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A Study on the Ozone Control Strategy using the OZIPR in the Seoul Metropolitan Area

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ABSTRACT

To establish area specific control strategy for ambient ozone in the Seoul Metropolitan Area (SMA), the maximum ozone concentration in each local government district in the SMA were estimated by using the OZone Isopleth Plotting Package for Research (OZIPR) model. The modeling period was June 2000 and the emission inventory data used were from National Institute of Environmental Research (NIER). Except the islands of Incheon, whole Seoul and Incheon areas were volatile organic compounds (VOCs) limited, i.e., decreasing the oxides of nitrogen (NO_X) emission alone may increase the maximum ozone concentration upto certain point. In Gyeonggi, 12 areas were VOCs limited while 12 areas were in between VOCs limited and NO_X limited, i.e., decreasing both NO_X and VOCs emission may decrease the maximum ozone concentration. Majority of the estimated ozone values were lower than the measured values. The reason could be inaccuracy in emission inventories and/or transport from other areas. The same calculation was carried out for June 2004 and it was found that Seoul was still in the VOCs limited condition.

Key words: Seoul metropolitan area, O_3, NO_X, VOCs, Control strategy

1. INTRODUCTION

Troposphere ozone has harmful effect on people such as chest pain, coughing, throat irritation, and congestion. In addition, ozone is known for damaging crop and ecosystem (US EPA, 2003). Ozone concentration in the tropospheric layer has increased continuously from 1989 in Korea, which was the year that air quality monitoring network was established. For example, in Gyeonggi, the number of exceedance cases of the air quality standards for concentration of 8-hour average ozone increased from 183 in 2000 to 1126 in 2006 (MOE, 2006).

Ambient ozone is generated through complex photochemical reactions among NO_X and VOC species. Thus, a proper reduction of NO_X and VOCs emission would result in the decrease of the ozone concentration. Nevertheless, it is difficult to manage the concentration of ozone by simply reducing emissions of one precursor because of highly non-linear characteristics of the ozone formation reactions. In some cases, the reduction of NO_X or VOCs alone would lead to the increase of ozone (Park and Kim, 2002). To better understand the relationship among ozone, NO_X, and VOCs, construction of ozone isopleths diagram is often found to be helpful (Gery and Crouse, 2002).

The OZone Isopleth Plotting package for Research-oriented version (OZIPR) is a trajectory type, air quality simulation model based on the US EPA's OZone Isopleth Plotting Program (OZIPP) model, utilizing complex chemical mechanisms, emissions, and various meteorological factors (Gery and Crouse, 2002). As the OZIPR is generally used to simulate the ozone episode occurring in an urban area, it can support policy makers deciding effective emission reduction strategy for improving air quality. Direct results from OZIPR are 1-hour maximum concentration in specific meteorological condition and ozone isopleth diagram. Depending on the emission amounts, OZIPR can produce appropriate result so the quantitative cause and effect analysis of policy is possible.

In this study, the OZIPR model has been used to estimate the ozone formation characteristics for 26 local governmental districts in the SMA for June 2000. From the modeling result, area specific photochemical characteristics for each district can be deduced and optimal ozone control strategies for each district can be established. In addition, to identify temporal trend, the same simulation was carried out on Seoul for June 2004.

