Bilateral Cooperation on $PM_{2.5}$
Between Japan and the Republic of Korea

Summary Report on 2016-2018 Joint Research

November 2019

TEMM 21, Kitakyushu, Japan

Acknowledgement

Forecasting model group:

<Authors>

Senior Researcher. LEE Daegyun (Integrated Air Quality Forecasting Center, National Institute of Environmental Research)

Researcher. NAM Kipyo (Integrated Air Quality Forecasting Center, National Institute of Environmental Research, Korea)

Dr. Seiji SUGATA (Regional Atmospheric Modeling Section, Center for Regional Environmental Research, National Institute for Environmental Studies),

<Special thanks to…>

Senior Researcher. LEE Jae-Bum (Integrated Air Quality Forecasting Center, National Institute of Environmental Research)

Researcher. LIM Yong-Jae (Air Environment Research Division, National Institute of Environmental Research)

Dr. Satoru CHATANI (Regional Atmospheric Modeling Section, Center for Regional Environmental Research, National Institute for Environmental Studies)

Senior Researcher. SHIN Hye-Jeong (Air Environment Research Division, National Institute of Environmental Research)

Emission inventory group:

<Authors>

Researcher. KANG Kyoung-Hee (Ambient Air Engineering Research Division, National Institute of Environmental Research)

Senior Researcher. LEE Tae-Woo (Transportation Pollution Research Center, National Institute of Environmental Research)

Senior Researcher. PARK Jung-Min (Ambient Air Engineering Research Division, National Institute of Environmental Research)

Dr. Tazuko MORIKAWA (Energy and Environment Research Division, Japan Automobile Research Institute),

<Special thanks to…>

Dr. Hiroaki MINOURA (Atmospheric Research Department, Asia Center for Air Pollution Research),

Senior Researcher. Kim Dai-Gon (Air Environment Research Division, National Institute of Environmental Research)
Senior Researcher. PARK Jun-Hong (Transportation Pollution Research Center, National Institute of Environmental Research)

Ministries:
Staff of the Air Environment Division, Ministry of the Environment, Japan
Staff of the Air Quality Policy Division, Ministry of Environment, Korea

Contents

I. Background

Recognizing the growing public concern regarding fine dust and the urgent call for regional clean air, the Ministers of Environment of Republic of Korea and Japan mutually acknowledged the importance of strengthening bilateral cooperation for control and reduction of $PM_{2.5}$, during a meeting held during the United Nation's Climate Change Conference in November 2013 in Warsaw, Poland. For further discussion, they met again the following year at the 16th Tripartite Environmental Ministers' Meeting (TEMM 16) in April 2014 in Daegu, Korea. They reached an agreement to launch a new bilateral channel for collaboration on $PM_{2.5}$ management and control.

In June 2015, the working-level administrators and related scientists held a kick-off meeting in Incheon, Korea to identify mutual interests for collaboration and produce detailed action plans. They agreed to share scientific knowledge and technologies within the fields of $PM_{2.5}$ forecasting and emission inventory and to exchange best policy practices, in mitigating and controlling emission, for five main topics:

- Evaluation of equivalence between automatic and manual standard methods on $PM_{2.5}$ mass concentration monitoring
- Improvement of $PM_{2.5}$ forecasting accuracy
- Sharing of real-time monitoring data of $PM_{2.5}$
- Joint research on emission inventory and transboundary pollution of $PM_{2.5}$
- Countermeasures toward achieving environmental standards of $PM_{2.5}$

For joint research, two groups were established: one for $PM_{2.5}$ forecasting model and the other for $PM_{2.5}$ emission inventory. Meetings were held biannually, rotating the host country. Attendees of the meetings included two Ministries of Environment (MOEJ and MEK), National Institute of Environmental Research of Korea (NIER), National Institute for Environmental Studies of Japan (NIES), Japan Automobile Research Institute (JARI), Asia Center for Air Pollution Research (ACAP), and Overseas Environmental Cooperation Center of Japan (OECC). In general, a meeting has three pillars—one for policy dialogue and the others for research.

As of August 2019, Korea and Japan marked their 11th meeting for the channel. It has provided a great opportunity for both countries to exchange information and practical ideas on fine dust management and scientific approach. It serves as a solid foundation to promote ambient air cooperation between the two countries. The countries' strengthening relationship is expected to assist in sharing policies and views and exploring joint actions for regional clean air.

Annually from 2016 to 2018, two meetings were held; during summer in Korea, and during winter in Japan (Table 1). Generally, meeting participants included policy administrators from the Ministry of the Environment of Japan (MOEJ) and Ministry of Environment of the Republic of Korea (MOEK). Scientists in the fields of atmospheric forecasting models and air pollutant emission inventories from National Institute for Environmental Studies of Japan (NIES), National Institute of Environmental Research of the Republic of Korea (NIER), Asia Center for Air Pollution Research (ACAP), and Japan Automobile Research Institute (JARI) attended (Table 2).

Table 1. History of Bilateral Meetings

Year	Meeting	Date / Venue
2016	4th Meeting	January 26-27, 2016 / Tokyo, Japan
	5th Meeting	August 25-26, 2016 / Gimpo International Airport, Korea
2017	6th Meeting	January 24-25, 2017 / Tokyo, Japan
	7th Meeting	August 29-30, 2017 / Jeju, Korea
2018	8th Meeting	January 30-31, 2018 / Fukuoka, Japan
	9th Meeting	August 20-21, 2018 / Jeju, Korea

Table 2. Participating Institutions

Participating Institutions		2016		2017		2018	
		4th	5th	6th	7th	8th	9th
Korea	Air Quality Policy Division, MOEK	●	●	●	●	●	●
	Integrated Air Quality Forecasting Center, NIER	●	●	●	●	●	●
	Climate and Air Quality Research Department, NIER	●	●	●	●	●	●
	Transportation Pollution Research Center, NIER	●	●	●	●	●	●
	Air Environment Research Division, NIER	●	●				●
	Global Environment Research Division	●					
	Number of Delegates*	6	8	6	8	6	8
Japan	Air Environment Division, MOEJ	●	●	●	●	●	●
	Office of Environmental Management, MOEJ	●	●	●	●	●	
	Center for Regional Environmental Research, NIES	●	●	●	●	●	●

Participating Institutions		2016		2017		2018	
		4th	5th	6th	7th	8th	9th
	Energy and Environment Research Division, JARI	●	●	●	●	●	●
	Atmospheric Research Department, ACAP	●		●	●	●	●
	Number of Delegates*	6	5	11	6	5	4

MOEJ: Ministry of the Environment, Japan
MOEK: Ministry of Environment, Korea
NIES: National Institute for Environmental Studies
NIER: National Institute of Environmental Research
ACAP: Asia Center for Air Pollution Research
JARI: Japan Automobile Research Institute
* Excluding the Japanese Secretariat

In general, the meetings discuss and share idea on the following topics:

- Presentations about research progress by the forecasting and emission inventory groups
- Group discussion of the details, based on the presentations
- Idea-sharing for next steps and future plan
- Additional information exchanges on the latest $PM_{2.5}$ policies, etc.

Table 3 through 5 below show the joint research progress from the Meeting 4 to the Meeting 9, respectively, according to the meeting agenda.

Table 3. Joint Research Progress – Forecasting Group

Period covered	Joint Research Progress
4th Mtg, 2016 – 6th Mtg, 2017	➢ Concluded Memorandum of Understanding (MOU) between NIES and NIER for data sharing for $PM_{2.5}$ modeling ➢ Compared the settings of each country's forecasting model ➢ Exchanged all monitoring data, covering December 2015, for mutual comparative analysis; $PM_{2.5}$, PM_{10}/SPM, SO_2, NO_2, CO, O_3
6th Mtg, 2017 – 9th Mtg, 2018	➢ Completed the updating and calibration of forecasting models; WRF3.8.1＋CMAQ v5.0.2 ➢ Extended the period for comparative analysis to include two weeks from four seasons of the $PM_{2.5}$ species analyses in Japan (i.e. Jan. 21 to 3 Feb. 3, 2015; May 7 to 21, 2015; July 22 to August 5, 2015; and Oct. 21 to Nov. 4, 2015) ➢ Expanded the monitoring data for exchange to include $PM_{2.5}$ (concentration and species), other air pollutants related to $PM_{2.5}$, and the weather data ➢ Air quality modeling and comparative analysis for the four case periods

Table 4. Joint Research Progress – Emission Inventory Group

Period covered	Joint Research Progress
4th Mtg, 2016 – 6th, Mtg, 2017	➢ Introduced emission inventories, especially on the areas of vehicles, VOCs, and stationary sources ➢ Regarding vehicles, exchanged the PM and NH_3 emission data from gasoline passenger cars ➢ Regarding VOC emissions from stationary sources, the species data were shared from Japan to Korea
6th Mtg, 2017 – 8th Mtg, 2018	➢ Regarding vehicles, exchanged the emission data from additional gasoline direct injection (GDI) vehicles, port fuel injection (PFI) vehicles, NH_3 emission data, and cold start emission data ➢ Regarding vehicles, estimated the emission factors from GDI on a preliminary basis; GDI/PM and cold start emission factors ➢ Regarding the VOCs, exchanged the Japanese data on the VOCs species for painting/ printing
8th Mtg, 2018 – 9th Mtg, 2018	➢ Regarding vehicles, sharing "success case" stories about vehicle emission countermeasures ➢ Recognizing that the methods for estimating evaporative VOCs emissions from stationary sources in Japan and Korea differ greatly ➢ Exchanged information about Korea and Japan's total national emission

