on the basis of research findings including a mass of observation data, meteorological data and numerical simulation data of air quality on the localized ozone and its precursors in Chengdu, Chengdu Environmental Protection Bureau drew up and implemented 2017 Chengdu Ozone Pollution Prevention and Control Action Program (OPCAP). This study elaborated on the specific measures of OPCAP and the subject of implementation of the said measures, and based on the localization of CMAQ parameters, conducted scientific evaluation on the achievement of OPCAP implementation. The research findings are set forth as follows: OPCAP made pollutants reduced to a large extent, for example, the industrial emissions of VOCs and NOx were reduced by 8600 tons and 2150 tons, respectively. Compared to the corresponding period of last year, in August 2017, meteorological change made O$_{3\text{max}}$, PM$_{10}$, PM$_{2.5}$, NO$_2$ and CO reduced by 34.9%, 24.2%, 23.9%, 16.6% and 6.0%, respectively. After a series of measures including OPCAP were taken, O$_{3 \text{sh max}}$ was reduced by 6~10µg/m$^3$ in most areas of Chengdu. Under equal meteorological conditions in August 2017, OPCAP made O$_{3 \text{sh max}}$ in the downtown of Chengdu reduced by 3.67% on average, and the concentration of NO$_2$, SO$_2$, PM$_{10}$, PM$_{2.5}$ and CO was reduced by 25.00%, 11.11%, 19.59%, 19.63% and 5.32% on a monthly average basis. As shown above, it can be seen that OPCAP worked on ozone pollution prevention and treatment. The technologies adopted in and the findings of this study may provide technological guidance on the mid-term and long-term ozone pollution prevention and treatment.

1. Introduction
Ozone was first discovered by German Scientist CF. Schonbein in 1840[1]. It is a pale blue toxic gas that is unstable with a distinctively pungent smell. It is a powerful oxidant that has been known[2]. As powerful oxidant, the distribution of ozone in the troposphere and its change directly affects the concentration and life span of other chemical substances and free radicals, etc. Ozone can also change the temperature structure of the troposphere by absorbing the Sun’s ultraviolet radiation. Accordingly, the circulation and balance of atmospheric chemistry are affected. Thus, ozone has become a critical element that can influence the process of atmospheric dynamics, thermodynamics, radiation and chemistry, etc.[3] In 1952, when studying smog in Los Angeles, Haagen Smit first found that the smog primarily resulted from ozone[4] and set forth the basis of photochemical smog theory that is ozone pollution is caused by the interaction between volatile organic compounds and nitrogen oxides[5].
Therefore, when dealing with the issue of regional ozone pollution treatment, we should first study the sensitive issue, i.e. the formation of urban ozone[6]. The formation of ozone depends on the ratio of VOC to NOx to a large extent[7], i.e. the urban ozone pollution zone is divided into NOx control zone and VOC control zone. In NOx control zone, the ozone pollution treatment strategy only focusing on VOC reduction will become meaningless with the reduction of NOx emission. The said strategy will even make the ozone pollution more serious. In NOx control zone, we should prioritize reduction of NOx emission while reducing VOC emission. Similarly, in VOC control zone, only reducing NOx emission will not decrease the concentration of ozone but will make the concentration of ozone increased. In VOC control zone, we should prioritize reduction of VOC emission while reducing NOx emission. To solve the problem of ozone pollution in Chengdu, Chengdu Environmental Protection Bureau adopted 2017 Chengdu Ozone Pollution Prevention and Control Action Program (hereinafter referred to as OPCAP, implemented from May 30, 2017 to September 10, 2017) and took targeted measures on reduction of ozone precursor emission so as to reduce ozone pollution, increase the days with good air quality of the year and accumulate valuable experience for the mid-term and long-term ozone pollution prevention and treatment in Chengdu[8]. OPCAP is determined on the basis of comprehensive research on a mass of observation data, meteorological data and numerical simulation data of air quality on the localized ozone and its precursors in Chengdu. OPCAP is drawn up in the light of the ratio of VOCs emission reduction to NOx emission reduction that is set in a scientific way based on the specific conditions of major pollution sources of Chengdu. It has been expounded and verified by many well-known academicians in the atmospheric field of China before its implementation. In the meantime, the central environmental protection supervision was carried out in Chengdu from August 10, 2017 to September 10, 2017, which further ensured the effectiveness of implementation of OPCAP. This study kept track of the whole process of OPCAP implementation and conducted scientific evaluation on the achievements of OPCAP with CMAQ.

