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Analysis of Impact Factors on the Variation of PM_{10} Concentration in Seoul, Korea
- Focus on PM_{10} Concentration Measured in 2003, 2004 -

Hyung-Do Song*, Hee-Chul Lee[1)], Chun-Kyoung Kwon, Rhok-Ho Kim[2)], Sang-Kyun Kim[3)] and Jae-Bum Lee[3)]

Research and Analysis Division, Metropolitan Air Quality Management Office, 34Wongojanro, Danwon-gu Ansan, Korea
[1)]Director-General, Metropolitan Air Quality Management Office, 34Wongojanro, Danwon-gu Ansan, Korea
[2)]Wonju Regional Environmental Management office, Danguro, Myungyundong, Wonju, Korea
[3)]National Institute of Environmental Research (NIER), Environmental Research Complex, Kyeongseodong, Seogu, Incheon 404-170, Korea

*Corresponding author. Tel: +82-31-481-1384, E-mail: hdsong@korea.kr

ABSTRACT

To identify the primary factor affected the decreased PM_{10} concentration in Seoul which is the capital city of Korea, wind speed and emissions in 2003 and 2004 were analyzed. The level of air pollution is intense in Seoul and continually increased since the late 1990s. However the concentration of PM_{10} has been greatly declined recently. In particular, the concentration of PM_{10} decreased 14% in 2003 and 2004 excluding the Asian dust periods. It is suggested that the major factors for the decrease are differences in wind speed between the two years and the period of constant breeze. In 2003, intense Asian dust events happened frequently and it increased the concentration of total PM_{10}. The intense dust events were influence by the speed and duration of the wind. It is considered that the meteorological condition was the primary drive for the change of the concentration of PM_{10}. The decreased emissions seem to be the additional factor for the change in the concentration of PM_{10}.

Key words: PM_{10}, Seoul, Wind speed, The period of constant breeze, Emissions

1. INTRODUCTION

Since the 1990s, the air quality in the National Capital region of Korea including Seoul has been improved due to active pollution control policies such as supply of oil with low sulfur content and the obligatory use of clean fuel. However, the pollution caused by secondary pollutants such as fine particles, NO_2 and ozone has not been improved due to the industrial activities and increasing number of automobiles. The concentrations of PM_{10} and NO_2 in the National Capital region in Korea are 2-3.5 times and 1.7 times higher than in US and Europe respectively.

Fine particles are particularly harmful to human health among the various air pollutants. A recent study supports the necessity to reduce the fine particles by revealing serious impacts of fine particles on annual individual risk and lifetime individual risk (Kim *et al.*, 2003). In an hygienic aspect, particles larger than 10 μm in diameter can be expelled through human respiratory system. However, particles less than 10 μm in diameter pose the greatest health concern because they can pass through the nose and throat and finally get into the lungs (Lee *et al.*, 1996; Park and Chung, 1992). Furthermore, they reduce the distance of visibility and produce smog. Therefore, fine particles are the main target for an emission control. To study the behavior of fine particles quantitatively, it is necessary to estimate the amount of emissions, the input and output from external origins plus source and sink in the air yet it is very difficult to conduct.

Asian dust events happen every spring in Korea (Kim *et al.*, 2002; Chung and Yoon, 1996). The Asian dust transports suspended dust from deserts or loess in China and Mongolia to Korea by wind or turbulent flow (Lin *et al.*, 2001) and it greatly increases the concentration of fine particles. Numbers of researches on the occurrence and characteristics of Asian dust have been ongoing since the 1990s (Kim *et al.*, 2004a; Hwang and Wang, 1998; Gao *et al.*, 1992; Okada *et al.*, 1990). To establish an efficient policy to reduce the concentration of fine particles, it is necessary to assess the impact of Asian dust on the air quality in Seoul.

Since 1998, the concentration of fine particles in Seoul continually increased and in 2002 it reached its highest point at 76 μg/m^3, among the all other regions in Korea. However, the concentration of fine particles in Seoul significantly decreased to 69 μg/m^3 in 2003 and to 61 μg/m^3 in 2004, and the trend was exclusive in Seoul. In this study, we examined the major factors causing the decreased level of PM_{10} in 2003 and 2004. We have observed the data obtained from 29 measurement grids in Seoul during 2003 and 2004, and analyzed the main reasons influenced by the trend.

2. EXPERIMENTAL METHODS

2. 1 Regional Air Quality Measurement Grids

In South Korea, ten types of measurement grids to monitor the major pollutants such as SO_2, NO_x, O_3, CO and PM_{10} are installed and operated. The data are to be utilized for making a plan to improve the air quality. Regional air quality measurement grids (the name has been changed to urban air quality measurement grids since January, 2006) are operated to monitor the urban air quality to monitor whether the air quality meets the environmental standards or not.

As of December 2004, there were twenty seven of measurement centers in Seoul (Fig. 1). The data obtained at the centers are collected to National Institute of Environmental Research and utilized for policy making and monitoring the level of air pollution.

2. 2 Status of Emission

Fine particles are originated from natural phenomena such as Asian dust events and anthropogenic emissions from industrial activities. National Institute of Environmental Research estimates the emissions using Clean Air Policy Support System (CAPSS). The anthropogenic PM_{10} emission trends estimated using CAPSS are shown in Table 1. PM_{10} emissions in Seoul increased from 1999 to 2003 and decreased in 2004 for the first time (Table 1).

Fig. 2 tells us that the total PM_{10} emission is mostly coming from on-road mobile sources rather than industrial processes. The PM_{10} emission from on-road mobile sources in Seoul is higher than that in Incheon and Gyeonggi-do. For instance, in 2004, 79% of PM_{10} came from the on-road mobile sources in Seoul, 59% in Incheon and 67% in Gyeonggi-do (NIER, 2004).

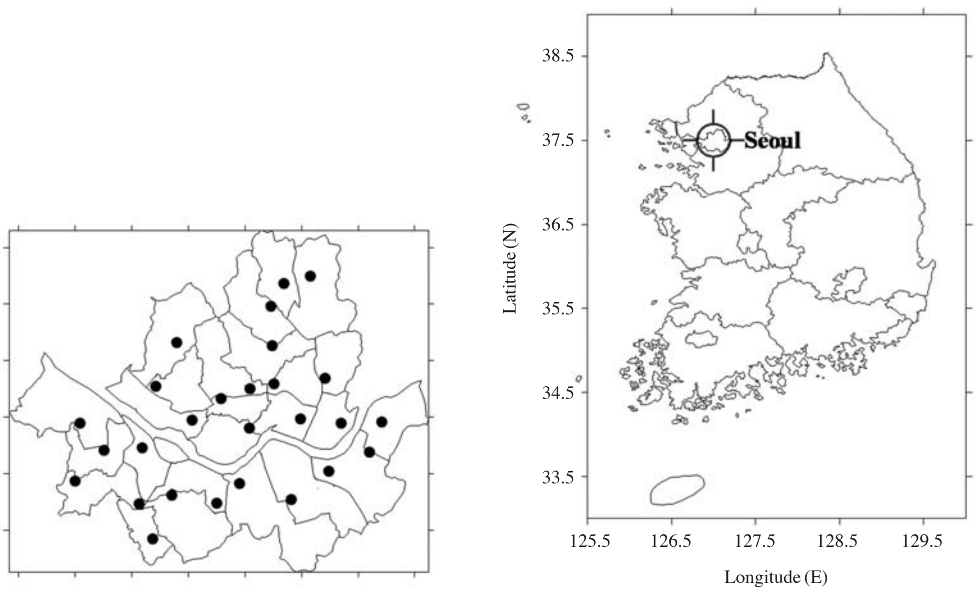


Fig. 1. Location map of monitoring stations in Seoul, Korea.