Table 5. Joint Research Progress – Other information exchanged

Mtg, Year	Joint Research Progress
4th, 2016	➢ Korea shared the Stage Ⅱ efforts at gas stations
5th, 2016	➢ Korea shared the $PM_{2.5}$ monitoring systems at its supersites ➢ Japan shared the HAPs monitoring efforts
6th, 2017	➢ Japan introduced the newly constructed supersite of $PM_{2.5}$ consecutive component analysis ➢ Korea explained the causal analysis of $PM_{2.5}$ and the subsequent countermeasures for diesel vehicles and coal power plants ➢ Korea introduced the large point source monitoring system, CleanSYS
7th, 2017	➢ Japan shared the recent policy consultation results on how to lower vehicle emissions in the future

1. Background

Both Korea and Japan utilize air quality models to predict air quality affected by the presence of ultrafine particulate matter, or $PM_{2.5}$, and the two countries sought to confirm the simulation capabilities and analyze the limitations of these models. Thus, they shared expertise to improve model predictability, jointly selected periods for measuring $PM_{2.5}$ levels and the major components of this fine dust inside their respective countries, and used their own model to conduct $PM_{2.5}$ simulations. A two-week period was selected in the spring (Case 1), summer (Case 2), fall (Case 3), and winter (Case 4) for analyzing the seasonal movement of $PM_{2.5}$ matter, and modeling was conducted for each period to assess the models' simulation capabilities by season. These periods correspond to those in 2015 in which local governments in Japan simultaneously performed manual component sampling of $PM_{2.5}$.

2. Case Study of Korea

2-1. Model Configuration

2-1-1. Weather and air quality models

During the "Bilateral cooperation between Korea and Japan on $PM_{2.5}$," the modeling subcommittees used Weather Research and Forecasting (WRF; Skamarock et al., 2008) Model Version 3.8.1, a mesoscale weather model, to simulate the seasonal meteorological fields in the Northeast Asian region for the analysis period under discussion. For the main physical parameterization schemes applied in the WRF Model, WRF Single Moment 3 Class (WSM3; Hong et al., 2004) was applied for the microphysics (MP) options. Noah LSM (Chen and Dudhia, 2001; Ek et al., 2003) was used for the land surface options, and the Yonsei University scheme (YSU; Hong et al., 2006) was employed for the Planetary Boundary Layer (PBL) physics options. The Kain-Fritsch scheme (Kain, 2004) was applied for the Cumulus Parameterization scheme.

In addition, the air quality model for simulating $PM_{2.5}$ in the East Asian region was Community Multi-scale Air Quality (CMAQ; Byun & Ching, 1999) Version 5.0.2. The aerosol chemistry was the 5th generation CMAQ Aerosol Module (AERO5; Binkowski and Roselle, 2003), the chemical mechanism was Statewide Air Pollution Research Center Version 99 (SAPRC 99; Carter, 2000), and the advection scheme was the YAMO scheme (Yamartino, 1993). Table 6 itemizes the physical and chemical options by the Korean side for simulating weather and air quality.

Table 6. Physical and chemical options used in WRF and CMAQ models

(a) WRF ver. 3.8.1	
Microphysics	WSM3
Long-wave radiation	RRTM
Short-wave radiation	Goddard
Land-Surface Model	Noah LSM
PBL	YSU
Cumulus	Kain-Fritsch
(b) CMAQ ver. 5.0.2	
Aerosol chemistry	AERO5
Chemical mechanism	SAPRC99
Advection	YAMO
Horizontal diffusion	Multiscale
Vertical diffusion	ACM2

2-1-2. Model domain establishment

The simulation range for the air quality model used to replicate the $PM_{2.5}$ concentrations in South Korea consists of modeling Domain 1 (D01) for the Northeast Asian region and modeling Domain 2 (D02) for the Korean Peninsula. The model simulation range, as shown in Figure 1 below, is organized as a nested grid, centered on 38.0ºN latitude and 126.0ºE longitude. Moreover, D01 has a horizontal grid resolution of 27 km, with 174 parallels of longitude and 128 meridians of latitude, while the horizontal resolution for D02 is 9 km with 67 longitudinal parallels and 82 latitude meridians. The vertical profile of the atmosphere applied to simulate air quality consists of 15 levels.

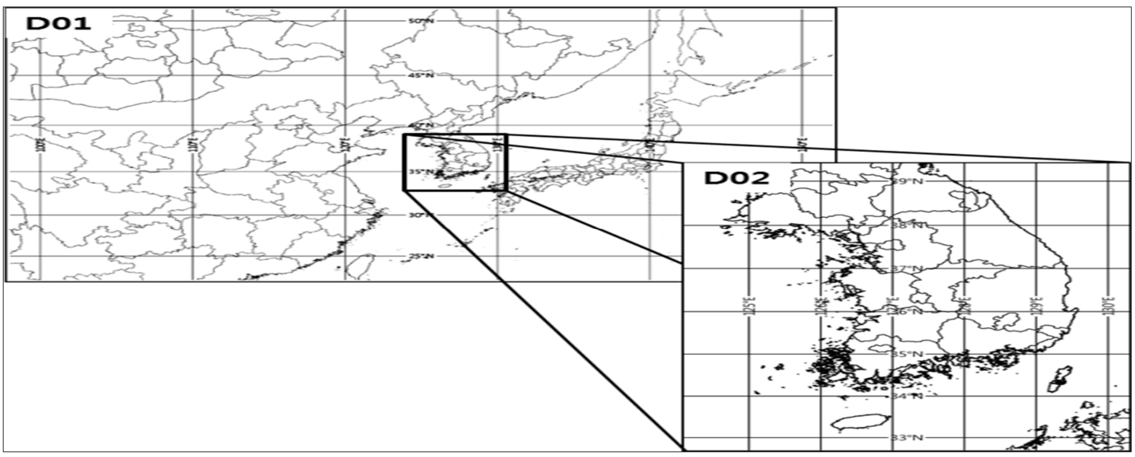


Figure 1. Domains for simulating $PM_{2.5}$

2-1-3. Weather and emission data of the Korean side for $PM_{2.5}$ simulation

The meteorological input data for WRF model is Final Operational Global Analysis (FNL; NCEP, 2000) data 1 × 1 degree grids provided by the National Center for Environmental Prediction (NCEP). As for the anthropogenic emission data used in the air quality model, the emission figures from outside Korea are from MIX 2010 (Li et al., 2017), while the emission figures from inside Korea are taken from the 2010 emission inventory of the Clean Air Policy Support System (CAPSS) by the National Institute of Environmental Research (NIER). Sparse Matric Operator Kernel Emissions (SMOKE; Benjay et al. 2001) provided data pre-processing for the air quality model to supply temporal and spatial allocations for the chemical speciation and emission amount. The Model of Emissions of Gases and Aerosols from Nature Version 2 (MEGAN 2; Guenther et al., 2006) was applied to obtain the amount of natural emissions.

2-1-4. IMS locations in South Korea for verifying $PM_{2.5}$ simulation results

Data from the Intensive Monitoring Stations (IMSs), operated by NIER (National Institute of Environmental Research), are used to verify the $PM_{2.5}$ simulation results generated by the air quality model. These stations have been installed at six locations—Baengnyeongdo, Seoul, Daejeon, Gwangju, Ulsan, and Jeju—and the hourly average $PM_{2.5}$ concentrations collected by them are applied for statistical validation.

