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Considering Condensable Particulate Matter Emissions Improves the Accuracy of Air Quality Modeling for Environmental Impact Assessment

Doo Sung Choi [1,†], Jong-Sang Youn [2,†], Im Hack Lee [3], Byung Jin Choi [4] and Ki-Joon Jeon [5,*]

1 Department of Building Equipment System & Fire Protection Engineering, University of Chungwoon, Incheon 22100, Korea; trebelle@chungwoon.ac.kr
2 Department of Energy and Environmental Engineering, The Catholic University of Korea, Bucheon 14662, Korea; jsyoun@catholic.ac.kr
3 Department of Environmental Engineering, University of Seoul, Seoul 02504, Korea; imhack@empas.com
4 Jubix, Gyeonggi-do 16419, Korea; cbjin@jubix.co.kr
5 Department of Environmental Engineering, Inha University, Incheon 22212, Korea
* Correspondence: kjjeon@inha.ac.kr
† Both authors contributed equally to this work.

Abstract: This study examines environmental impact assessment considering filterable particulate matter (FPM) and condensable particulate matter (CPM) to improve the accuracy of the air quality model. Air pollutants and meteorological data were acquired from Korea's national monitoring station near a residential development area in the target district and background site. Seasonal emissions of $PM_{2.5}$, including CPM, were estimated using the California puff (CALPUFF) model, based on Korea's national emissions inventory. These results were compared with the traditional environmental impact assessment results. For the residential development area, the seasonal $PM_{2.5}$ concentration was predicted by considering FPM and CPM emissions in the target area as well as the surrounding areas. In winter and spring, air quality standards were not breached because only FPM was considered. However, when CPM was included in the analysis, the results exceeded the air quality standards. Furthermore, it was predicted that air quality standards would not be breached in summer and autumn, even when CPM is included. In other words, conducting an environmental impact assessment on air pollution including CPM affects the final environmental decision. Therefore, it is concluded that $PM_{2.5}$ should include CPM for greater accuracy of the CALPUFF model for environmental impact assessment.

Keywords: environmental impact assessment; condensable particulate matter; air quality model; $PM_{2.5}$; air pollution

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1. Introduction

Particulate matter (PM) includes ammonium sulfate ($(NH_4)_2SO_4$), ammonium nitrate (NH_4NO_3), and trace amounts of soil components, including titanium, iron, zinc, and lead [1,2]. It is composed of various components, such as trace metals, organic matter, and sea salt particles [3–5]. Considering their small size, these particles can be easily inhaled and cause pulmonary and respiratory diseases [6,7], lung diseases [8], and cardiovascular diseases [9]. Furthermore, PM has been reported to influence the premature mortality rate [10,11].

PM can be classified into primary PM (directly emitted from the source) and secondary PM (formed by photochemical reactions in the atmosphere after being emitted in the gaseous phase) [12–14]. In Korea, the national emission inventory estimates the annual emissions of major air pollutants, including carbon monoxide (CO), nitric oxide (NO_x), sulfur oxide (SO_x), total suspended particles (TSP), particulate matter less than 10 μm (PM_{10}), particulate matter less than 2.5 μm ($PM_{2.5}$), black carbon, and volatile organic

compounds (VOCs) based on emission sources and regions [15,16]. The emission inventory for PM (TSP, PM_{10}, and $PM_{2.5}$) considers filterable PM (FPM), which is collected through a filter. However, unlike ambient air, the primary PM emitted from emission sources can be classified into FPM and condensable PM (CPM), and the aggregate of FPM and CPM is considered as the total PM [17]. CPM is in the gas phase under high-temperature conditions and condenses into PM immediately after emitting from the emission source. Corio and Sherwell [18] estimated that CPM accounts for about 76% of total PM10 emission from large stationary emission sources. Although the US EPA recognized the CPM issue in the early 1980s and developed a measurement method for stationary sources, it was not considered as a severe issue [19,20]. Sulfur trioxide (SO_3) in flue gas can react with water vapor to form sulfuric acid mist, which has often been misunderstood as CPM formation [21]. In recent years, not only studies on CPM emitted from stationary sources [22–24] but also studies using CPM as modeling inputs have been conducted [25]. In particular, Morino et al. [25] revealed the contribution of CPM to ambient PM by measuring CPM at stationary sources and confirmed the improvement in the prediction model for ambient PM by including CPM as a model input. Thus, it is necessary to include CPM in the air quality modeling of environmental impact assessments.