Table 1. Anthropogenic emissions of PM_{10} in Seoul (KME, 2007). (unit: ton)

Year	Energy industry combustion	Non-industry combustion	Industry combustion	Production process	On-road mobile sources	Off-road mobile sources	Waste treatment	Total
1999	15.4	483.4	7.6	–	2,281.2 (72%)	399.1	2.0	3,188.6
2000	16.0	445.2	6.9	–	2,757.0 (74%)	521.3	3.2	3,749.7
2001	18.0	427.1	9.0	–	3,509.1 (77%)	566.0	3.4	4,532.6
2002	13.3	340.7	4.9	–	3,399.0 (73%)	875.2	3.9	4,637.0
2003	14.4	312.5	5.1	–	3,429.8 (73%)	916.2	5.1	4,683.1
2004	13.2	324.0	3.3	–	3,507.8 (79%)	570.0	5.4	4,423.7

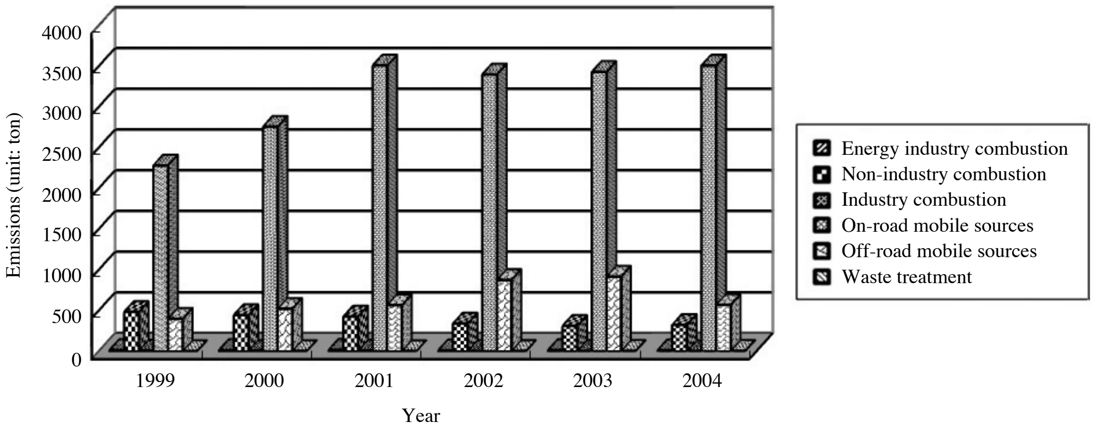


Fig. 2. Anthropogenic emissions of PM_{10} at Seoul for the period of 1999 to 2004 (unit: ton).

Table 2. The annual variation of meteorological conditions and PM_{10} concentrations in Seoul from 2000 to 2004.

Year	PM_{10} ($\mu g/m^3$)	PM_{10} ($\mu g/m^3$) (excluding Asian dust)	Occurrence days of Asian dust (day)	Wind speed (m/s)	Period of constant breeze (day) (≤ 2 m/s)	Emissions (ton)
2000	65	63	10	2.2	192	3749.7
2001	71	66	27	1.8	239	4532.6
2002	76	65	16	2.1	198	4637.0
2003	69	69	3	2.0	212	4683.1
2004	61	59	6	2.4	144	4423.7

The data described above do not contain fugitive dust in the air which is not emitted from combustion outlets. Fugitive dust comes mostly from natural sources. The amount of fugitive dust is hard to be estimated because it varies with weather condition. For the reason, fugitive dust is excluded from emissions data and only the emissions from combustion outlets are used for the managing index (Kim *et al.*, 2004a). According to the national emissions data calculated by a new estimating method, 78% of fugitive dust was emitted from paved roads and 22% from other sources including construction processes (Kim *et al.*, 2004b). Furthermore, the amount of fugitive dust emissions is much higher than other types of emissions. In case of U.S., fugitive dust is on the National emissions list and it contributes to 80% of total particles emissions (U.S. EPA, 2000). To establish a reduction policy for fine particles, it will be crucial to know whether or not the fugitive dust emissions can be declined simultaneously if the other fine particles emissions are reduced (Kim *et al.*, 2006).

2. 3 Annual PM_{10} Trends in Seoul

Based on the data obtained since 2000, PM_{10} concentration has risen little by little and suddenly reduced from 2002. The maximum concentration of PM_{10} was observed as 76 $\mu g/m^3$ in 2002, 69 $\mu g/m^3$ in 2003 and reduced to 61 $\mu g/m^3$ in 2004. Overall, the PM_{10} concentration has been declined by 20% from 2002 to 2004. In particular, in 2002, Asian dust events happened 16 times and it greatly affected the PM_{10} concentration. In April 2002, PM_{10} concentration hit 3,000 $\mu g/m^3$ (3,311 $\mu g/m^3$, Hanman-dong in Seoul), which set the highest record ever since. Moreover, Asian dust phenomena happened during the fall in the same year for the first time since 1991 (NIER Annual Report 2004, 2003, 2002). This can be considered that severe drought and accelerated desertification in areas within China and Mongolia are making the neighboring area of the Korean peninsula turn into the origin of Asian dust (Kim *et al.*, 2004b).

In the following year, the occurrence of Asian dust reduced to three times and the intensity of events also weakened. Although the Asian dust did not affect the total PM_{10} concentration in 2003 and 2004, the PM_{10} concentration reduced drastically for both years. Fig. 3 and Table 2 show the annual PM_{10} concentration trends in Seoul with and without the effect of Asian dust.

The annual PM_{10} concentration in Seoul was relatively constant from 2000 to 2003 without the consideration for the irregular Asian dust events. In general, the concentration declined when the wind speed was high

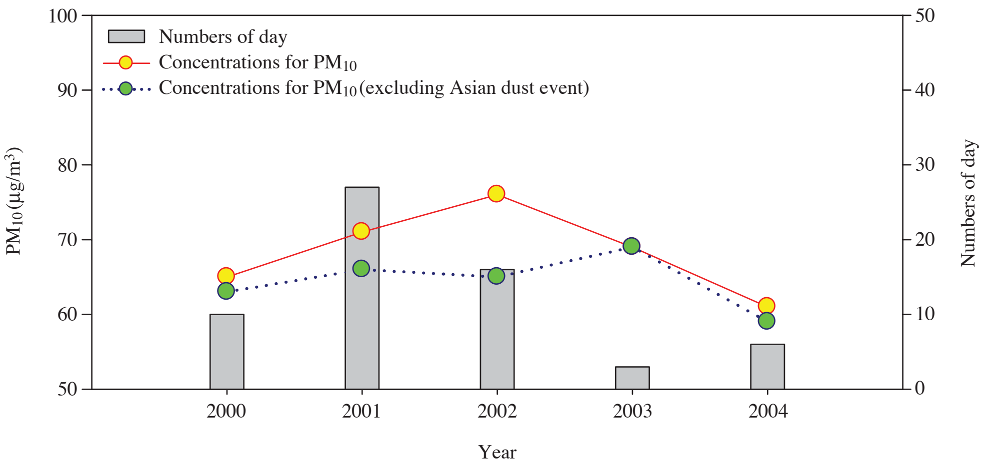


Fig. 3. The annual variations of mean concentrations for PM_{10} & occurrence days of Asian dust events at Seoul.