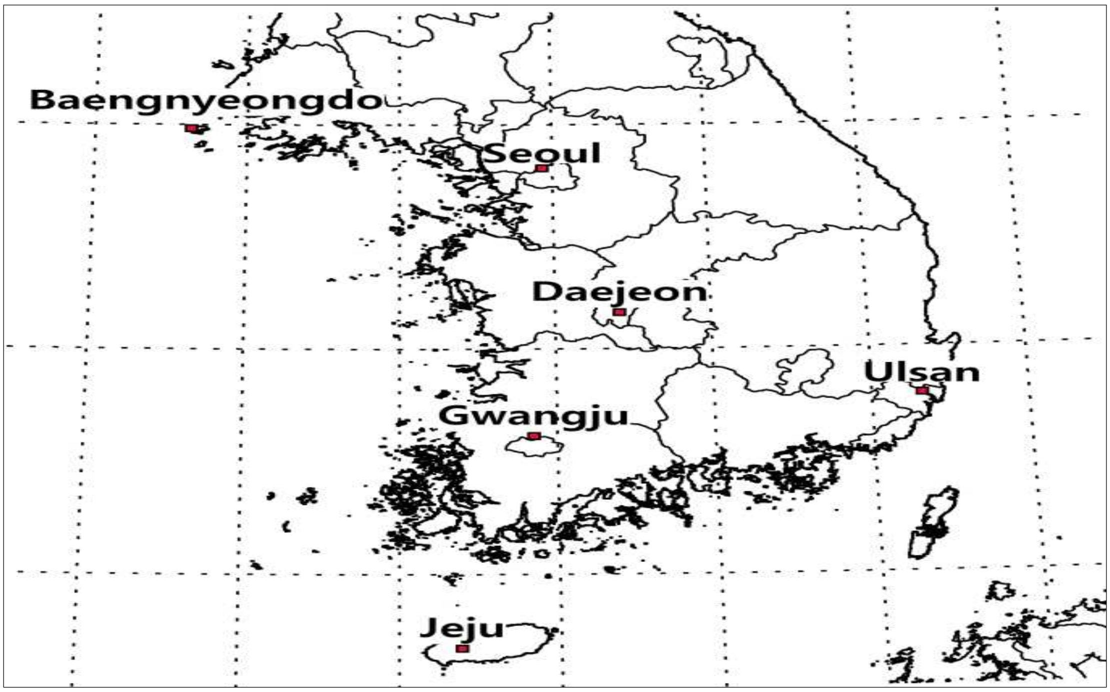


Figure 2. IMS locations in South Korea

2-2. Results

2-2-1. CASE 1 (Jan. 21 – Feb. 3 in 2015—Winter)

Synoptic weather analysis

Case 1 addressed winter conditions, from January 21 to February 3, 2015, when cold and dry continental air masses that accumulate over Siberia (the Siberian High or Siberian Anticyclone) between September and April trigger heavy snowfall and cold snaps. The synoptic weather patterns for Northeast Asia were analyzed from weather charts, and during the first half of Case 1—between January 21 and 26—the South Korean region was affected by a mobile polar high and the low-pressure system that followed, creating westerly winds over the Korean Peninsula's West Sea. Thus, the weather conditions were favorable for carrying pollutants of Chinese origin over long distances (Figure 3, (a) and (b)). The effects of an expanding Siberian High from January 27 through February 1 generated powerful northerly winds (Figure 3, (c)). Subsequently, the Peninsula was at the edge of a high-pressure system between February 2 and 3, and air stagnation set in. The weather conditions did not allow air pollution to disperse from areas inside Korea where emission amounts are high.

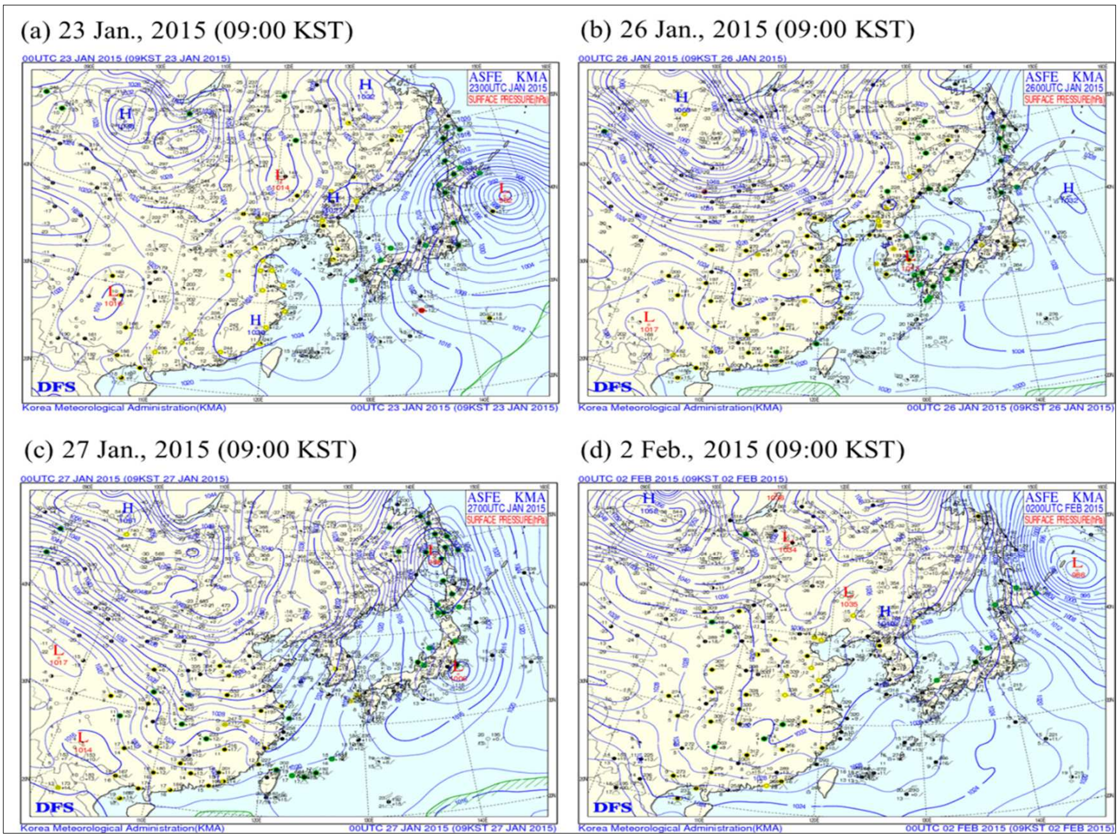


Figure 3. Surface weather map representing weather conditions in Case 1

Validation for simulated $PM_{2.5}$

$PM_{2.5}$ concentrations simulated through the CMAQ model have been validated by statistically comparing them with the concentrations measured in the six intensive monitoring stations of South Korea for the period of Case 1. Because of the validation, model simulation showed correlation coefficient (R) values of 0.86 for Baengnyeongdo, 0.83 for Ulsan, and 0.70 for Jeju—all exhibiting high correlations. Index of agreement (IOA) for the $PM_{2.5}$ concentrations was 0.93, 0.85, and 0.76 for Baengnyeongdo, Ulsan, and Jeju, respectively.

Furthermore, Mean Bias (MB) was used for analyzing the simulated $PM_{2.5}$ values. Compared with the measured $PM_{2.5}$ concentrations during the period of Case 1 in five regions of South Korea—except for the $PM_{2.5}$ of Baengnyeongdo—the simulated $PM_{2.5}$ has been underestimated. Regionally, simulated $PM_{2.5}$ concentrations for Seoul and Gwangju showed relatively low correlation compared to results for Baengnyeongdo, Ulsan, and Jeju, with R-values ranging from 0.5 and 0.6 and IOA values of about 0.65, respectively. The simulation results for Daejeon showed a -0.05 correlation with the observed values and an MB value of -21.7 ㎍/㎥. Thus, the model did not reflect $PM_{2.5}$ levels and trends in the actual atmosphere in some regions.

Table 7. Statistical validation of simulated $PM_{2.5}$ concentrations for the Case 1 timeline

CASE 1	Baengnyeongdo	Seoul	Daejeon	Gwangju	Ulsan	Jeju
R	0.86	0.50	-0.05	0.58	0.83	0.70
RMSE	9.1	12.6	25.7	9.8	8.4	5.1
MB	0.1	-0.5	-21.7	-6.6	-5.6	-3.0
IOA	0.93	0.66	0.36	0.67	0.85	0.76

Cause Identification

Figure 4 shows the time series of the measured and simulated $PM_{2.5}$ concentrations during Case 1 for Baengnyeongdo (Figure 4, (a)) and Ulsan (Figure 4, (b)), where the model showed relatively high accuracy, as well as Seoul (Figure 4, (c)) and Daejeon (Figure 4, (d)), where the model showed relatively low accuracy. In addition, Figure 5 shows the spatial distributions of surface $PM_{2.5}$ concentration, which represents the $PM_{2.5}$ behavior simulated by CMAQ model for the Case 1.

The weather map and observed $PM_{2.5}$ concentrations, as well as air quality model simulation results, were used to perform the analysis. It shows that on January 23, 2015, the Korean Peninsula felt the effects of a high-pressure system centered on Southeastern China, triggering the westerlies over the West Sea (Figure 5, (a)), which began to transport $PM_{2.5}$ originating from China. The long-range transported $PM_{2.5}$ contributed to increased concentrations in South Korean on January 24 and 25. Then, on January 26, South Korea was affected by low pressure centered on the southeastern coast of South Korea, and located at the edge of the Siberian High pressure, which tended to decrease $PM_{2.5}$ concentrations in some parts of the central and western regions of Korean Peninsula due to air stagnation (Figure 5, (b)). On January 27 and 28, the $PM_{2.5}$ concentration was significantly reduced nationwide in South Korea due to the influence of the clean air flowing through strong northern winds (Figure 5, (c)). Alternatively, the $PM_{2.5}$ concentration increased in many regions in South Korea due to the effects of long-range transported $PM_{2.5}$ from overseas (on January 30) and by the effects of long-range transported $PM_{2.5}$ and air stagnation (on February 2) (Figure 5, (d)).