In atmospheric studies, AERMOD (the AMS/EPA regulatory model) is one of the most widely used models for environmental impact assessment [26,27]. It is a steady-state plume model that calculates atmospheric diffusion, based on the concept of turbulent structure and scaling in the atmospheric boundary layer. Moreover, it can be used in simple (planar) district scenarios and complex terrain scenarios [28]. The CALPUFF (California puff) model is another model that is used in the evaluation of large atmospheric emission sources, such as industrial complexes, power plants, and incinerators [26,29]. CALPUFF is a multi-layered, multi-stage, unsteady puff diffusion model that simulates the effects of temporally and spatially varying weather conditions on the transport of pollutants [30]. Furthermore, it can be applied to rough and complex terrains. Although the CALPUFF model is useful, it does not consider photochemical reactions and chemical reactions of secondary pollutants. Therefore, chemical transport models, such as CMAQ [31], which consider atmospheric chemical reactions, have been recently used in atmospheric environmental impact assessments.

To improve the CALPUFF model, this study considered CPM in the emission inventory and applied it to the seasonal environmental impact assessment of the target district.

2. Materials and Methods

In this study, the 2013 emission inventory provided by the National Center for Fine Dust Information [32] was used as input data for the CALPUFF model. In addition, total suspended particles (TSPs) and $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 μm) were selected as the target air pollutants. Moreover, CPM emission factors for stationary sources were used, as published by the National Institute of Environmental Research [33] (Table 1). Liquified natural gas (LNG), diesel, and B-C oil were measured in a boiler without a control device. Furthermore, the bituminous coal emission factor was measured at the end of the control devices in a power plant facility. The concentration of CPM emissions was calculated by multiplying the FPM to CPM emission factor ratio with $PM_{2.5}$, obtained from Korea's emission inventory data.

Table 1. Condensable particulate matter (CPM) emission factors estimated by Gong et al., 2016 [33].

Fuel Type	TPM	FPM	CPM	Note
LNG boiler (mg/m^3)	206.67	3.79	202.88	uncontrolled
Light oil boiler (mg/L)	65.78	3.38	62.40	uncontrolled
B-C oil boiler (mg/L)	371.47	143.83	227.64	uncontrolled
Bituminous power plant (g/ton)	71.65	6.55	65.10	uncontrolled

Figure 1 shows a schematic of the CALPUFF model. The CALPUFF model consists of a CALMET module, a meteorological model, and a CALPUFF module, an air pollution model. The CALMET module uses a land cover map, meteorological data, and aerological data as input data to calculate meteorological model results and then inputs the emission inventory to derive the CALPUFF model results. The control file serves to input commands to control each module. To simulate the FPM and CPM emission behavior, a software was developed to calculate the amount of PM emissions from major emission sources in the target district and link this with the meteorological data acquired from the automatic weather system data from the four monitoring stations near the target area. Thus, this software was used to establish a methodology to verify the accuracy of the concentrations of FPM and CPM emissions and understand atmospheric behavior prediction through case studies.