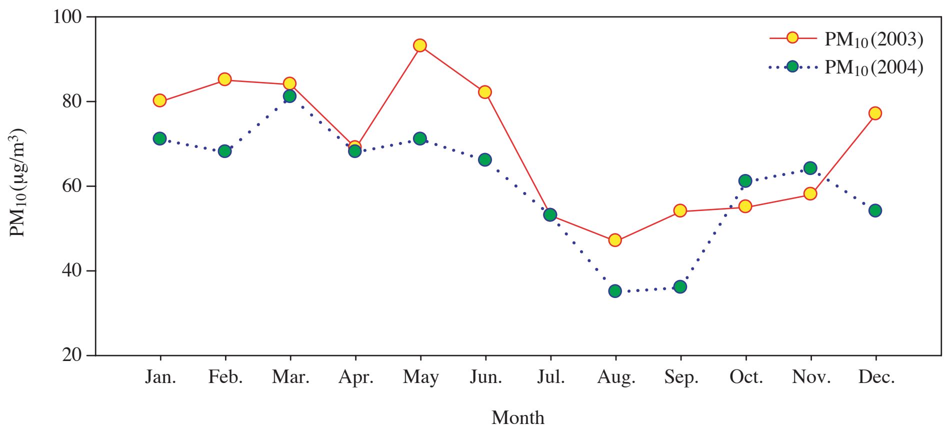


Fig. 4. The monthly variations of mean concentrations for PM_{10} at Seoul in 2003 & 2004.

and increased when the period of constant breeze (speed below 2 m/s) was long. Emissions do not likely to affect the PM_{10} concentration because it has not fluctuated much since 2001. Note that the emissions are excluding the amount of fugitive dust not emitted from combustion outlets, and thus there is a possibility that the actual emissions would be a greater amount.

This paper analyzed the impact of wind speed, the period of constant breeze and emissions on PM_{10} concentration in Seoul, particularly in 2003 and 2004.

3. RESULTS AND DISCUSSION

3. 1 Monthly Trends of PM_{10} Concentration in 2003 and 2004

The mean concentration of fine particles in Seoul declined by 8 μg/m^3 from 69 μg/m^3 in 2003 to 61 μg/m^3 in 2004. For the analysis of the factors affected by the concentration, we assessed the cases when the daily PM_{10} concentration was over the environmental standard, 150 μg/m^3 and the case when the daily PM_{10} concentration was over 100 μg/m^3 for more than 2 days.

Fig. 4 illustrates the monthly variation of mean PM_{10} concentrations in Seoul during 2003 and 2004. The PM_{10} concentration reduced by 8 μg/m^3 from 2003 to 2004, and the downward trend of PM_{10} concentration was strong in January, February, May, June, August, September and December in 2004. In addition, even the difference of monthly mean concentrations between the two years excluding the days with unusual high concentration caused by Asian dust events (values in parenthesis on Table 3) was also huge between 2003 and 2004, especially in January, February, June and November.

Table 3. The monthly difference of mean concentrations of PM_{10} in Seoul from 2003 to 2004. (unit: μg/m³)

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Ave.
2003	80 (66)	85 (66)	84 (72)	68 (66)	90 (71)	82 (72)	53 (47)	47	54 (41)	55 (52)	58 (50)	77 (59)	69 (59)
2004	71 (60)	68 (56)	81 (67)	67 (63)	71 (66)	66 (60)	53 (50)	35	36	61 (55)	64 (61)	54	61 (55)
Diff.	−9 (−6)	−17 (−10)	−3 (−5)	−1 (−3)	−19 (−5)	−16 (−12)	0 (3)	−12	−18 (−5)	6 (3)	6 (11)	−23 (−5)	−8 (−4)

* difference: value of concentrations for 2004 − value of concentrations for 2003
* ( ): the mean PM_{10} concentration without the high concentration

Table 4. The monthly variations of mean wind speed in Seoul during 2003 and 2004. (unit: m/s)

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Ave.
2003	2.5	2.2	2.3	2.5	1.8	2.0	1.8	1.4	1.1	2.0	2.0	2.4	2.0
2004	2.1	2.9	2.7	2.7	2.6	2.1	2.3	2.4	2.2	2.0	2.0	2.2	2.4
Diff.	−0.4	0.7	0.4	0.2	0.8	0.1	0.5	1.0	1.1	0	0	−0.2	0.4

Table 5. The monthly differences of mean concentrations of PM_{10} in 2003 and 2004. (unit: μg/m³)

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Ave.
2003	85	101	81	65	101	86	64	47	62	74	72	86	77
2004	74	90	79	70	83	74	57	–	–	73	73	59	73
Diff.	−11	−11	−2	5	−18	−12	−7	–	–	−1	1	−27	−4

* differences: the mean of 2003 was deducted from the mean of 2004

3. 2 Comparison on the Wind Speed and Monthly Concentration of PM_{10}

The mean wind speed in 2004 was 2.4 m/s, which increased by 0.4 m/s from 2.0 m/s in 2003. The monthly basis comparison reveals that there were huge gaps between the mean wind speed in February, May, August and September of each year. Overall, the wind speed was higher in 2004 than that in 2004 except January and December (Table 4).

To identify the impacts of wind speed on PM_{10} concentration, the differences of PM_{10} and wind speed of each month in 2003 and 2004 were compared (Table 5).

PM_{10} concentration of the days with wind speed below the mean of June 2003 which is 2 m/s was calculated as 86 μg/m³ in June 2003 and 74 μg/m³ in June 2004. The mean PM_{10} concentration for the days below the mean wind speed in 2004 was calculated as 73 μg/m³ and 77 μg/m³ in 2003, and therefore the gap was 4 μg/m³. In December, in particular, the concentration gap was 27 μg/m³. In addition, PM_{10} differences in January, February, May and June for each year were over 10 μg/m³ (Table 5). The data for the August and September in 2004 were not calculated because there were no such days with wind speed below 1.4 m/s and 1.1 m/s which were the mean wind speed of the same months in 2003.