Case summary

For the period of Case 1, the Siberian High influence—one of the seasonal characteristics of winter in the East Asia region—was shown, contributing to the long-range movement and removal of particulate matter. Except for the Daejeon area, the air pollution model was sufficient in simulating trends in concentrations, due to long-range transported $PM_{2.5}$ and air stagnation during winter in most regions. However, the model simulated the timing of $PM_{2.5}$ inflows from overseas earlier than the actual event in some parts of the country. Simultaneously, the model imprecisely simulated the inflow intensity of $PM_{2.5}$. In particular, the simulation accuracy of the downwind area was relatively lower when $PM_{2.5}$ was affected by westerly wind.

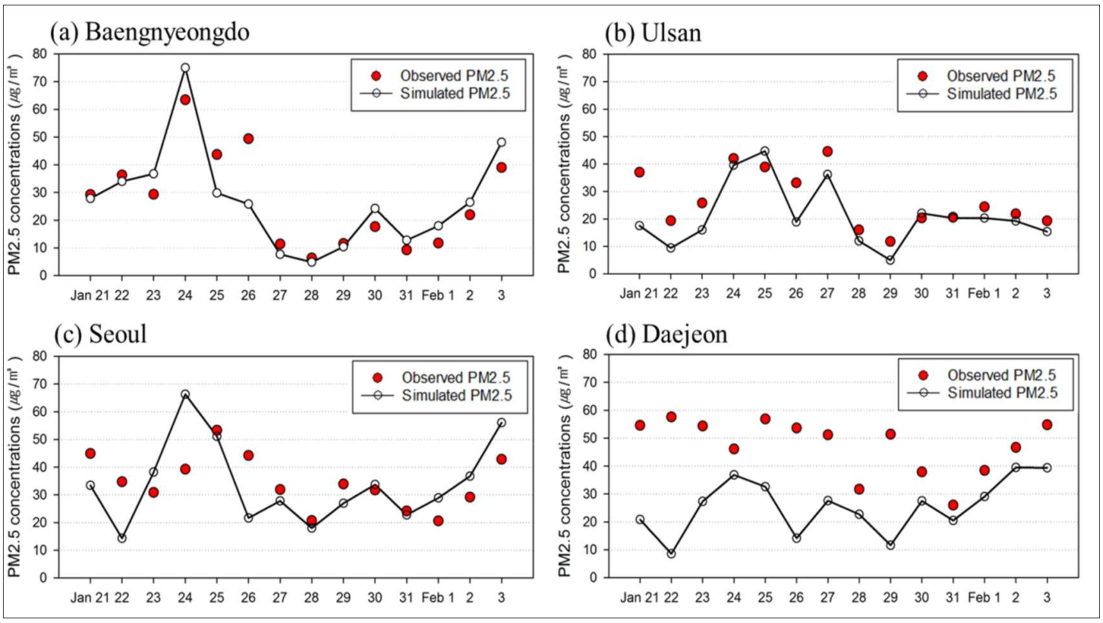


Figure 4. Time series of the observed (dotted lines) and simulated (solid lines) $PM_{2.5}$ concentrations during Case 1

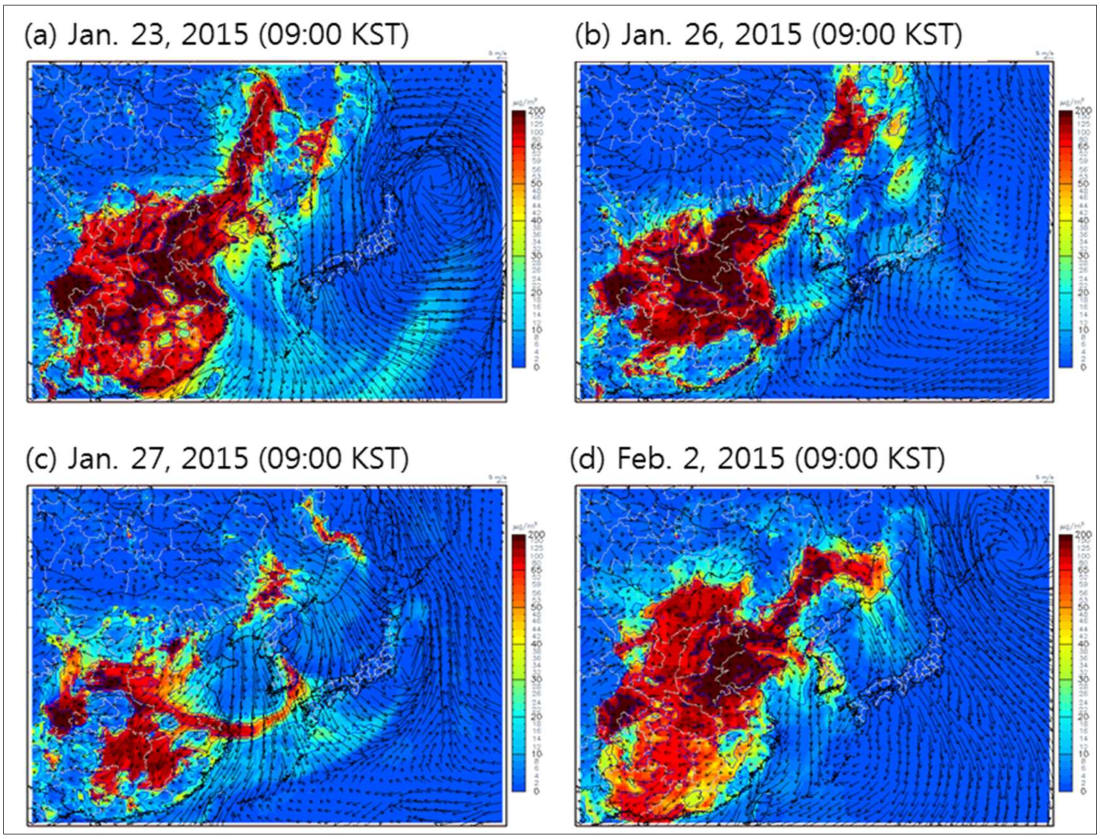


Figure 5. Spatial distributions of surface $PM_{2.5}$ concentrations representing Case 1

2-2-2. CASE 2 (May 7 - 21—Spring)

Synoptic weather analysis

Case 2 covered a section of spring, between May 7 and 21. The atmosphere was stagnated over the Korean Peninsula as it was located in the high-pressure sphere from May 7 to 10 (Figure 6, (a)). Afterwards, on May 11, it was located at the edge of the influence of high pressure centered on Japan, while clean, and mainly southerly, wind blew across South Korea (Figure 6, (b)). Thereafter, the low-pressure effects centered on the Manchuria area, bringing westerlies on May 12 and 13 and forming favorable weather conditions for pollutants originating from China to be transported long distances, reaching the Korean Peninsula (Figure 6, (c)).

On May 14, South Korea was affected by southwesterly winds due to the low-pressure effects (Figure 6, (d)). Fog rolled in from the West Sea from May 15 and 16, and air stagnation occurred over most of South Korea (Figure 6, (e)). Afterwards, South Korea was affected by the southerly winds on May 17 and 18 (Figure 6, (f)), westerly winds on May 19 (Figure 6, (g)), northerly winds on May 20 (Figure 6, (h)), and westerly winds, again, on May 21 (Figure 6, (i)). Such repetitive changes in the prevailing wind direction resulted from the passage of a moving anticyclone from the Chinese mainland, followed by the development of a low-pressure system. This reflected the periodically shifting weather pattern of Northeast Asia during the summer.