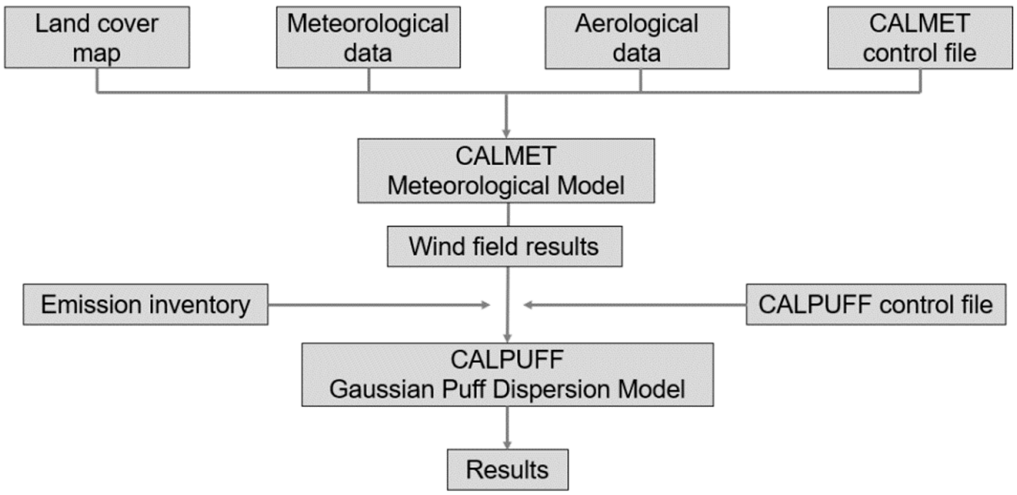

Figure 1. Schematic of the CALPUFF modeling process for environmental impact assessment.

The target area was the Bugok residential development district in Gunpo-si, Gyeonggi-do, with a project area of 470,000 m^2 (residential area of 200,795 m^2, commercial and business area of 6104 m^2, and public area of 263,101 m^2), accommodating approximately 9300 people. To compare and verify the accuracy of the PM concentration via model calculations, real-time data provided by the Korea Environment Corporation (KEC) monitoring station in and around the target district were used.

3. Results and Discussion

The CPM conversion factor management program developed in this study provided a function for searching and managing conversion factors by fuel type. Additionally, CPM emissions were calculated by applying the CPM conversion factor for each fuel to point, line, and surface emission sources. In the CPM emission factor management program of each fuel type, information on the FPM and CPM emission factors of $PM_{2.5}$ emission sources, including construction, buildings, and vehicles, was provided and managed during the development of the residential area. Thus, it was meticulously configured so that details on emission factors for each construction instrument, vehicle type, and building energy fuel could be searched. Seasonal variation is one of the most important parameters for environmental impact assessment, so we applied one month of each season [34,35].

3.1. Seasonal Results for Environmental Impact Assessment (Winter, January)

Figure 2a–d show the modeling results (5.5 × 5.5 km) by segregating the FPM and CPM emissions generated during the operational stage of the Bugok residential development district based on the area to be analyzed and on whether the emission sources outside the target district were considered. The FPM and CPM emissions were calculated by considering the emission sources in the Bugok residential development district. The FPM

concentration was estimated to be 0.0038 μg/m^3, and the CPM concentration was predicted to be 0.27 μg/m^3. Meanwhile, $PM_{2.5}$ was analyzed by considering emission sources that were outside the target district and excluding the emission sources in the Bugok residential development district. The FPM concentration was predicted to be 10.63 μg/m^3, and the CPM concentration was estimated to be 14.82 μg/m^3. Therefore, the TPM (CPM + FPM) concentrations by emission sources inside and outside the target district were calculated to be 0.27 and 25.45 μg/m^3, respectively.