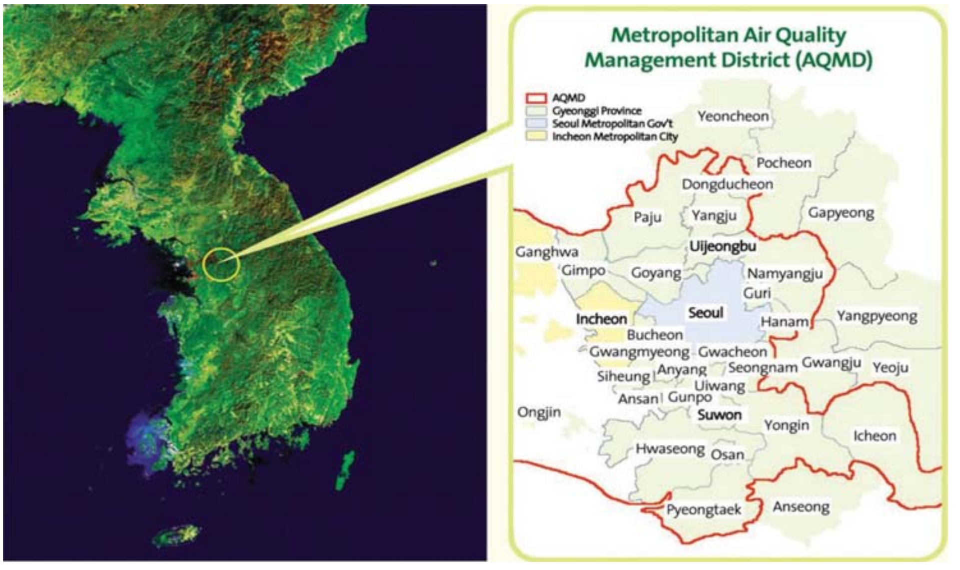

Fig. 1. The modeling domain which is the Seoul metropolitan air quality management district (MOE, 2005).

2. RESEARCH METHODS

2. 1 Research Area and Period

The modeling domain was 26 local government districts in the SMA including Seoul, Incheon, and 24 local governments in Gyeonggi as shown in Fig. 1. In this study, Seoul was divided into 4 areas; northwest (NW), northeast (NE), southwest (SW), and southeast (SE). Incheon was also divided into 4 areas; middle south (MS), west (W), east (E), and Kanghwa-Do & Ongjin-Gun (islands of Incheon, I). Therefore, the number of the total researching area was 32.

The period in this study was from 8 am to 8 pm of an average day in June, 2000. June is one of the optimal months (among May to August) to observe changes in the ambient ozone level due to photochemical reactions (Park and Kim, 2002). The year 2000 was the first year for which the newly developed National air pollutant emission inventory, called the CAPSS (Clean Air Policy Support System) was available in Korea. In the new emission inventory, more detailed information of temporal and spatial emission was available (Shin *et al.*, 2011).

2. 2 OZIPR Model

The OZIPR model is a Lagrangian model which is easy to apply, although it deals with various meteorological and emission conditions, and complex chemical mechanism. Detailed description on the OZIPR model has been given in the User's Guide for Executing OZIPR (Gery and Crouse, 2002). Detailed explanation on its applications on Seoul is given in Park and Kim (2002).

Ozone isopleths diagram produced by OZIPR could help us to determine the characteristics of each research area. From the ozone isopleths diagram, the region below the ridge line of the ozone isopleths plot is what we commonly denote as "NO_X limited". On the other hand, that above the ridge line corresponds to "VOCs limited" (see Figs. 2 & 4). It is apparent that above the ridge line a reduction in NO_X with constant VOCs emission level would lead to an increase in the maximum O_3 concentration upto certain level. Also, below the ridge line, reduction in VOCs has almost no effect on the maximum O_3 concentration (Seinfeld and Pandis, 2006). The region at about the ridge line of the ozone isopleths plot is the area between VOCs limited and NO_X limited. In this region, decrease in the maximum O_3 concentration can be induced by simultaneous reduction of NO_X and VOCs emissions. Therefore, it is significant and necessary that dividing the SMA into several local government districts to fine down the results of the ozone concentration in different areas.

In order to run the OZIPR, several variables should be decided and given. These variables include chemical mechanism, initial concentrations of the chemical species related to ozone formation, VOCs speciation ratio, NO_2/NO_X ratio, the transport concentrations of ozone from upper layer and surface layer, deposition rate profiles, meteorological conditions, and temporally varying emission rates.

The CB-IV (Carbon Bond IV) was used to simulate photochemical reactions. It can distinguish different species with distinction of combined carbon structure. The chemical species of VOCs in CB-IV photochemical mechanism which were ultimately put into OZIPR are shown in Table 1.

Table 1. Speciation of the CB-IV photochemical mechanism (Gery *et al.*, 1989).

Species	Descriptor
ALD_2	Acetaldehyde and higher aldehydes
ETH	Ethene ($CH_2{=}CH_2$)
FORM	Formaldehyde ($CH_2{=}O$)
ISOP	Isoprene (C_5H_{18})
OLE	Olefin carbon bond (C=C)
PAR	Paraffin carbon bond (C-C)
TOL	Toluene (C_6H_4-CH_3)
XYL	Xylene (C_6H_5-$(CH_3)_2$)
NR	Non reaction

The initial concentrations of VOCs (208.8 ppb) were taken from the data reported by Na and Kim (2001), the initial concentration of NO_X and CO was adopted from the monthly report of atmospheric environment (MOE, 2000). The input data of the initial concentrations of NO_X and CO were the average value of observing points in each area. In the several areas among 24 cities in Gyeonggi the average values of the whole Gyeonggi were used, when there was no observing point in its own area.