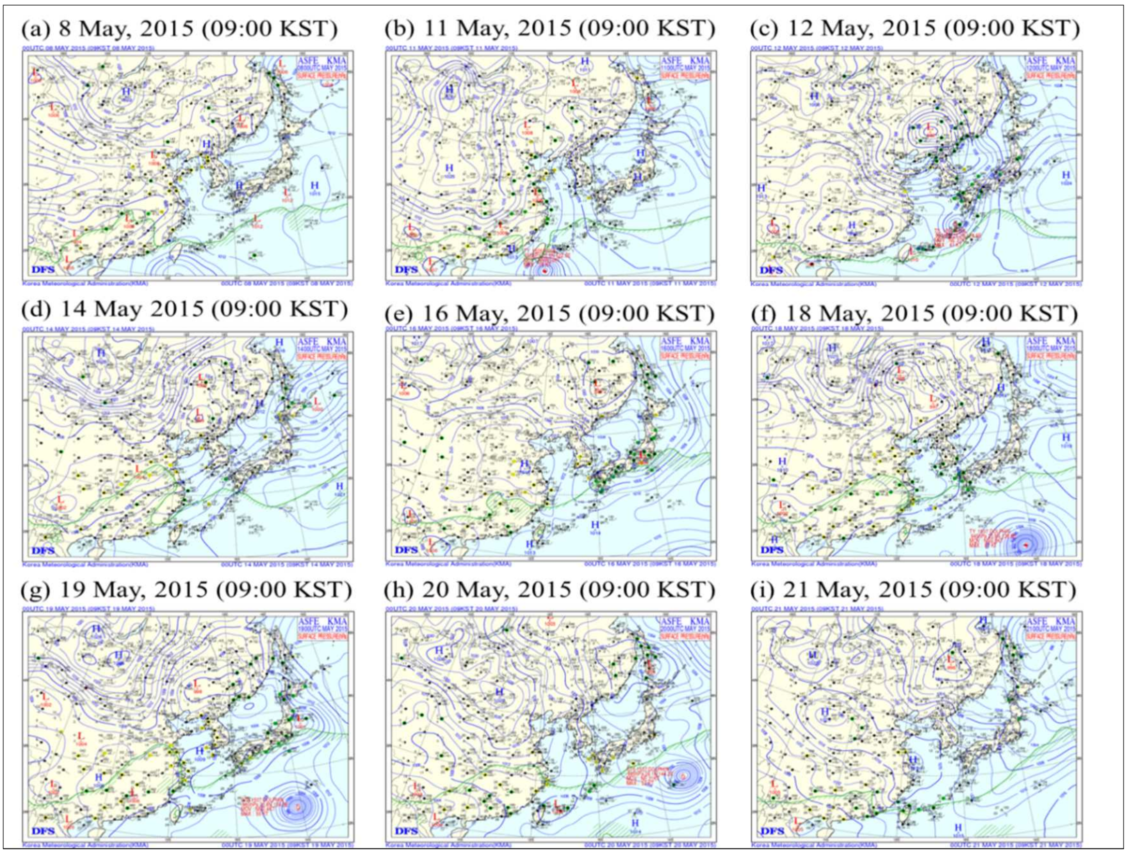


Figure 6. Surface weather map representing weather conditions in Case 2

Validation for simulated $PM_{2.5}$

Because of statistical analysis using observed $PM_{2.5}$ concentrations data collected from six IMSs during Case 2, the simulated $PM_{2.5}$ concentrations through the air quality model showed R-values of 0.91 and 0.72 and IOA value of 0.94 and 0.83 for Jeju and Ulsan, respectively, and highly correlated with the measured $PM_{2.5}$ concentrations. The model also showed a similar level of $PM_{2.5}$ results, with MB values of 1.3 and -0.9, respectively, for the Jeju and Ulsan regions.

However, the statistical validation for Baengnyeongdo, Seoul, Daejeon, and Gwangju—which are on the west side of the Korean Peninsula—resulted in R-values ranging between 0.35 and 0.65, which was a low correlation with the observed $PM_{2.5}$ concentrations. At the same time, the MB values for

Baengnyeongdo and Daejeon were at least -10 ㎍/㎥, meaning the air quality model greatly underestimated the $PM_{2.5}$ concentrations.

Table 8. Statistical validation of simulated $PM_{2.5}$ concentrations for the Case 2 timeline

CASE 2	Baengnyeongdo	Seoul	Daejeon	Gwangju	Ulsan	Jeju
R	0.35	0.41	0.65	0.59	0.72	0.91
RMSE	14.8	12.7	16.4	10.4	7.4	2.8
MB	-12.4	-1.7	-13.5	-5.7	-0.9	1.3
IOA	0.51	0.63	0.62	0.66	0.83	0.94

Cause Identification

The time series data on the daily mean $PM_{2.5}$ concentrations for Ulsan and Jeju, which showed relatively high correlation between observed and simulated $PM_{2.5}$ concentrations during Case 2, are shown in Figure 7 (a) and 7 (b). The time series data of Baengnyeongdo and Seoul, which showed a relatively low tendency agreement, are shown in Figure 7 (c) and Figure 7 (d). The observed $PM_{2.5}$ data and the simulation results for South Korea's inland sites (i.e. those besides Baengnyeongdo and Jeju) during Case 2 indicate high $PM_{2.5}$ concentrations, mainly in Seoul and Ulsan between May 7 and 9 (Figure 8, (a)) when air stagnation elevated airborne pollution. They also reveal how easterly winds helped lower the $PM_{2.5}$ concentrations in high-concentration areas beginning May 10 (Figure 8, (b)). In addition, westerlies from May 12 long-range transported $PM_{2.5}$ from outside of the country, first reaching Baengnyeongdo in northwestern South Korea before covering the entire South Korean region by May 13 (Figure 8, (c) and (d)). On May 14th, $PM_{2.5}$ concentration dropped—mainly in the southern regions of South Korea, Ulsan and Jeju, due to the introduction of relatively clean southerly winds (Figure 8, (e))—while on May 15, the concentrations of $PM_{2.5}$ increased due to the air stagnation as air flow converged over inland areas of South Korea (Figure 8, (f)). The nighttime radiative cooling from the 16th brought higher surface $PM_{2.5}$ concentrations, while PBL heights rose during the daytime, allowing surface $PM_{2.5}$ concentrations to lessen in a repeated cycle.

By region, the air quality model showed a good simulation accuracy of $PM_{2.5}$ concentration tendency and its level in the Ulsan and Jeju regions of southern Korea. However, it showed low simulation accuracy for Baengnyeongdo and Seoul in the mid-western area of the country. When comparing the measured and simulated $PM_{2.5}$ concentrations for Baengnyeongdo, the air quality model underestimated the impact of long-range transported $PM_{2.5}$ from China, which continued since May

10. In the Seoul region, the model did not adequately reflect the increase in $PM_{2.5}$ concentrations on May 15, triggered by the air stagnation.

Case summary

Case 2 covers a spring period, when wind direction and velocity are affected by moving anticyclones and following low-pressure systems. This effect, in turn, alters the long-range $PM_{2.5}$ transport and air stagnation, which increases $PM_{2.5}$ concentration levels in short, repetitive cycles. The model simulation results show a correlation of at least 0.6 with the observed $PM_{2.5}$ concentrations for most of the IMS locations, which are notable results. However, low correlativity is apparent for South Korea's mid-western region, and the model underestimated $PM_{2.5}$ levels. In particular, the model did not sufficiently simulate the increase in $PM_{2.5}$ concentrations due to the air stagnation in Seoul on May 15, and it underestimated the effects of long-range transported $PM_{2.5}$ from China during Case 2.

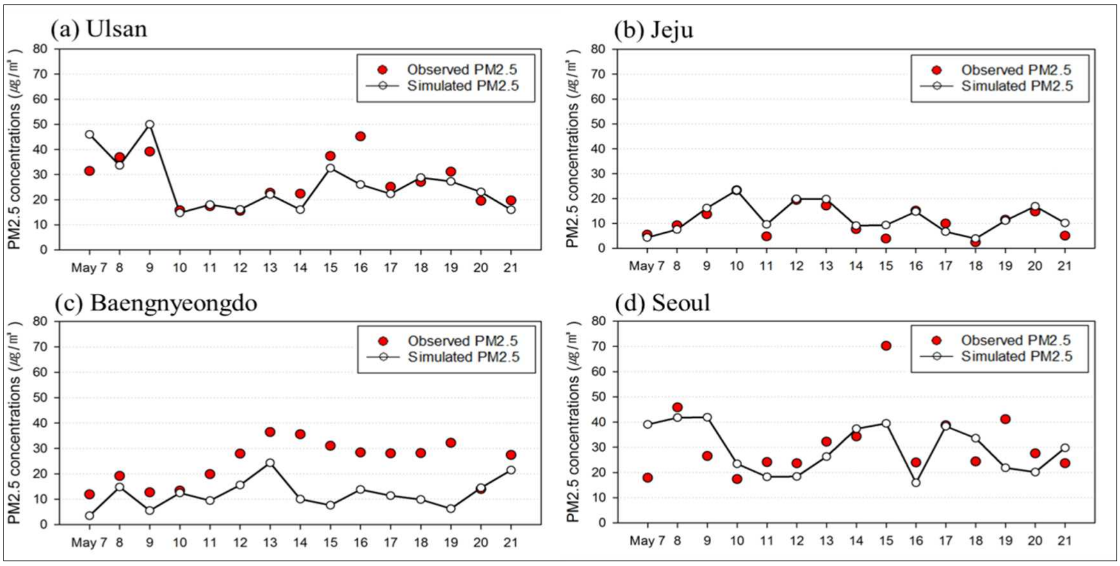


Figure 7. Time series of the observed (dotted lines) and simulated (solid lines) $PM_{2.5}$ concentrations during Case 2