2. Particulars of Action Program
OPCAP measures were in conformity with the uniform arrangement of Chengdu Environment Protection Bureau, involving the following aspects of the city including production suspension and regulation of the enterprises that did not reach the emission standard, production limitation and control of the enterprises that reached the emission standard, traffic control, control on use of spraying solvent and solvent for lineation, prohibition on biomass burning in the whole city, inspection tour, investigation and supervision and other control measures. The program was implemented in 22 areas of Chengdu. The government departments of these areas on environmental protection, economy and information technology, traffic and urban management and law enforcement, etc. were requested to make joint efforts for smooth implementation of the program. OPCAP work arrangement is set forth as follows:

- Apart from promulgating OPCAP, Chengdu Environmental Protection Bureau also requested the major enterprises to carry out production and construction in different periods of time so as to avoid the peak hour, took stricter special emission control measures aimed at enterprises of specific scales; and irregularly conducted random inspections in the city over gas stations, oil depots and industries including vehicle maintenance.
- Chengdu Municipal Commission of Economy and Information Technology limited capacity of the cement industry and at the same time intensified the special examination on pollutants emitted from enterprises.
- The said two departments also worked together, making a list on the enterprises whose capacity shall be reduced and whose emission shall be limited at the key prevention and control stage and the list on the enterprises whose capacity shall be reduced and whose emission shall be limited in the period of special control and taking actions strictly on the basis of the said lists.
- Chengdu Urban and Rural Construction Commission arranged different periods of construction for different construction engineering projects to avoid the peak hour in summer;
Chengdu Municipal Public Security Bureau and Transport Committee of Chengdu carried out researches on vehicles, implemented stricter traffic restrictions based on the last digit of license plate numbers and took traffic control measures such as increasing checkpoints aimed at disqualified vehicles and the frequency of such check.

Chengdu Meteorological Bureau established a normalized operation mechanism of artificial precipitation to conduct artificial precipitation only if the specific conditions of precipitation were met. In addition, Chengdu Environmental Protection Bureau called for joint control over pollutant emission with its seven surrounding cities including Deyang, Mianyang, Suining, Leshan, Ya’an, Meishan and Ziyang, as shown in Figure 1.

Figure 1. Scope of OPCAP Implementation

3. Technologies Adopted on Evaluation

Air quality models such as CMAQ are generally adopted for air quality prediction and forecast as well as evaluation on influence of taking measures on pollution prevention and control[9-13]. This study is conducted on the basis of CMAQ 5.0.2. Automated data processing is realized through integration of SimpleBIO, DynaLTO, EMISPRO and SMOKE and dependence on NAMPCS platform. SimpleBIO is a simple dynamic natural source emission model[14] developed based on the classic natural source algorithm[15] proposed by scholars including Alex Guenther; DynaLTO is a LTO cycle emission model of civil aircrafts at the airport[16] developed based on Python; EMISPRO is a scenario inventory processing system developed in this study; and SMOKE is the NetCDF format that undergoes localized modification in the light of the pollution source emission inventory of Chengdu. Figure 2 shows the integration framework of the evaluation technology system (hereinafter referred to as CDAQS) of this study.

The evaluation shown in Figure 2 was carried out as follows:

- First, the base year pollution source emission inventory was examined, checked and modified, the base year air quality was simulated and the effectiveness of the model was verified (Scenario 00).
- Then, on the basis of the base year emission inventory, emission reduction on the source emission inventory was parameterized in the light of the implementation of OPCAP measures so that the measure scenario emission inventory was acquired. Apart from the basic scenario, this study designed another two simulant scenarios at this phase, i.e. scenario 01 that is designed by adding OPCAP measures to the basic scenario and scenario 02 that is designed by adding the effect of the central environmental protection supervision to scenario 01.
- At last, the target year air quality simulation was carried out. The result of the simulation was that under the measure scenario, the air quality was improved.
Figure 2. Integration Framework of The Evaluation Technology System (CDAQS) of This Study

Figure 3 shows the evaluation technology procedures.