The transport concentration of ozone on upper layer result was the result from Hong *et al.* (2005). We assumed that NO and NO_2 were the only compositions of NO_X and possess 90% and 10% of the total amount of NO_X, respectively. Thus, NO_2/NO_X emission ratio would be equal to 0.1 (Finlayson-Pitts and Pitts, 1999). The observed values of the atmospheric temperature, atmospheric pressure, and relative humidity were used as the input meteorological data. The initial mixing height was specified as 200 m at 8 am for variable change of mixing height. Maximum mixing height was from the monthly mixing ratio analyzed by Choi and Baek (1998). The default values were used for the deposition rate profiles.

OZIPR modeling has three major limitations; from chemical mechanism used, box model itself, and meteorological input. In chemical mechanism, little experimental information is available on the products from secondary reactions of first-generation reaction product, and the mechanism does not contain reactions for a wide number of oxygenated hydrocarbons, such as alcohols, ethers, and esters. A significant limitation from the box model approach is that quantities being modeled are distributed homogeneously throughout the box, and in order to reduce the uncertainties the observing region should be smaller enough. The OZIPR model is well known as a model of estimating photochemical producing ozone, so nighttime conditions can be difficult to represent in a photochemical model. Thus, more in-depth studies are warranted (Gery and Crouse, 2002).

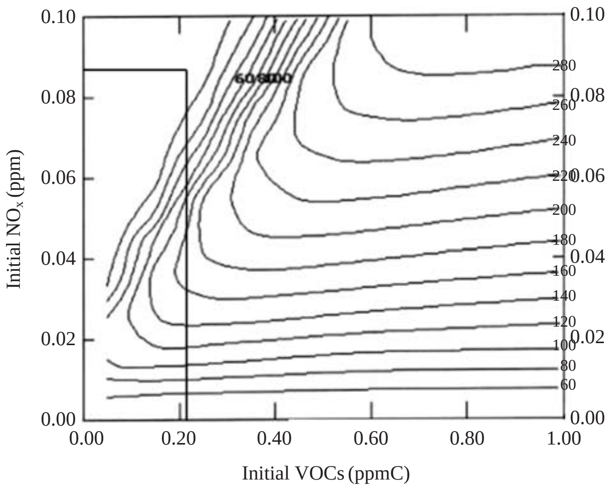

Fig. 2. Ozone isopleths for northwest of Seoul using the OZIPR, a typical example of VOCs limited area in June 2000.

3. RESULTS AND DISCUSSION

3. 1 Area Specific Characteristics

3. 1. 1 Seoul

The four areas in Seoul showed the same trend, VOCs limited, in June 2000, as shown in Fig. 2 for the northwest area. It means in Seoul, in order to reduce ozone concentration, the strategy of reducing VOCs emission or increasing NO_X emission should be taken. Since increasing NO_X emission is not an acceptable option, careful simultaneous reduction of VOCs and NO_X emissions should be taken to reduce ozone concentration in Seoul. If NO_X emission reduction is taken as the top priority, the ambient ozone concentration level would increase with the reduction of NO_X emission upto a certain level. Then, with further NO_X emission reduction, the ozone concentration should decrease. However, this option is a difficult one and not a feasible option. The estimated maximum ozone concentrations in each area were 48.1 ppb at northwest area, 54.0 ppb for northeast area, 59.5 ppb for southwest area, and 60.2 ppb for southeast area.

3. 1. 2 Incheon

For the simulation, Incheon was also divided into four areas. The estimated results of the maximum ozone concentrations in the middle south area and east area in Incheon were 106 and 107 ppb, respectively. These high ozone concentrations might affect both human health and agricultural system. The estimated ozone concentration at west area showed the lowest ozone concentration (24.6 ppb) among all four areas. These three areas were all VOCs limited areas. Thus, in high ozone concentration areas, the VOCs emission reduction strategy is viable. In the low ozone concentration area, west area, the balanced simultaneous reduction of NO_X and VOCs emission should be carried out to make the ozone level low.