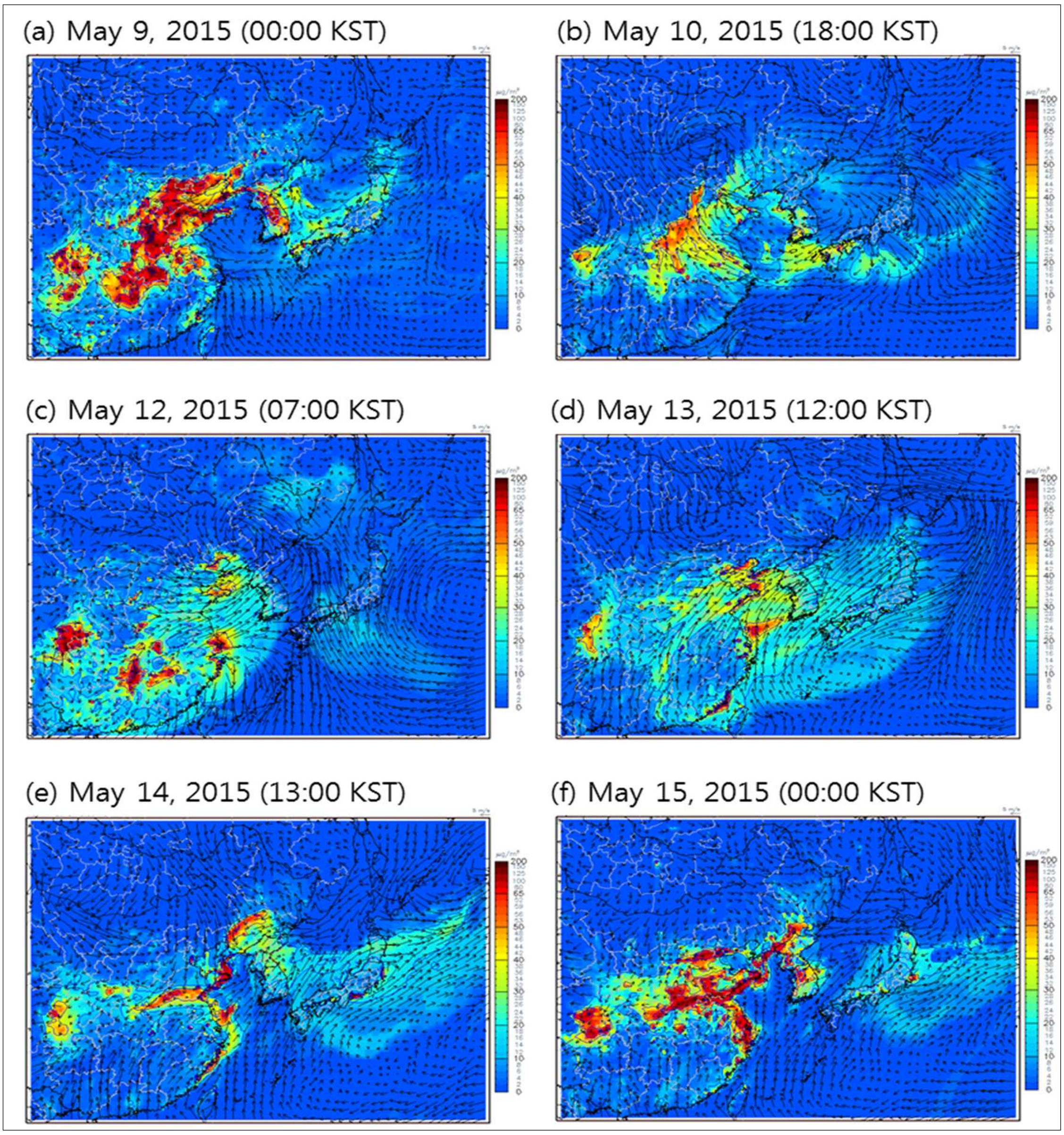


Figure 8. Spatial distributions of surface $PM_{2.5}$ concentrations representing Case 2

2-2-3. CASE 3 (July 22 - Aug. 5 in 2015—Summer)

Synoptic weather analysis

The period for Case 3 spanned the summer months from July 22 through August 5, 2015. During this time of year, Northeast Asia experiences an expansion of the North Pacific High, and low pressure prevails over the mainland. The North Pacific marine air mass generates much rainfall and long spells of oppressive weather. From the middle to the end of the Case 3 timeline (July 22–28), the Korean Peninsula was within the area affected by the North Pacific High—as well as typhoons—therefore, exposing it to clean southerlies (Figure 9, (a), (b)). Moreover, the Korean Peninsula was impacted by a high-pressure system over the Northwest Pacific on July 29, triggering westerly winds and weather conditions conducive for bringing in external airborne pollution from afar (Figure 9, (c)). Air stagnation (Figure 9, (d)) set in for three days, between July 30 and August 1, and thereafter, the area surrounding the Korean Peninsula was exposed to southwesterly winds generated by the North Pacific High (Figure 9, (e)).

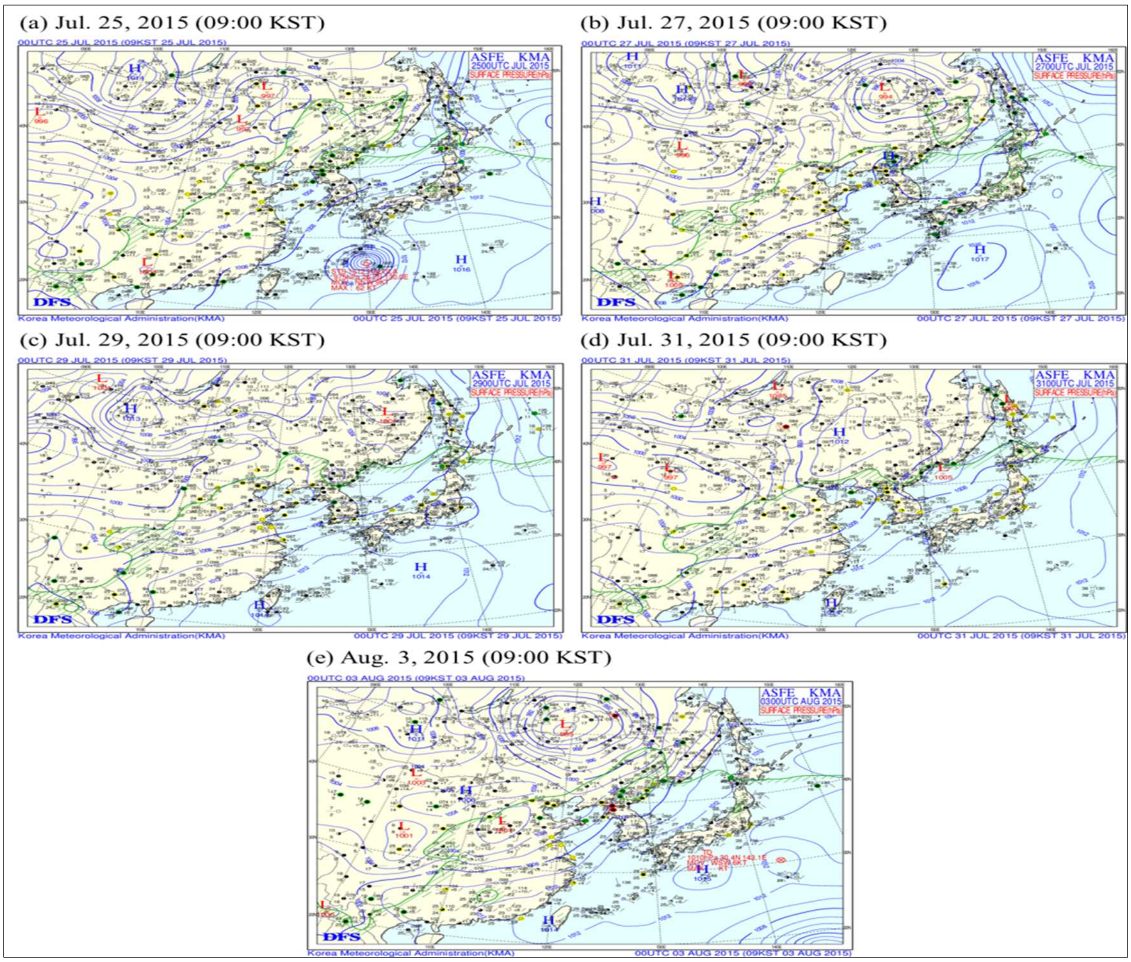


Figure 9. Surface weather map representing weather conditions in Case 3

Validation for simulated $PM_{2.5}$

Observed $PM_{2.5}$ data, collected from South Korea's six IMS sites, were used to statistically verify the simulated $PM_{2.5}$ concentrations for the Case 3 period. According to the findings, the model showed a high correlation with the observed $PM_{2.5}$ concentrations for all sites except for Baengnyeongdo, in which R-values were 0.74-0.96 and IOA values were 0.73-0.86. However, the air quality model underestimated the actual $PM_{2.5}$ concentrations collected at most of the IMSs. Specifically, the model underestimated the $PM_{2.5}$ concentrations in Baengnyeongdo, Daejeon, Gwangju, and Ulsan by at least

7.0 ㎍/㎥ during Case 3 period. The model's low (0.4) R-value and -13.6 MB value for Baengnyeongdo indicates an inability to simulate $PM_{2.5}$ movement within this region.