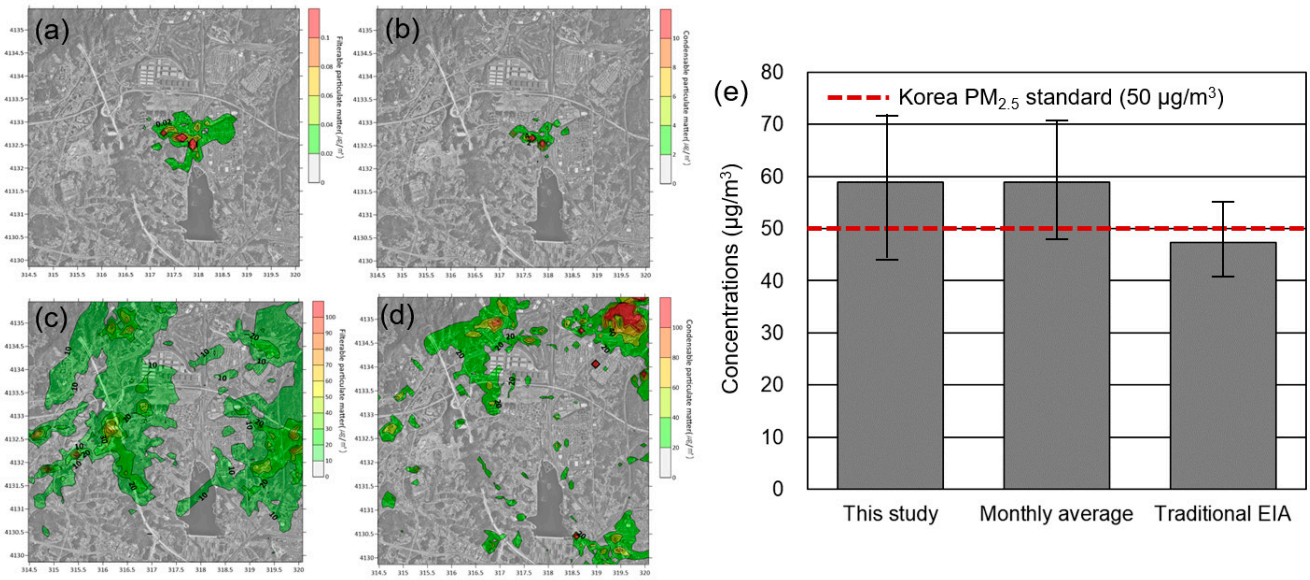

Figure 2. Winter modeling results of (**a**) FPM and (**b**) CPM concentrations in target district, and (**c**) FPM and (**d**) CPM concentrations outside target district. (**e**) Comparison of the results with the monthly average $PM_{2.5}$ concentration obtained from the monitoring station as well as the results of the traditional environmental impact assessment (EIA).

The modeling results were compared with $PM_{2.5}$ data acquired from the air pollutant monitoring stations near the target district. Figure 2e shows the results of this study, monthly averages of the monitoring stations, and traditional environmental impact assessment results. In terms of traditional environmental impact assessment, the $PM_{2.5}$ concentration at the study site was estimated to be 47.28 μg/m^3. This was the sum of the annual average PM concentration inside the target district and the $PM_{2.5}$ concentration data acquired from the monitoring station outside the target district. The modeling result of this study was 58.87 μg/m^3, including the long-range transboundary emissions (33.15 μg/m^3), the FPM concentration inside the target district (0.0038 μg/m^3), the FPM concentration outside the target district (10.63 μg/m^3), the CPM concentration inside the target district (0.27 μg/m^3), and the CPM concentration outside the target district (14.82 μg/m^3). In particular, the average concentration of TPM, the sum of FPM and CPM, in the target district was 25.72 μg/m^3, which was approximately two times lower than the concentration measured in winter at the monitoring station (58.87 μg/m^3).

Table 2 shows the $PM_{2.5}$ concentrations in winter in Deokjeok, Seogwipo, and Seosan, which are the national background concentration monitoring stations located in the far west and south side of Korea. As they are located in the far west and south side of Korea, data collected from monitoring stations are used for evaluation of air pollutants' long-range transportation from polluted areas [36,37]. The observed PM concentrations at the Deokjeok, Seogwipo, and Seosan stations were 31.55, 41.77, and 47.26 μg/m^3, respectively. The difference between the modeling results and the observed values estimated in this study was considered to be due to the effect of the long-range transboundary emissions from other countries.

Table 2. Seasonal $PM_{2.5}$ concentration collected from Korea's national background monitoring station.