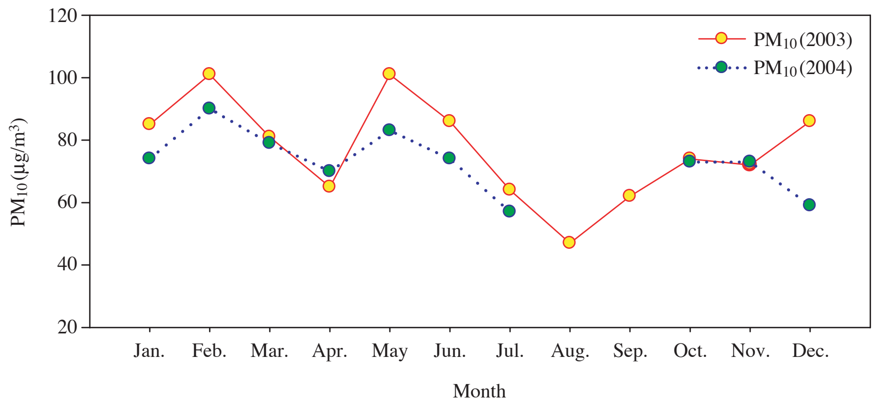
Table 6. The PM_{10} differences when the wind speed is lower and higher than the mean.

Year	Speed below the mean	Speed above the mean	Difference
2003	77 μg/m³	59 μg/m³	18 μg/m³
2004	73 μg/m³	55 μg/m³	18 μg/m³

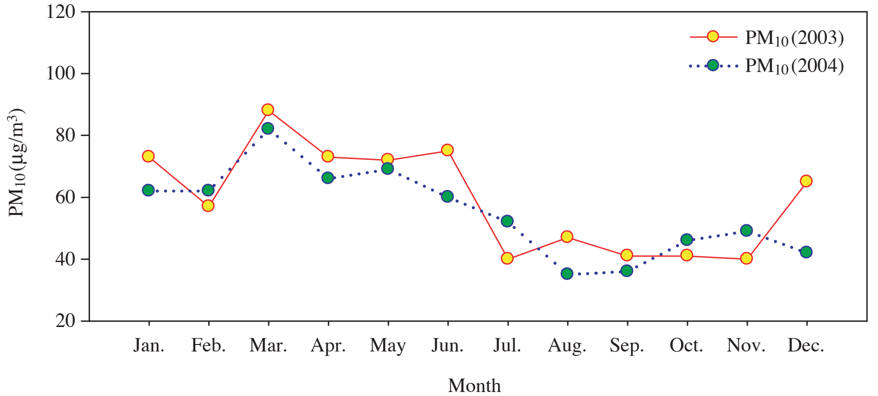
The PM_{10} concentration of the days with wind speed below the mean was over 10 μg/m³ higher than that of the days with speed above the mean. In 2003, the annual PM_{10} concentration of the days below the mean wind speed was calculated as 77 μg/m³ and 59 μg/m³ of the days above the mean speed (Table 6).

The concentration of PM_{10} greatly reduced by 18 μg/m³ when the wind speed was high due to ventilation and washing out effects of the strong wind.

The trend in 2004 was also similar in 2003 and the concentration difference was 4 μg/m³. The concentration of PM_{10} when the wind speed was below the mean was 73 μg/m³ and 55 μg/m³ when the speed was above the mean. As it mentioned earlier, the high PM_{10} concentration was observed much more frequently when



(a) Less than monthly mean wind speed



(b) More than monthly mean wind speed

Fig. 5. Monthly variations of mean PM_{10} concentration in Seoul from 2003 to 2004; the concentration trend when the wind speed is lower and higher than the mean.

Table 7. The PM_{10} trend when the wind speed is lower and higher than the mean.

	Jan.		Feb.		Mar.		Apr.		May		Jun.	
2003	80 (2.5)		85 (2.2)		84 (2.3)		68 (2.5)		90 (1.8)		82 (2.0)	
	85 (20)	73 (11)	101 (18)	57 (10)	81 (17)	88 (14)	65 (16)	73 (14)	101 (19)	72 (12)	86 (20)	75 (10)
2004	71 (2.1)		68 (2.9)		81 (2.7)		67 (2.7)		71 (2.6)		66 (2.1)	
	74 (22)	62 (9)	90 (6)	62 (23)	79 (12)	82 (19)	70 (11)	66 (19)	83 (5)	69 (26)	74 (12)	60 (18)
	Jul.		**Aug.**		**Sep.**		**Oct.**		**Nov.**		**Dec.**	
2003	53 (1.8)		47 (1.4)		54 (1.1)		55 (2.0)		58 (2.0)		77 (2.4)	
	64 (17)	40 (14)	47 (16)	47 (15)	62 (19)	41 (11)	74 (13)	41 (18)	72 (17)	40 (13)	86 (18)	65 (13)
2004	53 (2.3)		35 (2.4)		36 (2.2)		61 (2.0)		64 (2.0)		54 (2.2)	
	57 (7)	52 (24)	–	35 (31)	–	36 (30)	73 (17)	46 (14)	73 (19)	49 (11)	59 (22)	42 (9)

Monthly mean concentration (monthly mean wind speed)
PM_{10} conc. (days with below the mean)
PM_{10} conc. (days with above the mean)

the wind speed was low.

The PM_{10} trends with the monthly mean wind speed are shown in Fig. 5 and Table 7. In general, the PM_{10} concentration was lower in 2004 than in 2003. Meanwhile, the concentration in March and April increased due to the input of fine particles from China by strong wind from the west.

3. 3 Case Studies in 2003 and 2004

3. 3. 1 Selection of the Cases

The differences of monthly PM_{10} concentration between 2003 and 2004 ranged from 1 μg/m^3 to 23 μg/m^3. To select the cases to be analyzed, the arithmetic mean of the PM_{10} data from all measurement centers in Seoul was calculated, and then the spatial mean was computed accordingly. Cases are chosen if the monthly mean difference exceeds 10 μg/m^3.

3. 3. 2 Case Analysis for February, May, September and December

The high concentration of PM_{10} occurred twice in February 2003. The high concentrations were observed under the weather condition under which diffusion and transport were limited.

As shown in Fig. 6(a), the mean wind speed was 2 m/s and around 1.5 m/s in the later part of the month. This can be considered that the low wind speed made the air stable and consequently the diffusion of pollutants in the air was restricted because of the low degree of ventilation. In 2004, the stagnant high atmospheric pressure weakened the wind speed, and thus the low ventilation resulted in the high concentration of PM_{10} on February 1 and on 17 through 21. However, the precipitation started from the night on 21 through 22 washed the fine particles out so the PM_{10} concentration was greatly reduced after February 22 (Fig. 6(b)).

In 2003, the PM_{10} concentration on May 22 through 24 far exceeded 150 μg/m^3, the daily environmental standard. PM_{10} concentration was continually high on May 19 through 24, and the mean in Seoul was 214 μg/m^3 on May 22 and 209 μg/m^3 on May 23. The maximum concentration was observed at Gueui-dong and Sungsu-dong as 263 μg/m^3. The high concentrations were observed all through the Korean peninsula and the distance of visibility was lower than 10 km in the capital region. This occasional high concentration of PM_{10} is characteristic in Korea and caused by migratory anticyclones periodically piled on the peninsula. During the period, the pollutants were accumulated in the air when the wind speed was lower than 2 m/s. The wind speed was below 2 m/s (mean was 1.8 m/s) on the majority of the days in May except 5 days, so the accumulation was intensified by the low circulation and ventilation of the air.