The estimated ozone concentration of Kanghwa-Do & Ongjin-Gun was 71.9 ppb, which was higher than Seoul. However, this area was the only NO_X limited area among the four areas in Incheon as shown in Fig. 3. It is reasonable since this area was relatively clean area, the photochemical reaction would be limited by the concentration of NO_X (Seinfeld and Pandis, 2006). Therefore, in these islands area, NO_X emission control should be beneficial.

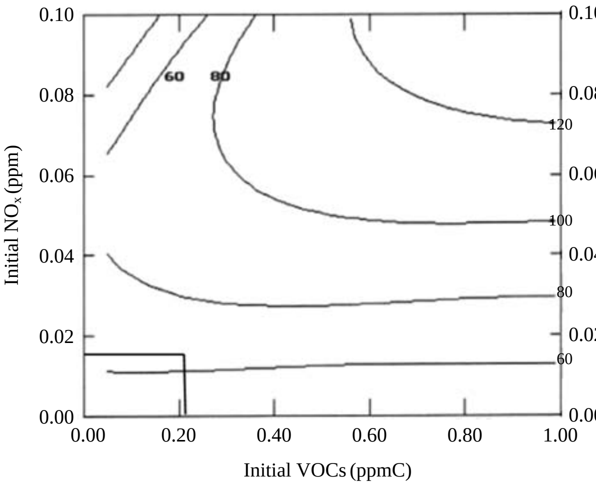

Fig. 3. Ozone isopleths for islands of Incheon using OZIPR, a typical example of NO_X limited area in June 2000.

3. 1. 3 Gyeonggi

Gyeonggi was divided into 24 areas on the basis of the local government district. Table 2 shows the estimated maximum ozone concentrations at each area along with the characteristics of each area, i.e., whether the areas is VOCs limited, NO_X limited, or in between.

It was found that 12 areas such as Suwon, Uijeongbu, and Anyang were VOCs limited areas while the other 12 areas such as Gwangmyeong, Dongducheon, and Gwacheon were in between VOCs limited and NO_X limited as shown in Fig. 4. In these areas, simultaneous reduction of NO_X and VOCs would effective.

This result shows that characteristics of ozone distribution in each local government of Geonggy vary widely and that precaution should be taken to reduce the ozone levels in each area, because the current emission control policy is regional-wide one (Seoul, Incheon, and Gyonggi) and does not consider area level characteristics, it is desirable to consider the area specific

Table 2. The estimated maximum 1-hour ozone concentration and the characteristics of twenty-four areas in Gyeonggi in June 2000.

	Maximum concentration (ppb)	Characteristics
Suwon	56.8	VOCs limited
Seongnam	53.1	VOCs limited
Uijeongbu	133	VOCs limited
Anyang	39.1	VOCs limited
Bucheon	70.7	VOCs limited
Gwangmyeong	150	Between VOCs limited and NO_X limited
Pyeongtaek	80.8	VOCs limited
Dongducheon	111	Between VOCs limited and NO_X limited
Ansan	128	VOCs limited
Goyang	124	VOCs limited
Gwacheon	134	Between VOCs limited and NO_X limited
Guri	83.1	VOCs limited
Namyangju	113	Between VOCs limited and NO_X limited
Osan	66.5	VOCs limited
Siheung	153	Between VOCs limited and NO_X limited
Gunpo	51.6	VOCs limited
Uiwang	121	VOCs limited
Hanam	122	Between VOCs limited and NO_X limited
Yongin	124	Between VOCs limited and NO_X limited
Paju	102	Between VOCs limited and NO_X limited
Icheon	115	Between VOCs limited and NO_X limited
Gimpo	116	Between VOCs limited and NO_X limited
Hwaseong	112	Between VOCs limited and NO_X limited
Yangju	113	Between VOCs limited and NO_X limited

emission control strategy.

The maximum ozone concentrations in each area are shown in Table 2. It can be seen that Anyang recorded the lowest concentration of 39.1 ppb, while Siheung got the highest concentration of 153 ppb. The estimated maximum ozone concentrations in 16 areas including Gwangmyeong and Gwacheon were above the ambient air quality standard, 100 ppb. Thus, the need for ozone control strategy is imperative.