(Unit: μg/m^3)	Deokjeok	Seogwipo	Seosan
Winter	47.26 ± 26.56	31.55 ± 19.48	41.77 ± 27.62
Spring	43.73 ± 22.65	58.67 ± 29.75	44.53 ± 18.12
Summer	23.45 ± 6.80	34.58 ± 6.88	23.79 ± 7.32
Autumn	30.45 ± 12.33	28.19 ± 9.63	29.53 ± 13.32

3.2. Seasonal Results for Environmental Impact Assessment (Spring, April)

Figure 3a–d show the results of the predicted spring PM concentration. The results of the prediction of FPM and CPM concentrations in the target district were 0.0026 μg/m^3 and 0.20 μg/m^3, respectively. An estimation of the PM concentration outside the target district revealed that the FPM concentration was 10.56 μg/m^3 and the CPM concentration was 9.59 μg/m^3. The concentration of TPM by emission source inside and outside the target district was 0.20 μg/m^3 and 20.16 μg/m^3, respectively. Thus, the TPM concentration around the target district was estimated to be 20.36 μg/m^3.

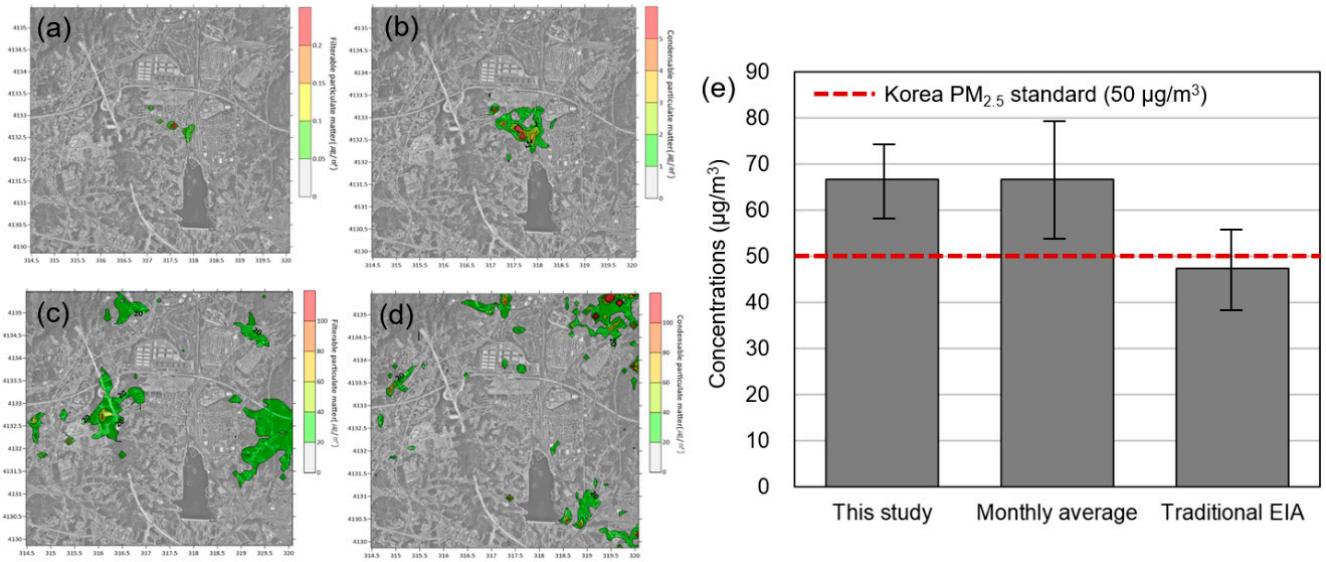

Figure 3. Spring modeling results of (**a**) FPM and (**b**) CPM concentrations in target district, and (**c**) FPM and (**d**) CPM concentrations outside target district. (**e**) Comparison of the results with the monthly average $PM_{2.5}$ concentration from the monitoring stations and the traditional EIA results.

Figure 3e shows the predicted results of this study, measurements of the monitoring station in spring, and the traditional environmental impact assessment results. The modeling result of this study, including the CPM concentration, was 66.70 μg/m^3, which included the long-range transboundary emissions (46.34 μg/m^3), the FPM concentration inside the target district (0.0026 μg/m^3), the FPM concentration outside the target district (10.56 μg/m^3), the CPM concentration inside the target district (0.20 μg/m^3), and the CPM concentration outside the target district (9.59 μg/m^3). In particular, the average concentration of TPM in the target district was 20.36 μg/m^3, which was approximately three times lower than the monthly average of 66.70 μg/m^3 at the monitoring station.