The PM_{10} concentration on September in 2003 and 2004 was 54 μg/m^3 and 36 μg/m^3 respectively, which decreased by 18 μg/m^3 from 2003 to 2004. The reason for the decrease is the occasional high concentration (over 100 μg/m^3) of PM_{10} started from September 14, 2003 to September 17 (Fig. 6(e)). The concentrated pollutants in the air seem to be induced by the long ranged-transport from China by typhoon occurred before September 14. After the September 14, the mean wind speed decreased below 2 m/s, and it made the pollutants accumulated in the air by lowering diffusion and transport.

Precipitation days in September 2003 and 2004 were 6 days and 5 days respectively, and the monthly precipitation was higher in 2003 than in 2004. The mean wind speed increased twofold from 1.1 m/s to 2.2 m/s and in September 2003, the wind speed was maintained below 2 m/s, so the ventilation of the air was limited.

The concentration of PM_{10} was very high on December 22, 2003 through December 26. In Seoul, in particular, the concentration during the period went over 150 μg/m^3, the daily environmental standard (Fig. 6(g)). For instance, the mean PM_{10} concentration on December 24 was 245 μg/m^3. On the day, the wind speed was below 2 m/s and a radiation inversion layer of 300 m was formed by stagnant high atmospheric pressure, and therefore the favorable condition for the accumulation of pollutants was developed by limited diffusion and transport.

3. 3. 3 The Case Analysis for June and August

Fig. 7 illustrates the daily trend of PM_{10} and the wind speed in June and August of the each year. The trends of concentration and weather conditions were different in June and August from other months. There were 6 days of occasional high PM_{10} concentration in June 2003 and 2 days in 2004. Even though the occasional high concentrations were excluded, the mean was 72 μg/m^3 in June 2003 and 60 μg/m^3 in June 2004, which declined by a huge gap, 12 μg/m^3 (16 μg/m^3 decrease when the occasional high concentration data are included). On June 11, 2004, the noticeable daily mean concentration exceeding 150 μg/m^3 was observed, and the concentration decreased later the month by washing out effects during the long rainfall season. There was little difference in precipitation amount, precipitation days, and mean wind speed between the two years. However, the concentration difference between the two years was huge. This can be explained by the slow wind speed below 2 m/s for 20 days in June 2003 and the 9 days of reduced period of constant breeze in June 2004. The slow wind speed during June 2003 made the air stagnate, and thus increased the overall PM_{10} concentration.

In August, noticeable high concentration was not observed. The precipitation in August 2003 was 3.5 times higher than that in August 2004 and the precipitation days were twofold in August in 2003. However, the mean wind speed was 1.4 m/s, which accounts for

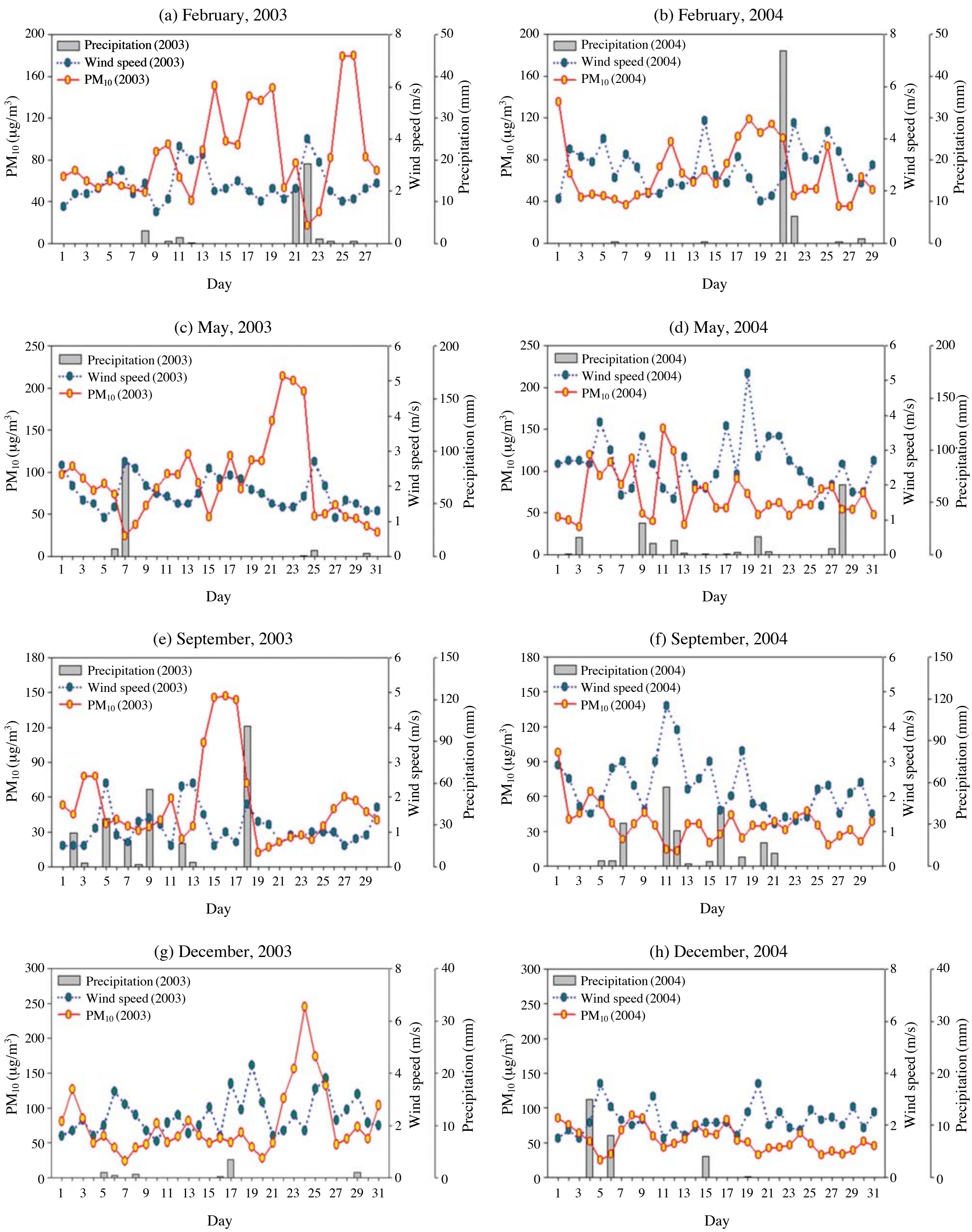


Fig. 6. Comparison on the variation of PM_{10} concentrations in Seoul during February, May, September and December in 2003 and 2004.