3. 2 Comparison of the Estimated and Observed Ozone Concentrations

Estimated ozone concentrations in each area were compared with the observed ozone values shown in Fig. 5 and the number description for the area is given

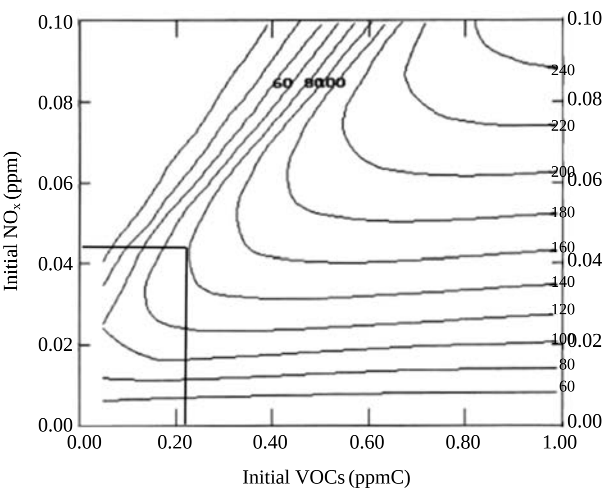

Fig. 4. Ozone isopleths for Gwangmyeong in Gyeonggi using OZIPR, a typical example of in between area in June 2000.

in Table 3. On the average, the estimated values were 18% lower than the observed values. The observed maximum concentrations of ozone in 1-hour average were from the Ministry of Environment (MOE, 2000).

Modeling was carried out based on the emissions of VOCs and NO_X and meteorological conditions without considering transport among the areas. Therefore, it is possible that the ozone level in the areas where the difference between the estimated and observed ozone concentration was small were mainly affected by the precursor emissions. On the while, in the areas with large difference including the whole Seoul and middle south and west areas of Incheon, and major areas in Geonggy such as Suwon, Sungnam, and Anyang, the ozone concentration of these areas would be mainly affected by other than the precursor emissions such as long range transport, and/or meteorological and atmospheric conditions.

3. 3 Temporal Variation of the Area Specific Characteristics

Since the ozone formation characteristics of each area were estimated for June 2000, it is probable that these might be changed with time due to precursor emission change. In order to observe whether the specific characteristics have been changed, a modeling of ozone concentration characteristic in Seoul was carried out for June 2004. Modeling result was shown in Fig. 6. Details on the modeling in June 2004 are given in Shin *et al.* (2011).

From the result, it is found that Seoul was still a VOCs limited area in June 2004. Comparing with June 2000, the average concentrations of both VOCs and NO_X increased in June 2004 (Shin *et al.*, 2011). However, the ozone concentration in June 2004 was lower

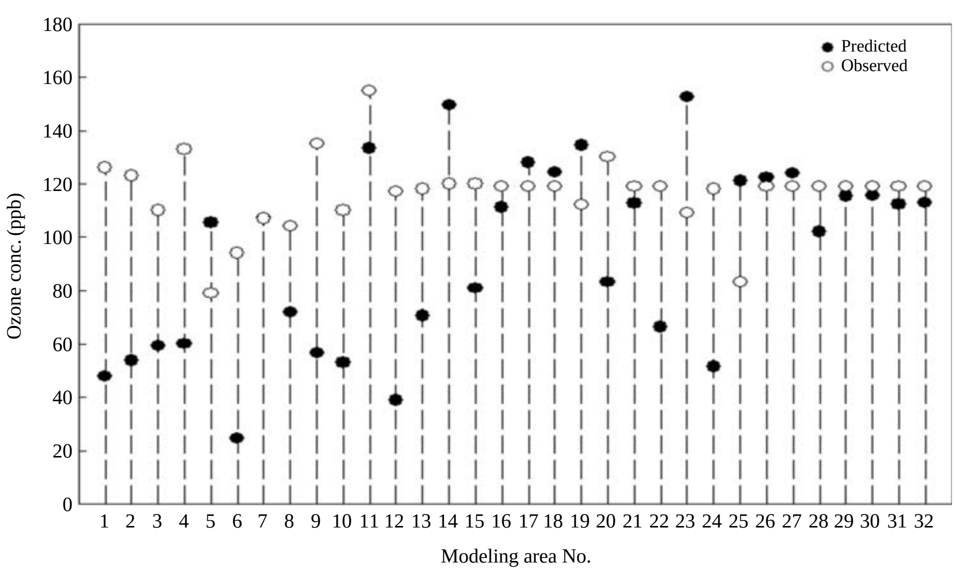

Fig. 5. The comparison of the estimated and observed maximum 1-hour ozone concentration in the Seoul Metropolitan Area; Seoul, Incheon, and Geonggy in June 2000. The numbers represent each area given in Table 3.