Table 2 shows the PM concentrations in winter in Deokjeok, Seogwipo, and Seosan. The observed PM concentrations at the Deokjeok, Seogwipo, and Seosan stations were 43.73 μg/m^3, 58.67 μg/m^3, and 44.53 μg/m^3, respectively. The difference between the modeling results and the observed values in this study was assumed to be the effect of the long-range transboundary emissions from other countries.

3.3. Seasonal Results for Environmental Impact Assessment (Summer, July)

Figure 4a–d show the results of the prediction of concentrations in summer. The results of the prediction of FPM and CPM concentrations inside the target district were evaluated as 0.0002 μg/m^3 and 0.04 μg/m^3, respectively. By estimating the PM concentration outside the target district, the FPM concentration was predicted to be 8.69 μg/m^3, and the CPM concentration was 7.67 μg/m^3. The concentration of TPM from emission sources inside and outside the target district was 0.04 μg/m^3 and 16.36 μg/m^3, respectively. The TPM concentration around the target district was 16.40 μg/m^3.

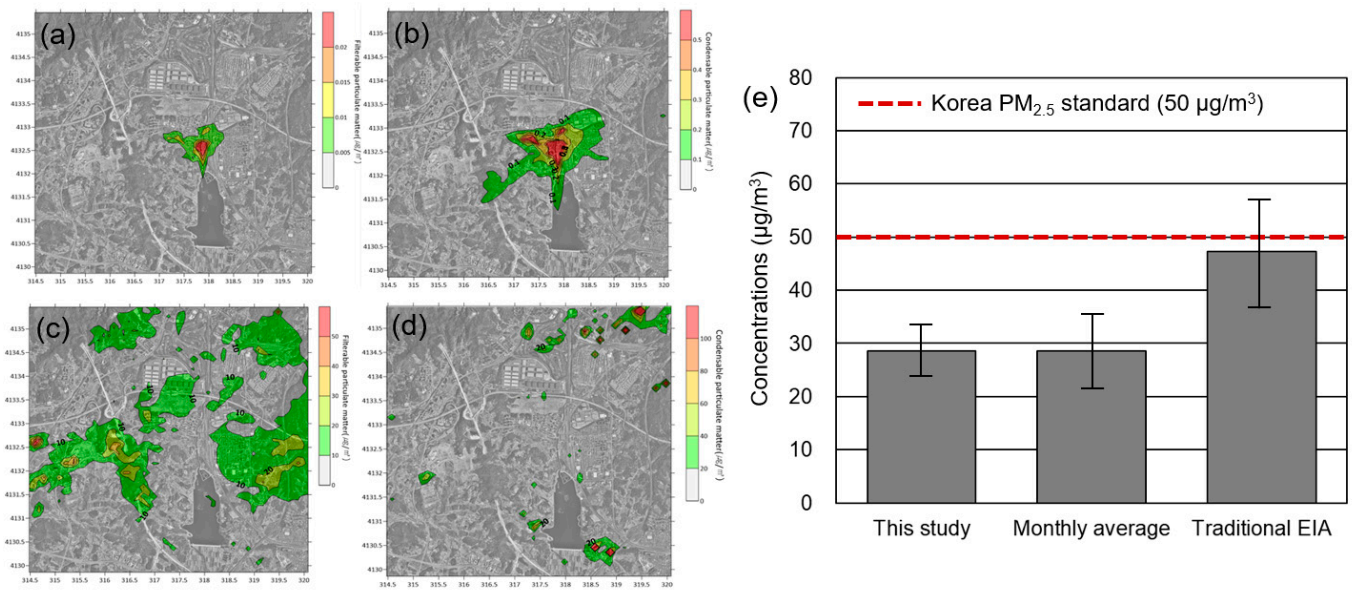

Figure 4. Summer modeling results of (**a**) FPM and (**b**) CPM concentrations in target district, and (**c**) FPM and (**d**) CPM concentrations outside target district. (**e**) Comparison of the results with the monthly average $PM_{2.5}$ concentration obtained from the monitoring stations and the results of traditional EIA.