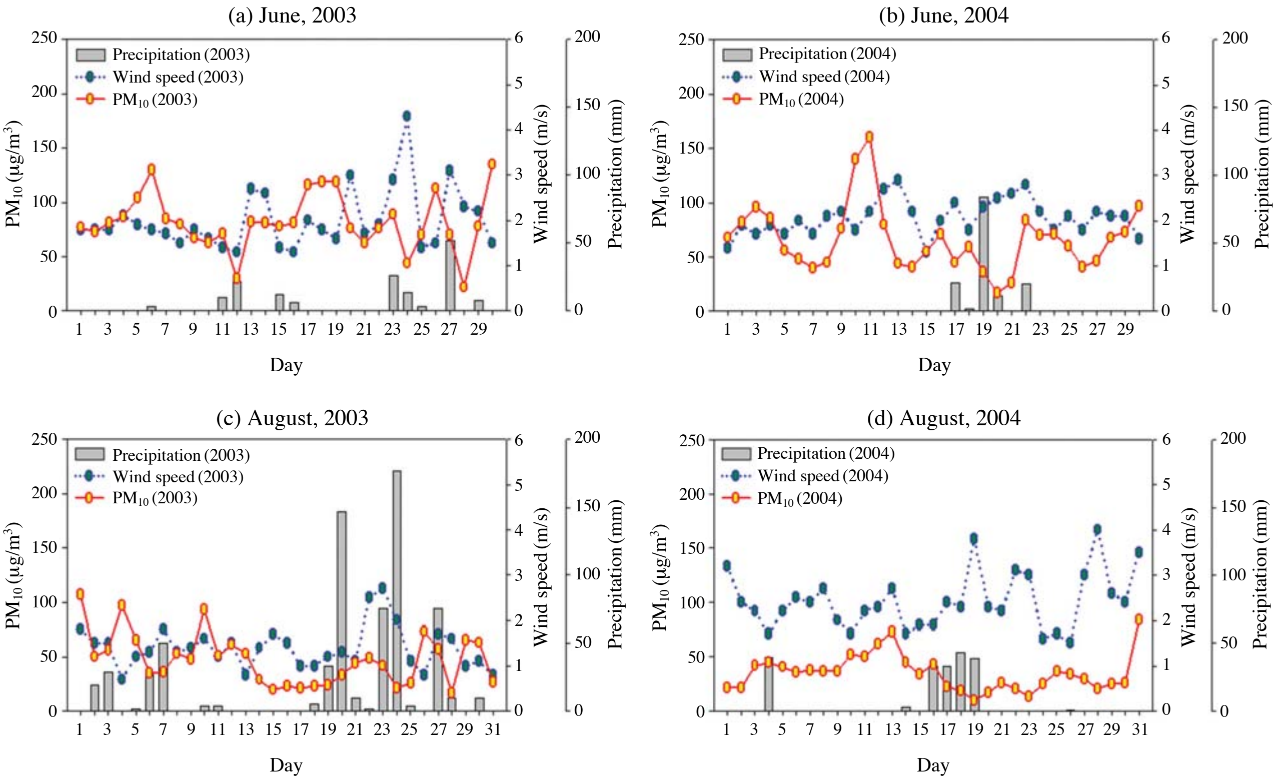


Fig. 7. Comparison on the variation of PM_{10} concentration in Seoul during June and August in 2003 and 2004.

Table 8. Comparison of weather condition in August.

Year	August		
	Precipitation	≥ 10 mm/day	Wind speed
2003	684 mm	11	1.4 m/s
2004	193 mm	5	2.4 m/s

58% of the value, 2.4 m/s, which was observed in 2004 (Table 8).

The overall PM_{10} concentration was low in August for both 2003 and 2004 because of the high precipitation amount and the frequent precipitation days. In 2003, the days with the precipitation over 10 mm/day were 11 days (5 days in 2004), yet the wind speed was below 2 m/s mostly in August except 2 days. The concentration of PM_{10} decreased in the days with precipitation by washing out effect, but the overall PM_{10} concentration of other days without precipitation was higher than that of 2004 because of the slow wind speed.

3. 4 The Factors Affected the Decreased PM_{10} in Seoul

3. 4. 1 Decreased Period of Constant Breeze

The annual and monthly wind speed trends were examined and the specific term, the period of constant breeze was used when the wind speed was below 2 m/s. The period of constant breeze in 2004 was relatively short and the monthly mean wind speed was very high. The period was 212 days (58% of the 365 days) in 2003, yet only 144 days (39% of the year) were in 2004. The frequency of the period in 2004 was also

Table 9. The period of constant breeze during February, May, June, August and September in 2003 and 2004: mean in parentheses.

Month	Period of constant breeze (below 2 m/s)	
	2003	2004
February	4 times 10 days (2.2 m/s)	2 times 4 days (2.9 m/s)
May	4 times 23 days (1.8 m/s)	5 times 10 days (2.6 m/s)
June	5 times 20 days (2.0 m/s)	2 times 9 days (2.1 m/s)
August	2 times 29 days (1.4 m/s)	3 times 8 days (2.4 m/s)
September	3 times 27 days (1.1 m/s)	3 times 11 days (2.2 m/s)

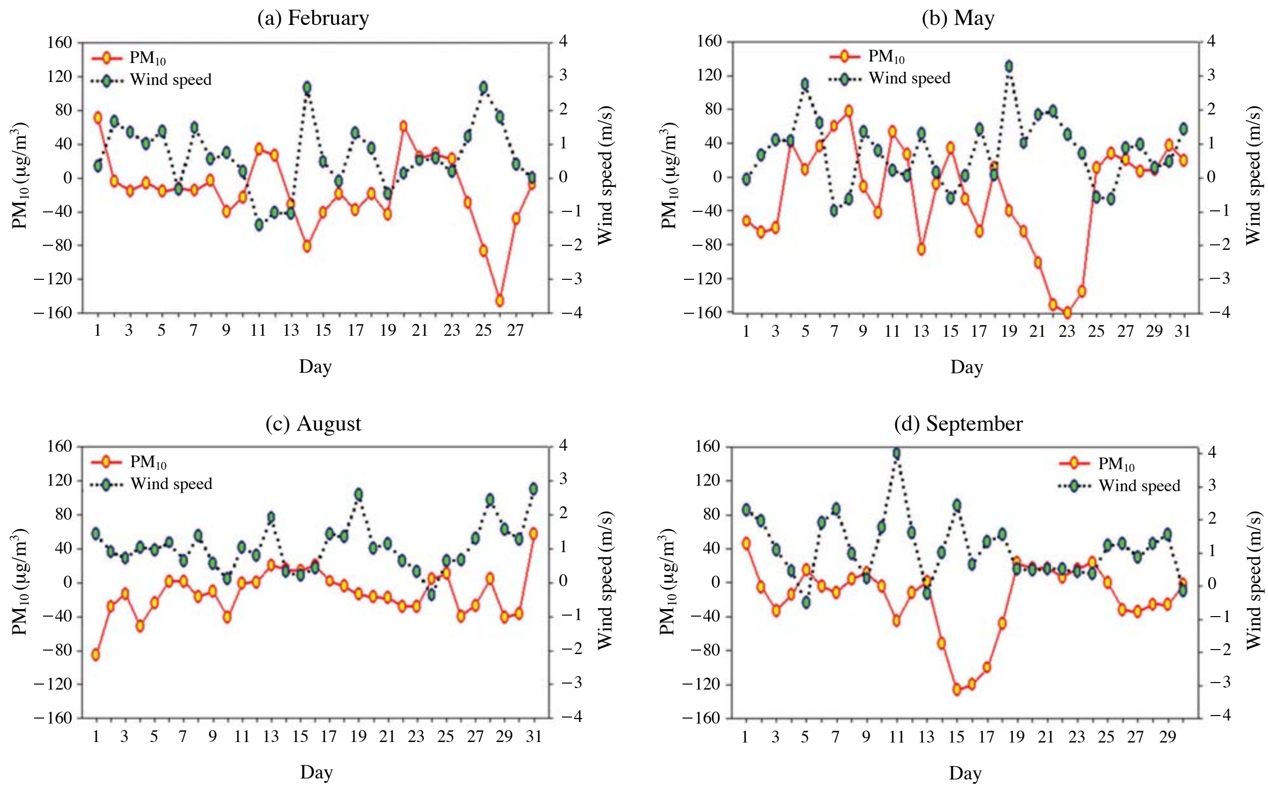


Fig. 8. The daily PM_{10} differenced based on the difference in wind speed, (a) February, (b) May, (c) August, and (d) September.