Table 3. Modeling domain identification of the SMA shown in Fig. 5.

Seoul (4)					Incheon (4)		
1. NW	2. NE	3. SW	4. SE	5. MS	6. W	7. E	8. I
Gyeonggi (24)							
9 Suwon	10 Seongnam	11 Uijeongbu	12 Anyang	13 Bucheon	14 Gwangmyeong	15 Pyeongtaek	16 Dongducheon
17 Ansan	18 Goyang	19 Gwacheon	20 Guri	21 Namyangju	22 Osan	23 Siheung	24 Gunpo
25 Ui wang	26 Hanam	27 Yongin	28 Paju	29 Icheon	30 Gimpo	31 Hwa seong	32 Yangju

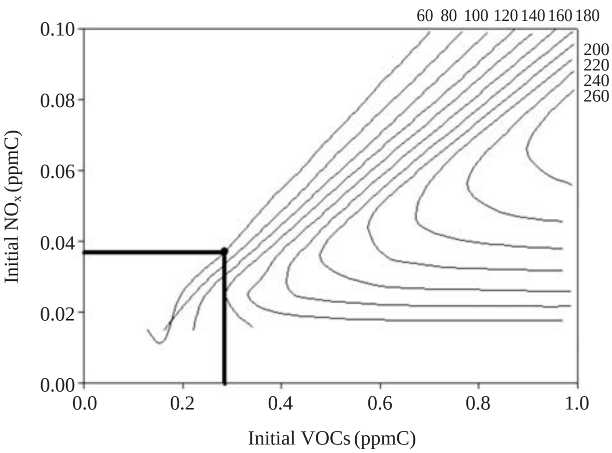

Fig. 6. Ozone isopleths for Seoul using OZIPR in June 2004.

than that in June 2000. In principle, increase in VOCs emission could lead to an increase of ozone concentration. Thus, it could be assumed that decreasing effect by NO_X had much more contribution to the ozone concentration change than VOCs'. Evidently, several other parameters might also lead to the decrease of the ozone concentration like meteorological conditions and transport effect. Still, as mentioned earlier, the result demonstrates that the reduction of NO_X concentration in a VOCs limited area like Seoul could bring the increase of the ozone concentration.

4. SUMMARY AND FURTHER STUDY

To establish an effective ozone control strategy, it is important to accurately describe the characteristics the ozone formation in an area. Emission reduction of one precursor might lead to an increase of the ozone concentration. For preventing ozone concentration increase efficiently, an area specific control strategy for the SMA areas should be set up.

In this study, OZIPR modeling was used to obtain the ozone producing trend in each local government district in the SMA. Different reduction strategies for NO_X and VOCs emission should be taken based on the ozone production characteristics. All areas of Seoul were VOCs limited, in which maximum ozone concentration could be reduced by controlling VOCs emission concentration. Ozone concentration in middle south and east area of Incheon could also be reduced by controlling VOCs emission concentration. West of Incheon could keep low ozone concentration by controlling both NO_X and VOCs simultaneously. The islands of Incheon were NO_X limited, thus controlling of NO_X emission concentration could decrease the ozone concentration. In Gyeonggi, 12 areas were VOCs limited, the other 12 areas were in between VOCs limited and NO_X limited, thus ozone concentrations of these areas could decrease by controlling emission concentration of either VOCs or NO_X. The same trend was observed for Seoul in June 2004.

Majority of the estimated ozone values were lower than the measured values, it is mainly because of inaccuracy of inventory and the neglect of transport. The measured data were from specific area while the estimated one was calculated based on the average condition for wider area. For instance, the measured data in Seoul were from a specific area named Bulgwang-dong, however, the estimated one was calculated based on the average conditions of northwest part of Seoul. This study did not contain the factor like transport effect among areas, but included emission amount and meteorological conditions. Also, since transport effect was not considered in the model, in an area with strong transport effect, there would be a large difference between the measured and estimated values.

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