Figure 3. Evaluation Technology Procedures of This Study

4. Result Analysis

4.1. Ozone Pollution Situation During Evaluation

Figure 4 shows the ozone pollution level of Chengdu from April to September in recent two years.
After analyzing the ozone concentration data of Chengdu in recent two years, we found the following characteristics of ozone pollution.

4.1.1. The time of O₃ pollution came earlier and the concentration obviously increased. In 2017, Chengdu O₃ pollution started on April 14, 20 days earlier than the previous year (in 2016, Chengdu O₃ pollution started on May 4). In April and May, the 90th Percentile Daily Maximum 8 Hours Average Concentration of O₃ increased by 27.7% and 12.6% respectively compared to the corresponding period of the previous year, as shown in Table 1.

Table 1. Statistical Table of Monthly Average Concentration of O₃ in Downtown, Chengdu (μg/m³)

| Time      | April | May  | June | July | August |
|-----------|-------|------|------|------|--------|
| 2017      | 166   | 197  | 158  | 207  | 180    |
| 2016      | 130   | 175  | 187  | 188  | 220    |
| Year-on-year Change | 27.7% | 12.6% | -15.5% | 10.1% | -18.2% |

4.1.2. During the implementation of OPCAP, the days of O₃ pollution were obviously decreased and the pollution level was lowered. During the implementation of OPCAP, there were 30 days of pollution, obviously decreased (by 7 days) compared to the corresponding period of last year. During the period of Sichuan environmental protection supervision (from August to September 10), the days of pollution was even decreased by 11 days compared to last year, as shown in Table 2.

Table 2. A Year-on-year Comparison of Days of O₃ Pollution in Downtown from April to August in 2016 and 2017 (Day)

| Year | April | May | June | July | August | From April to August |
|------|-------|-----|------|------|--------|---------------------|
| 2017 | 5     | 11  | 3    | 19   | 8      | 46                  |
| 2016 | 0     | 4   | 7    | 11   | 16     | 38                  |
4.2. Analysis on Influence of Meteorological Factors

An analysis was carried out on the meteorological conditions in August of the recent two years with numerical simulation. The result is shown in Table 3.

| Table 3. Simulation Differences of Meteorological Conditions in August of the Recent Two Years |
|-----------------------------------------------|-----------------|
| August 2016 | August 2017 |
|------------------------------|----------------|
| Average Wind Velocity | 1.64 | 2.33 |
| Average Temperature | 26.36 | 25.95 |
| Average Relative Humidity | 82.76 | 82.18 |
| Average Boundary Layer Height | 500.37 | 511.66 |
| Maximum Boundary Layer Height | 1460.78 | 1403.99 |
| Cumulative Precipitation | 258.04 | 280.08 |
| Average Solar Radiation Intensity | 266.02 | 250.69 |

From Table 3, we can see that in August 2017, the wind velocity and precipitation slightly up, the temperature and solar radiation intensity slight down and the boundary layer height almost the same compared to the same period in 2016. In August 2017, the wind velocity and boundary layer height facilitated diffusion of precursors, but the increased precipitation and the decreased radiation hindered the formation of O\(_3\). Thus, compared to the same period in 2016, the meteorological conditions in August 2017 were more favorable to the formation and accumulation of ozone. Table 4 shows the pollutant concentration differences only caused by the differences in meteorological conditions.

| Table 4. Statistical Table on Influence of Meteorological Condition Change Based on Numerical Simulation on Pollutant Concentration |
|-----------------------------------------------|-----------------|
| Name | NO\(_2\) | SO\(_2\) | PM\(_{10}\) | PM\(_{2.5}\) | O\(_3\)\(_{\text{max}}\) | CO |
| August 2016 | 60.9 | 7.3 | 70.7 | 50.2 | 335 | 1.00 |
| August 2017 | 50.8 | 8.1 | 53.6 | 38.2 | 218 | 0.94 |
| Meteorological Contribution | -16.6% | 11.0% | -24.2% | -23.9% | -34.9% | -6.0% |