Table 9. Statistical validation of simulated $PM_{2.5}$ concentrations for the Case 3 timeline

CASE 3	Baengnyeongdo	Seoul	Daejeon	Gwangju	Ulsan	Jeju
R	0.40	0.80	0.96	0.76	0.74	0.86
RMSE	18.8	9.5	9.7	9.4	11.8	3.2
MB	-13.6	0.8	-8.7	-7.3	-8.7	-2.0
IOA	0.50	0.86	0.83	0.74	0.73	0.83

Cause Identification

The time series data on daily average $PM_{2.5}$ concentrations for Daejeon (Figure 10, (a)) and Jeju (Figure 10, (b)) showed a high correlation between the simulated results generated by the air quality model and the observed $PM_{2.5}$ concentrations during the Case 3 period. The time series data for Baengnyeongdo (Figure 10, (c)) and Ulsan (Figure 10, (d)), however, was not in such agreement. Figure 11 indicates the spatial distribution of $PM_{2.5}$ concentrations representing the Case 3 period. An analysis that integrated the observed data with the simulated data found that the Korean Peninsula was influenced by the North Pacific High during the Case 3 period, between July 22 and 28, and that southerlies were blowing in, providing generally clean air conditions across the entire country (Figure 11, (a), (b)).

Southwesterly winds began blowing during the daytime on July 29, and long-range transported $PM_{2.5}$ from China was observed coming into South Korean skies (Figure 11, (c)). That night, air stagnation set in over South Korea's central inland region, triggering a clear increase in $PM_{2.5}$ concentrations. Over the following three days (July 30 through August 1), weak westerly winds blew over the inland region of South Korea, and $PM_{2.5}$ concentrations rose in eastern parts of the country, such as Ulsan (Figure 11, (d)). The effects of the North Pacific High were felt again on August 2, and southerly winds arose, bringing in clean air that reduced $PM_{2.5}$ levels (Figure 11, (e)).

As for region-specific model performance, high R-values (0.74-0.96) were registered for all areas except Baengnyeongdo; therefore, a high correlation was observed between the simulated and observed $PM_{2.5}$ results. Importantly, the Daejeon area showed an R-value of 0.96, signifying accurate simulation for the timing of the $PM_{2.5}$ inflows and dispersals. In contrast, the observed $PM_{2.5}$ concentrations for the Baengnyeongdo region—affected by the long-range transported $PM_{2.5}$ from

China continuously since July 29—were greatly underestimated by the air quality model. The model-simulated results for the Ulsan region had an R-value of 0.74 against the observed $PM_{2.5}$ concentrations, providing a noteworthy correlation; however, it underestimated the actual $PM_{2.5}$ concentration by 8.7 ㎍/㎥.

Case summary

Summer in Northeast Asia is characterized by the expansion of North Pacific High and low pressures centered on China, resulting in heavy rain and muggy weather influenced by oceanic air masses. Much rain fell from July 22–August 5 of this joint study's Case 3 period, mainly showing the effects the North Pacific High that is typical for this season. The air quality model efficiently simulated overall changes in $PM_{2.5}$ concentrations for all regions except Baengnyeongdo during the period under analysis. However, limitations of the model were also revealed, as the simulated $PM_{2.5}$ concentrations were lower than the actual figures for South Korea in the summer, and the model's underestimation of the influence of long-range transported $PM_{2.5}$ from China was confirmed. Thus, the emission levels in Northeast Asia and the air quality model's internal deposition process require examination.

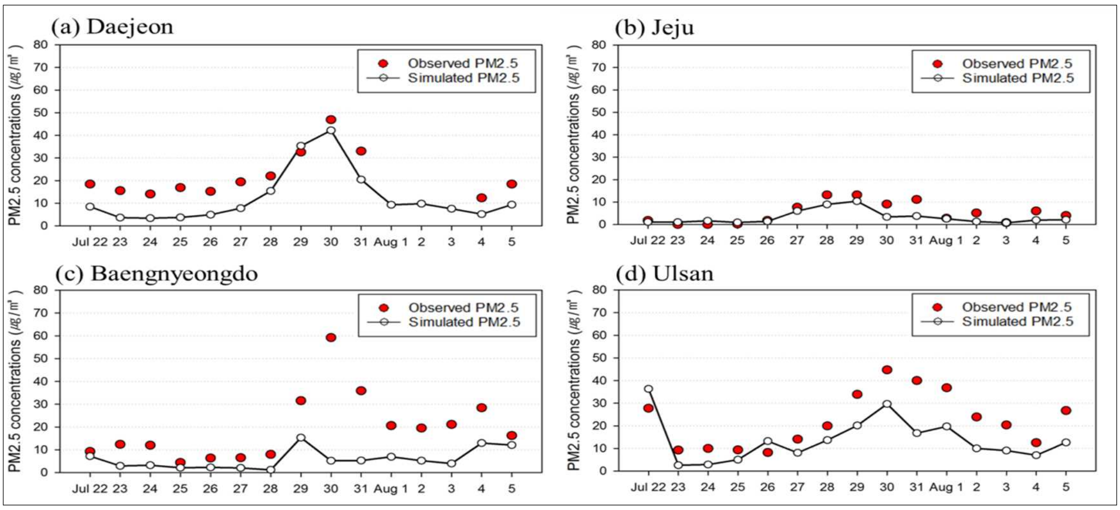


Figure 10. Time series of the observed (dotted lines) and simulated (solid lines) $PM_{2.5}$ concentrations during Case 3

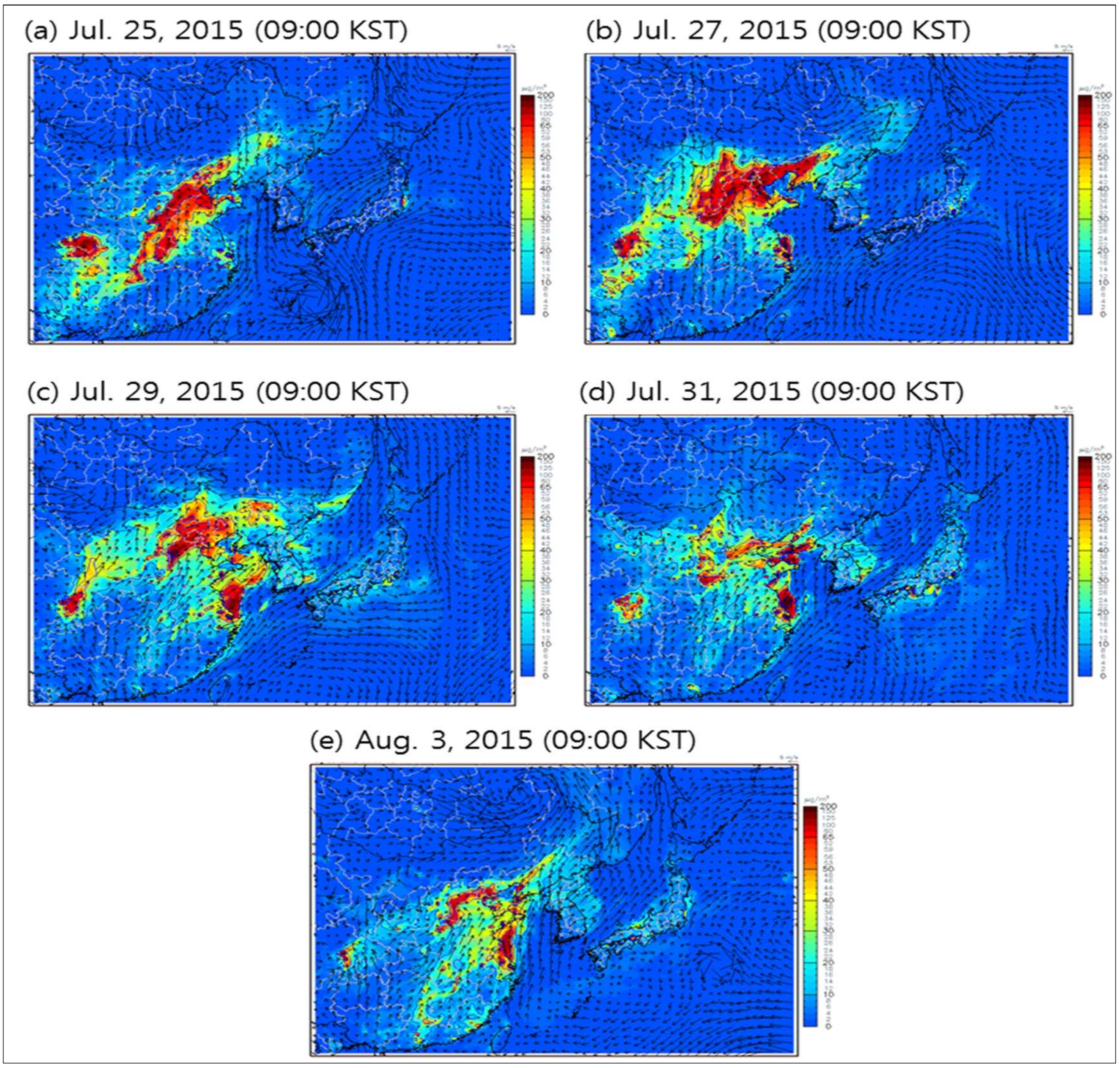


Figure 11. Spatial distributions of surface $PM_{2.5}$ concentrations representing Case 3

2-2-4. CASE 4 (Oct. 21 - Nov. 4 in 2015—Fall)

Synoptic weather analysis

The analysis period for Case 4 is from October 21 to November 4, which assesses fall. In the fall season, Northeast Asia has a meteorological feature in which sunny and rainy days are repeated in short cycles due to the effects of low pressure and moving high pressures from China. During the Case 4 period, the air over the Korean Peninsula was stagnated between October 21 and 23 (Figure 12, (a)), while air stagnation and frequent changes in air currents were seen from October 24 to 31 because of the moving anticyclone (Figure 12, (d)). On November 2, northwesterly winds began to blow, creating the necessary conditions for airborne pollution to be transported to long distances to reach the skies over the Korean Peninsula (Figure 12, (e)). The Korean Peninsula was in the center of a high-pressure system on November 3 and 4, bringing air stagnation, once again (Figure 12, (f)).