Table 10. The high PM_{10} concentration occurrence in 2003 and 2004.

Month	2003	2004
January	8-13 (6 days)	1, 6-7, 30-31 (5 days)
February	14, 17-19, 25-26 (6 days)	1, 17-21 (6 days)
March	14-15, 23-27 (7 days)	11-14, 30-31 (6 days)
April	15, 16 (2 days)	23 (1 day)
May	19-24 (6 days)	11-12 (2 days)
June	5-6, 17-19, 30 (6 days)	10-11 (2 days)
July	1-2 (2 days)	10-11 (2 days)
August	–	–
September	14-17 (4 days)	–
October	31 (1 day)	7-8 (2 days)
November	1, 6-7 (3 days)	18-19 (2 days)
December	22-26, 31 (6 days)	–
Total days of occurrence	49 days	28 days

reduced in February, May, June, August and September. In addition, the monthly mean wind speed greatly reduced (Table 9).

The PM_{10} concentration decreased in 2004 due to the high wind speed promoting ventilation. The increased wind speed declined the annual mean PM_{10} concentration by 5 $\mu g/m^3$.

Fig. 8 illustrates the difference of PM_{10} and the wind speed for February, May, August and September in both years. The values in 2003 were deducted from the values in 2004. The more the negative value in the difference, the higher the PM_{10} concentration and the wind speed in 2003. Overall, the greater the differences in speed indicated the bigger difference in PM_{10}. The period of constant breeze also impacted on the concentration differences.

Table 11. The mean high PM_{10} concentration in 2003 and 2004. (unit: μg/m³)

	Jan.		Feb.		Mar.		Apr.		May		Jun.	
	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
PM_{10}	142	127	156	113	127	140	104	185	168	138	121	150
	Jul.		Sep.		Oct.		Nov.		Dec.		Mean	
	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
PM_{10}	145	105	136	–	146	155	130	109	154	–	141	130

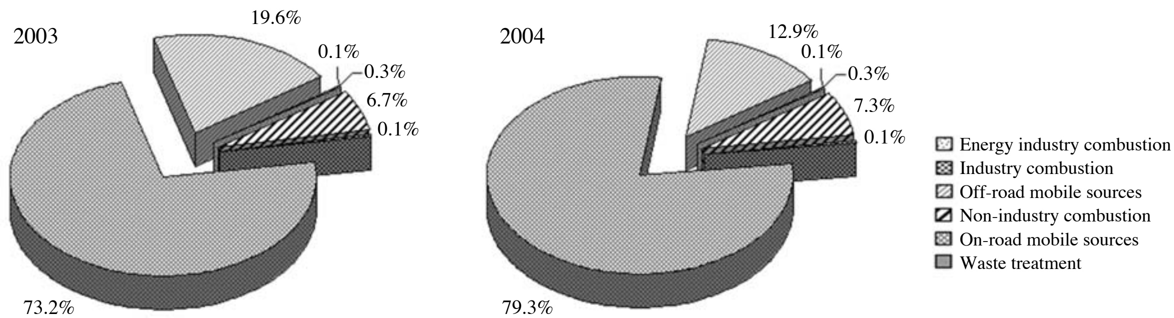


Fig. 9. Mean contributions of each emission sources to the PM_{10} in Seoul in 2003 and 2004 (unit: ton).

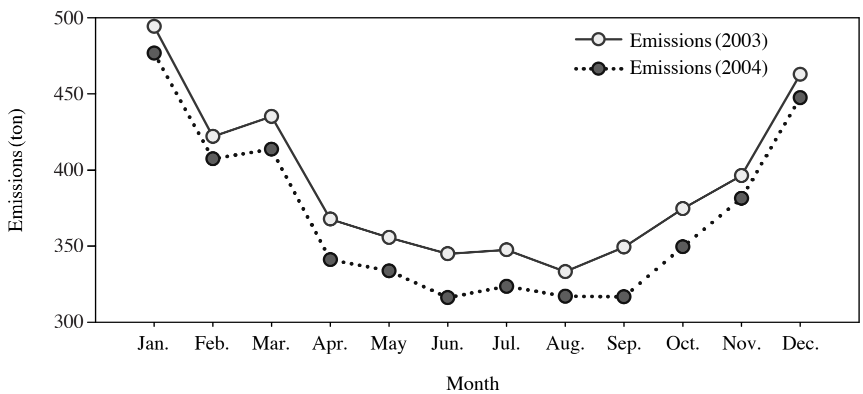


Fig. 10. The monthly variation of PM_{10} emissions in Seoul in 2003 and 2004 (unit: ton).

3. 4. 2 Decreased Frequency and Intensity of Occasional High Concentrations

As it mentioned in the section 3.1, the occasional high PM_{10} concentration are specified when the mean daily concentration exceeds 150 μg/m³ or 100 μg/m³ for more than two days. Table 10 arranges the selected dates for the occasional high concentration.

The days with occasional high concentration in 2003 were 49 days, which increased by 75% from the 28 days in 2004, and the daily mean concentration was also high in 2003. As shown in Table 11, the mean concentration was over 150 μg/m³ for February, May and December in 2003, and noticeably the mean for May 19 through 24 was 168 μg/m³. The mean for the 49 occurrence days in 2003 was 141 μg/m³ and 130 μg/m³ for the 28 occurrence days in 2004, and thus the difference between the two years was 11 μg/m³. Without the occasional high concentration, the difference was calculated as 5.5 μg/m³.