Table 4 shows that in terms of the impact that meteorological condition differences had on the pollutant concentration, the meteorological conditions in August 2017 were obviously better than those in the same period of 2016. Apart from SO\(_2\) whose concentration increased by 11% due to meteorological conditions, the meteorological conditions made pollutant obviously reduced. As for the meteorological effect, compared to the corresponding period in 2016, in August 2017, O\(_3\)\(_{\text{max}}\), PM\(_{10}\), PM\(_{2.5}\), NO\(_2\) and CO were reduced by 34.9%, 24.2%, 23.9%, 16.6% and 6.0% respectively due to meteorological conditions.

4.3. Analysis on Achievement of Ozone Pollution Prevention and Control

Figures 5 ~ 8 show the temporal and spatial distribution of the maximum 8 hours average concentration of ozone (i.e. O\(_3\)\(_{8h\text{max}}\)) in August 2017 in the downtown of Chengdu.

Figure 5 shows that in the time series of O\(_3\)\(_{8h\text{max}}\) in August 2017, the variation trend of the stimulant value (Scenario 02) and that of the value actually measured can basically be matched. The statistical result on relativity shows that the relativity of the stimulant value and the value actually measured are more than 0.65. Under the meteorological field in August 2017, if no control measure is taken to improve the air quality (i.e. the basic scenario), the spatial distribution of O\(_3\)\(_{8h\text{max}}\) in Chengdu will be what is shown in Figure 6. For the time being, regional ozone pollution occurred in Chengdu and the peak value of O\(_3\)\(_{8h\text{max}}\) reached 320\(\mu\)g/m\(^3\). However, the real situation is that a series of measures were taken aimed at ozone pollution and the effect of these measures on ozone concentration reduction is shown in Figure 7 and Figure 8. Figure 7 shows that after OPCAP was adopted, although in a very small area along Longquanzhuang Mountain, the ozone concentration slightly increased, that of
most areas in Chengdu was reduced to some extent. In terms of reduction effect, in most areas of Chengdu, O$_{3\_8h\_max}$ was reduced by 6~10 μg/m$^3$ and in some western areas along mountains, the maximum reduction of O$_{3\_8h\_max}$ reached 18 μg/m$^3$.

Figure 5. Time Series Comparison Between Simulant Concentration and Concentration Actually Measured of O$_{3\_8h\_max}$ in August 2017 (Scenario 02)

Figure 6. Spatial Distribution of O$_{3\_8h\_max}$ in Chengdu Without Any Prevention and Control Action Taken (The Basic Scenario)

Figure 7. Spatial Distribution of O$_{3\_8h\_max}$ Emission Reduction Effect in Chengdu After OPCAP Was Adopted (Scenario 01)

Figure 8. Spatial Distribution of O$_{3\_8h\_max}$ Emission Reduction Effect in Chengdu After the Central Environmental Protection Supervision Was Conducted (Scenario 02)
In addition, the central environmental protection supervision activities were carried out in August 2017. The central environmental protection supervision intensified the implementation of OPCAP and extended the scope of such implementation. In accordance with the statistics on measure implementation from the government departments at different levels in Chengdu, this study acquired the situation on ozone concentration reduction through simulation, as shown in Figure 8.

Figure 8 shows that after the central environmental protection supervision was conducted, O$_{3\text{,}8\text{h max}}$ emission was obviously reduced in Chengdu. In Chengdu, the concentration was reduced in almost all the areas between Longquan Mountain and Longmen Mountain, though the ozone concentration in some areas downwind from the downtown slightly increased.

The numerical simulation result indicates that the maximum emission reduction concentration of O$_{3\text{,}8\text{h max}}$ in Chengdu could reach 30μg/m$^3$ after OPCAP was implemented and the central environmental protection supervision was carried out. The major areas of ozone pollution reduction were located in the west of the second and third circles. The reduction of O$_{3\text{,}8\text{h max}}$ in the downtown of Chengdu remained 6-12μg/m$^3$. This indicates that the central environmental protection supervision mainly worked on ozone concentration reduction in the west of the second and third circles of Chengdu, but its effect on the ozone concentration reduction in the downtown was very limited. The reduction in the downtown of Chengdu mainly came from the effective implementation of OPCAP.