Figure 3e shows the predicted results of this study, spring measurements of the monitoring station, and traditional environmental impact assessment results. The modeling result of this study, including the CPM concentration, was 28.65 μg/m^3, which included the long-range transboundary emissions (12.24 μg/m^3), the FPM concentration inside the target district (0.0002 μg/m^3), the FPM concentration outside the target district (8.69 μg/m^3), the CPM concentration inside the target district (0.04 μg/m^3), and the CPM concentration outside the target district (7.67 μg/m^3). The concentration of TPM in the target district was estimated to be 16.40 μg/m^3, which was 1.7 times lower than the average concentration measured at the monitoring station in summer (28.65 μg/m^3).

Differences in the predicted summer PM concentrations were considered to be due to the effect of the long-range transboundary emissions. Moreover, the observed PM concentrations at the three stations of Deokjeokdo, Seogwipo, and Seosan were 23.45 μg/m^3, 34.58 μg/m^3, and 23.79 μg/m^3, respectively (Table 2).

3.4. Seasonal Results for Environmental Impact Assessment (Autumn, October)

Figure 5a–d show the results of the autumn concentration prediction. The FPM and CPM concentrations inside the target district were estimated to be 0.0017 μg/m^3 and 0.20 μg/m^3, respectively. By evaluating the PM concentration outside the target district, the FPM concentration was predicted to be 11.29 μg/m^3, and the CPM concentration was predicted to be 9.63 μg/m^3. The concentration of TPM by emission source inside and outside the target district was 0.20 μg/m^3 and 20.92 μg/m^3, respectively. The TPM concentration around the target district was estimated to be 21.12 μg/m^3.