The occurrence of occasional high concentration was greatly affected by wind speed. As shown in Table 12, 79.6% of the total occurrence happened in 2003 when the wind speed was below the mean and 57.1% happened in 2004. In 2003, the high concentration occurred every month except August, and the frequency and intensity were high during the spring and winter. On

Table 12. The days of high concentration under the change of wind speed in 2003 and 2004. (unit: days)

Month	Jan.		Feb.		Mar.		Apr.		May		Jun.	
Wind speed	$<$ mean	$\geq$ mean	$<$ mean	$\geq$ mean	$<$ mean	$\geq$ mean	$<$ mean	$\geq$ mean	$<$ mean	$\geq$ mean	$<$ mean	$\geq$ mean
2003	5	1	6	–	4	3	1	1	5	1	5	1
2004	4	1	3	3	2	4	–	1	1	1	1	1
Month	Jul.		Aug.		Sep.		Oct.		Nov.		Dec.	
Wind speed	$<$ mean	$\geq$ mean	$<$ mean	$\geq$ mean	$<$ mean	$\geq$ mean	$<$ mean	$\geq$ mean	$<$ mean	$\geq$ mean	$<$ mean	$\geq$ mean
2003	2	–	–	–	3	1	1	–	3	–	4	2
2004	1	1	–	–	–	–	2	–	2	–	–	–

the other hand, the frequency and intensity were much lower in 2004 except January, February and March. Meanwhile, the high concentrations were observed in March for both years even when the wind speed was over the mean, which can be explained as the effect of Asian dust from China by strong westerly wind.

3. 4. 3 Decreased Emissions

The emissions in 2003 and 2004 are illustrated in Fig. 9. In 2004, on-road mobile sources increased 6% and off-road mobile sources decreased about 6%. The trends are similar in all years and it tells us that the mobile sources contribute to the most to the PM_{10} emissions.

The monthly change of emissions was not different for 2003 and 2004 (Fig. 10). The emissions in the winter were 1.5 times higher than of the emissions in the summer. The difference of the total annual emissions was 260 tons, which declined by 5.5%. The reduced emissions are coming from the decreased emissions from the off-road mobile sources. The emission from off-road mobile sources was greatly reduced by 346 tons while a little amount from the other industrial sources decreased. The change in emissions would affect the decreased PM_{10} concentration although it is difficult to calculate the contributions numerically.

4. CONCLUSIONS

The PM_{10} concentration observed in Seoul in 2002 was the highest, and this can be explained by intense Asian dust out of comparison in 2002. However, the PM_{10} concentration excluding the effect of Asian dust was higher in 2003 than that in 2002 and the lowest value was observed in 2004. The Asian dust effect was slight in 2003 and 2004, yet the concentration difference between the two years was 10 $\mu g/m^3$. The paper analyzed the factors affected by the noticeable difference of PM_{10} between 2003 and 2004. Furthermore, the trends and progress of PM_{10} in Seoul were observed to reserve basic data for establishment of an efficient reduction policy.

The primary factor affecting the reduced PM_{10} since 2000 was the wind speed and the period of constant breeze. From 2000 to 2004, there was a close relationship between the PM_{10} and the two variables, wind speed and the period of constant breeze. In 2003 and 2004, in particular, the difference in the mean wind speed was 0.4 m/s, and the period of constant breeze was 212 days in 2003 and 144 days in 2004. The marked difference of the two variables induced the occasional high PM_{10} concentration frequently in 2003 and also the wide gap of PM_{10} between the two years. The occasional high concentration was observed for 49 days in 2003 and the mean concentration was 141 $\mu g/m^3$. In 2004, it was observed for 28 days and the mean was 130 $\mu g/m^3$, which decreased by 11 $\mu g/m^3$ from 2003. The intense high PM_{10} concentration accounted for more than 5 $\mu g/m^3$ difference for the annual mean. The other possible factors which can be assumed to reduce the concentration, precipitation and the precipitation days were similar in the two years. Meanwhile, the emissions in Seoul showed the downward trend only in 2004 and the on-road mobile sources accounted for over 90% of the total emissions. The emissions from on-road mobile sources were dominant in Seoul rather than other industrial processes. Therefore, the on-road mobile sources would contribute the most to the PM_{10} concentration. The total emissions of fine particles declined by 260 tons, or 5.5%, in percentile, from 2003 to 2004. The total emissions are excluding the amount of fugitive dust, and therefore the impact of emissions on the PM_{10} concentration in Seoul is hard to be estimated. Researches relating to the emissions and fugitive dust are necessary in the near future to compute the exact emissions and to assess the impact of emissions on PM_{10} concentration.

REFERENCES

Chung, Y.S., Yoon, M.B. (1996) On the occurrence of yellow sand and atmospheric loadings, Atmospheric Envi-

ronment 30, 2387-2397.
Gao, Y., Arimoto, R., Merril, J.T., Duce, R.A. (1992) Relationships between the dust concentration over eastern Asia and the remote North Pacific, Journal of Geophysical Research Atmospheres 97, 9867-9872.
Huang, M., Wang, Z. (1998) A model for long-range transport of yellow-sand in East Asia, Scientia Atmospheric Sinica 22, 625-637.
Kim, C.H., Park, I.S., Lee, S.J., Kim, J.S., Jin, H.A., Sung, H.G. (2004a) On the Recent Air Pollution Levels Observed in the Regional Air Monitoring Network, Journal of Korean Society for Atmospheric Environment 20, 215-224.
Kim, H.G., Jung, Y.W., Hong, J.H. (2004c) Estimation of Fugitive Dust Emission by Administrative Districts, Journal of Korean Society for Atmospheric Environment 20, 263-276.
Kim, K.H., Kim, M.Y., Shin, J.Y., Choi, G.H., Kang, C.H. (2002) Insight into the Factors Determining the Aerosol Distribution Characteristics of the Asian Dust on the Basis of the Concurrent Analysis of $PM_{2.5}$, PM_{10}, and TSP During the Spring Season of 2001, Journal of Korean Society for Atmospheric Environment 18, 419-426.
Kim, Y.K., Song, S.K., Gang, J.E. (2004b) Characteristics of Concentration Variations and Synoptic Conditions by the Lasting Time of Asia Dust, Journal of Korean Society for Atmospheric Environment 20, 465-481.
Kim, Y.P. (2006) Air Pollution in Seoul Caused by Aerosols, Journal of Korean Society for Atmospheric Environment 22, 535-553.
Kim, Y.S., Park, H.S., Lee, Y.J., Lim, Y.W., Shin, D.C. (2003) Risk-based Priority Ranking for Air Pollution Problems in Seoul, Journal of Korean Society for Atmospheric Environment 19, 205-216.
Lee, H.M., Kim, D.S., Lee, J.H. (1996) An Assessment of the Long-Term Concentration of Heavy Metals and Associated Risk in Ambient PM-10, Journal of Korea Air Pollution Research Association 12, 555-566.
Lin, T.H. (2001) Long-range transport of yellow sand to Taiwan in spring 2000: observed evidence and simulation, Atmospheric Environment 35, 5873-5882.
NIER (2002) Annual Report of Air Quality in Korea.
NIER (2003) Annual Report of Air Quality in Korea.
NIER (2004) Annual Report of Air Quality in Korea.
Okada, K., Naruse, Tanaka, T. (1990) X-ray spectrometry of individual Asia dust-storm particles over the Japanese islands and the North Pacific ocean, Atmospheric Environment 24A, 1369-1378.
Park, S.E., Chung, Y. (1992) Airborne Suspended Particulates Concentration and Cancer Risk Assessment of Polycyclic organic matter in Seoul, Journal of Korea Air Pollution Research Association 8, 247-256.
U.S. Environmental Protection Agency (2000) National Air Pollutant Emission Trends, 1990-1998; EPA-454/R-00-002; Research Triangle Park. NC. USA.

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