Table 5 shows the pollutant reduction situation under the implementation of different prevention and control measures obtained through numerical simulation.

| Name           | NO$_2$ | SO$_2$ | PM$_{10}$ | PM$_{2.5}$ | O$_{3\text{,}8\text{h max}}$ | CO  |
|----------------|--------|--------|-----------|------------|----------------------------|-----|
| Basic Scenario | 50.8   | 8.1    | 53.6      | 38.2       | 218                        | 0.94|
| Scenario 01    | 38.1   | 7.2    | 43.1      | 30.7       | 210                        | 0.89|
| Scenario 02    | 32.8   | 2.2    | 20.4      | 14.4       | 205                        | 0.82|
| Reduction Rate of Scenario 01 | -25.00% | -11.11% | -19.59%  | -19.63%   | -3.67%                      | -5.32%|
| Reduction Rate of Scenario 02    | -35.4% | -72.8% | -61.9%    | -62.3%     | -6.0%                       | -12.8%|

Notes: Except for ozone, the concentration of pollutants is the monthly average concentration.

Table 5 shows that OPCAP measures alleviated the pollution caused by all kinds of pollutants. Under the meteorological conditions in August 2017 that were relatively good, the temporal and spatial scope of ozone pollution was comparatively weak and the concentration was low, but the average reduction of maximum 8 hours concentration of ozone in the downtown of Chengdu by OPCAP still reached 3.67%. And the concentration of NO$_2$, SO$_2$, PM$_{10}$, PM$_{2.5}$ and CO was reduced by 25.00%, 11.11%, 19.59%, 19.63% and 5.32% on a monthly average basis, respectively. After the environmental protection supervision was started, the reduction of all pollutants in the whole region of Chengdu was obvious, the concentration of NO$_2$, SO$_2$, PM$_{10}$, PM$_{2.5}$ and CO was reduced by 35.4%, 72.8%, 61.9%, 62.3% and 12.8% on a monthly average basis, respectively and the concentration of O$_{3\text{,}8\text{h max}}$ was reduced by 6% on average.

5. Conclusion
This study evaluated the achievements of OPCAP. It shows that OPCAP made pollutants reduced to a large extent, for example, the industrial emissions of VOCs and NOx were reduced by 8600 tons and 2150 tons, respectively. The evaluation result is set forth as follows. To the formation and accumulation of ozone, the meteorological conditions in August 2017 were more favorable compared to those of the same period in 2016. As for the meteorological effect, except for SO$_2$ whose concentration increased by 11%, the concentration of pollutants was obviously reduced due to meteorological effect. Compared to the corresponding period of last year, in August 2017,
meteorological change made $O_{\text{max}}$, PM$_{10}$, PM$_{2.5}$, NO$_2$ and CO reduced by 34.9%, 24.2%, 23.9%, 16.6% and 6.0%, respectively. Where none of prevention and control measures was taken to improve air quality, in August 2017, regional ozone pollution would still occur in Chengdu and the peak value of $O_{3,8h \text{ max}}$ would reach 320μg/m$^3$. After a series of measures including OPCAP were taken, in most areas of Chengdu, $O_{3,8h \text{ max}}$ was reduced by 6~10μg/m$^3$ and in some western areas along mountains, the maximum reduction of $O_{3,8h \text{ max}}$ reached 18μg/m$^3$. The maximum emission reduction concentration of $O_{3,8h \text{ max}}$ in Chengdu could reach 30μg/m$^3$ after OPCAP was implemented and the central environmental protection supervision was carried out at the same time. The major areas of ozone pollution reduction were located in the west of the second and third circles. However, the reduction of $O_{3,8h \text{ max}}$ in the downtown of Chengdu remained 6-12μg/m$^3$. Under equal meteorological conditions in August 2017, OPCAP made $O_{3,8h \text{ max}}$ in the downtown of Chengdu reduced by 3.67% on average and the concentration of NO$_2$, SO$_2$, PM$_{10}$, PM$_{2.5}$ and CO reduced by 25.00%, 11.11%, 19.59%, 19.63% and 5.32% on a monthly average basis.

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