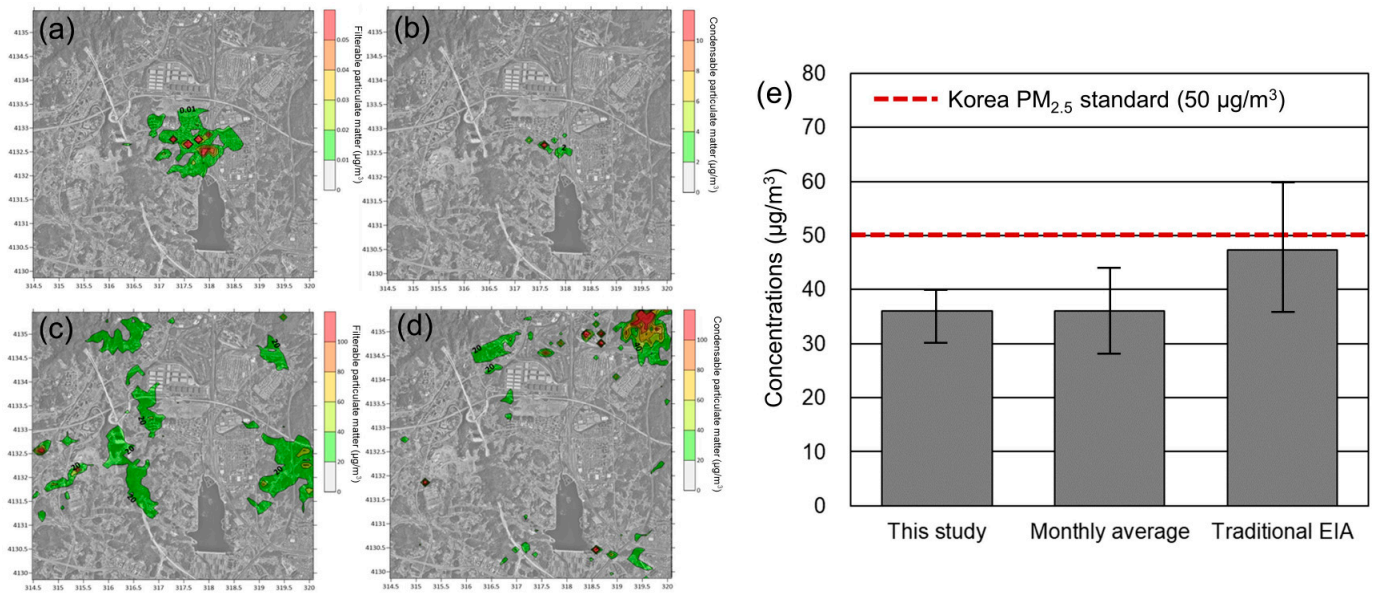

Figure 5. Autumn modeling results of (**a**) FPM and (**b**) CPM concentrations in target district, and (**c**) FPM and (**d**) CPM concentrations outside of target district. (**e**) The results of this study were compared with the monthly average $PM_{2.5}$ concentration obtained from the monitoring stations and the results of traditional EIA.

Figure 5e shows the predicted results of this study, spring measurements of the monitoring station, and traditional environmental impact assessment results. The predicted value of this study, including the CPM concentration was 36.06 μg/m^3, which included the long-distance inflow (14.95 μg/m^3), the in-pipe FPM concentration (0.0017 μg/m^3), the outside FPM concentration (11.29 μg/m^3), the in-pipe CPM concentration (0.20 μg/m^3), and the CPM concentration outside the building (9.63 μg/m^3). In particular, the average FPM and CPM concentrations in the study site were predicted to be 21.12 μg/m^3, which was 1.7 times lower than the average concentration measured in the autumn at the monitoring station (36.06 μg/m^3). The difference in the predicted autumn PM concentration was considered to be due to the long-distance migration. Moreover, it was confirmed that the $PM_{2.5}$ concentrations at Deokjeokdo, Seogwipo, and Seosan were 30.45 μg/m^3, 28.19 μg/m^3, and 29.53 μg/m^3, respectively.

Differences in the predicted autumn PM concentrations were considered to be due to the effect of the long-range transboundary emissions. The observed PM concentrations in the three stations recorded from Deokjeokdo, Seogwipo, and Seosan were 30.45 μg/m^3, 28.19 μg/m^3, and 29.53 μg/m^3, respectively (Table 2).

We included CPM and FPM in the PM prediction model which showed a less than 5% difference compared to the monitoring station data, while the results of traditional environmental impact assessment showed a difference of 20–40% compared to the monitoring station data. Ghim et al. [38] performed an evaluation of a PM2.5 prediction model including only FPM emissions, and the predicted value of PM2.5 was found to be 69% of the monitoring station data. Thus, including CPM emissions in the PM prediction model is one of the ways to increase the accuracy of the model for environmental impact assessment. Even with the results of measuring CPM and FPM at the large stationary emission source, the portion of CPM occupies more than 80% [39], which disproves that the PM concentration should be predicted using both CPM and FPM emissions. In addition, the US EPA recommends that the interim guidance for new source review permit programs should include the CPM in determining a new major stationary source permission [40]. Thus, environmental impact assessment should consider CPM as one of the factors of air quality analysis.

4. Conclusions

In this study, the PM concentration in the atmosphere was predicted by including CPM emissions in the environmental impact assessment. For the residential development area, the seasonal $PM_{2.5}$ concentration was predicted by considering the FPM and CPM emissions in the target area as well as the surrounding areas. In winter and spring, when only FPM was considered, the air quality standards were not breached. However, when CPM results were included in the analysis, air quality standards were exceeded. However, it was predicted that even if CPM is included, air quality standards would not be breached in summer and autumn. This means that air quality forecasting results, including CPM, may alter the results. In addition, the sum of the predicted values of seasonal CPM and FPM was 1.7 to 3 times lower than that of the actual measurement. Compared to the background concentration measurement, it was found to be a result of long-distance travel. Therefore, it is necessary to consider CPM in the emission inventory to carry out environmental impact assessment, air quality modeling, analysis and diagnosis of emissions according to the characteristics of each sector's emission source, and prediction of the $PM_{2.5}$ concentration in the surrounding areas. In this study, environmental impact assessment was performed by considering only primary PM using the CALPUFF model. What remains to be undertaken by future research is an environmental impact assessment including secondary PM.

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