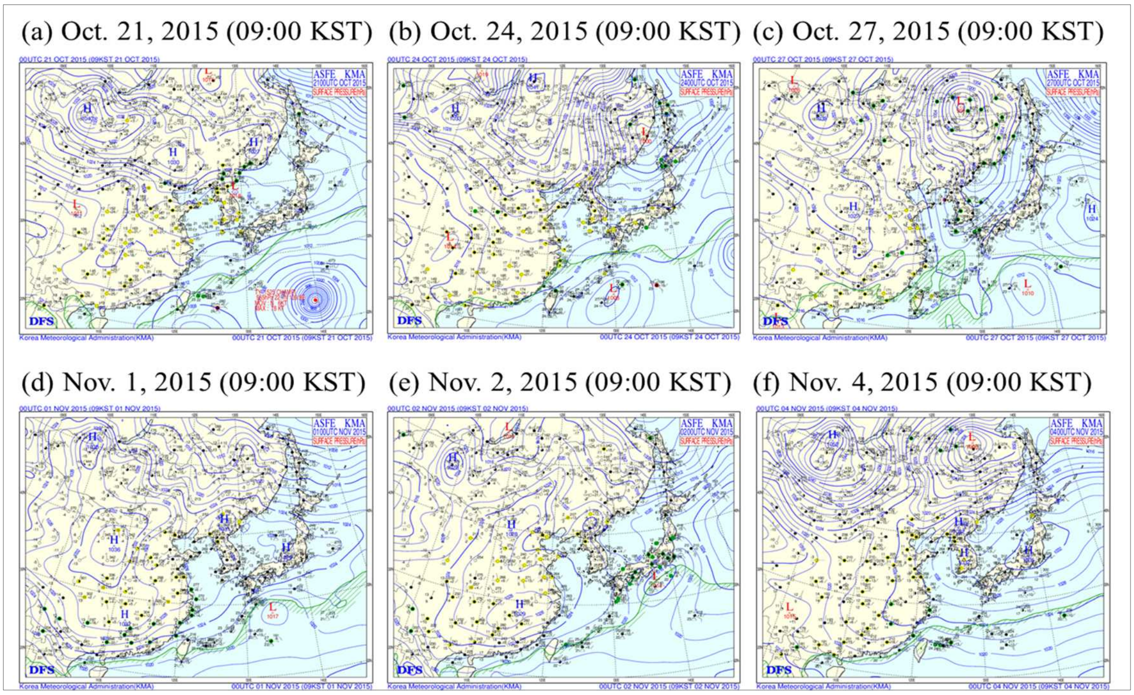


Figure 12. Surface weather map representing weather conditions in Case 4

Validation for simulated $PM_{2.5}$

The daily average $PM_{2.5}$ concentration data obtained at the six IMS sites during the Case 4 period were used to statistically analyze the $PM_{2.5}$ figures simulated by the model, and the statistical analysis results are presented in Table 10. The model simulation results for Case 4 registered an R-value of 0.72 and higher for all six sites, while the IOA values are at least 0.82. Thus, Case 4 has the best the tendency of agreement between the simulated and observed values among the four cases. However, the model underestimated $PM_{2.5}$ levels in the Daejeon, Gwangju, and Jeju regions by 5.0 ㎍/㎥ or more, and the model's simulated $PM_{2.5}$ figures for Seoul and Ulsan were overestimated.

Table 10. Statistical validation of simulated $PM_{2.5}$ concentrations for the Case 4 timeline

CASE 4	**Baengnyeongdo**	**Seoul**	**Daejeon**	**Gwangju**	**Ulsan**	**Jeju**
R	0.86	0.87	0.86	0.87	0.72	0.92
RMSE	9.4	17.2	20.0	14.5	12.6	7.4
MB	-2.5	7.9	-13.3	-4.7	2.5	-5.3
IOA	0.91	0.90	0.87	0.92	0.82	0.91

Cause Identification

The air quality model covering the Case 4 period was precise for Baengnyeongdo (Figure 13, (a)) and Jeju (Figure 13, (b)), while accuracy was somewhat low for Daejeon (Figure 13, (c)) and Gwangju (Figure 13, (d)), as evidenced by the observed and simulated $PM_{2.5}$ concentrations in the time series data. According to both the surface $PM_{2.5}$ concentration data taken at the IMS sites and the model simulations, air stagnation between October 21 and 23 in the Case 4 period brought high $PM_{2.5}$ concentrations to the center of South Korea's southeast. On the other hand, clean easterlies reduced $PM_{2.5}$ concentrations over the eastern part of the country on the 21st and 22nd. However, air stagnation occurred on the 23rd (Figure 14, (a)), followed by westerly winds on the 24th that brought in $PM_{2.5}$ matter from faraway places (Figure 14, (b)). Clean easterlies blew in on the 25th and 26th, and clean winds from the north followed on the 27th and 28th; $PM_{2.5}$ concentrations dropped to low levels in all regions (Figure 14, (c)). On October 29, air stagnation occurred over the South Korean inland, causing $PM_{2.5}$ concentrations to rise, but strong seasonal winds blew in from the north on the 30th and 31st, bringing the $PM_{2.5}$ concentrations down again. Air stagnation centered over the inland region on November 1 (Figure 14, (d)), and northwesterly winds arose on November 2, affecting the inflows of particulate matter that originated from far away (Figure 14, (e)). Air stagnation brought $PM_{2.5}$ concentrations up (Figure 14, (f)) on November 3 and 4.

The air quality model in Case 4, which covers the fall period, adequately simulated the actual $PM_{2.5}$ concentration levels and fluctuations. However, the model underestimated the $PM_{2.5}$ concentrations in all the regions besides Seoul and Ulsan, and this problem was most apparent in Daejeon and Gwangju on October 23 and 24, when the weather was foggy.

Case summary

The Case 4 period of this joint study saw weather patterns akin to those that occurred in Case 2, namely air stagnation and barometric changes brought on by the moving anticyclone effect. $PM_{2.5}$ concentration levels fluctuated according to these weather changes. In addition, the air quality model registered an R-value of 0.85 for all six intensive monitoring stations and exhibited the best simulation performance among all four cases. However, the Daejeon and Gwangju regions experienced both air stagnation and fog on October 23 and 24, which negatively affected the accuracy of the air quality model's $PM_{2.5}$ concentration simulation.

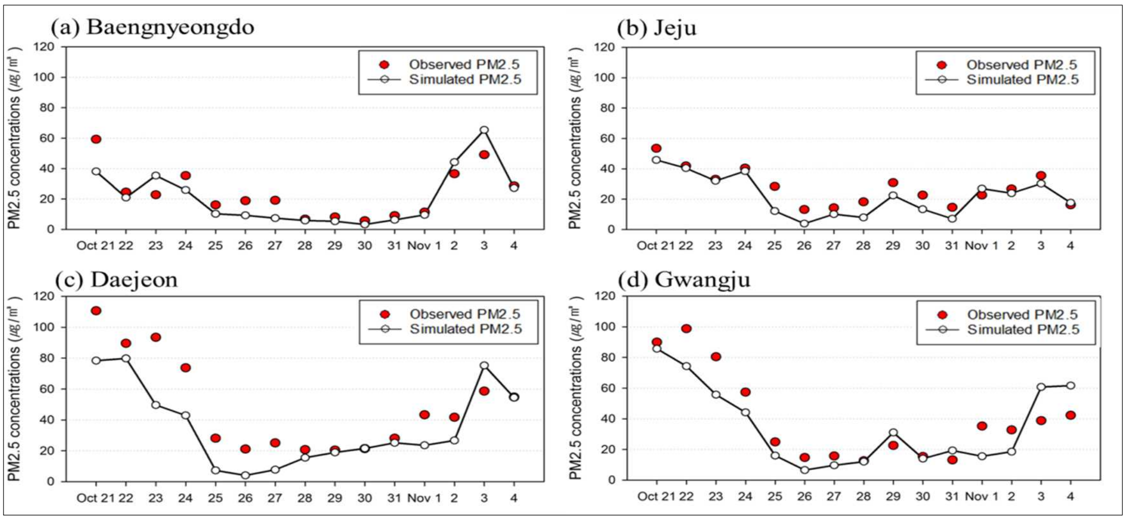


Figure 13. Time series of the observed (dotted lines) and simulated (solid lines) $PM_{2.5}$ concentrations during Case 4

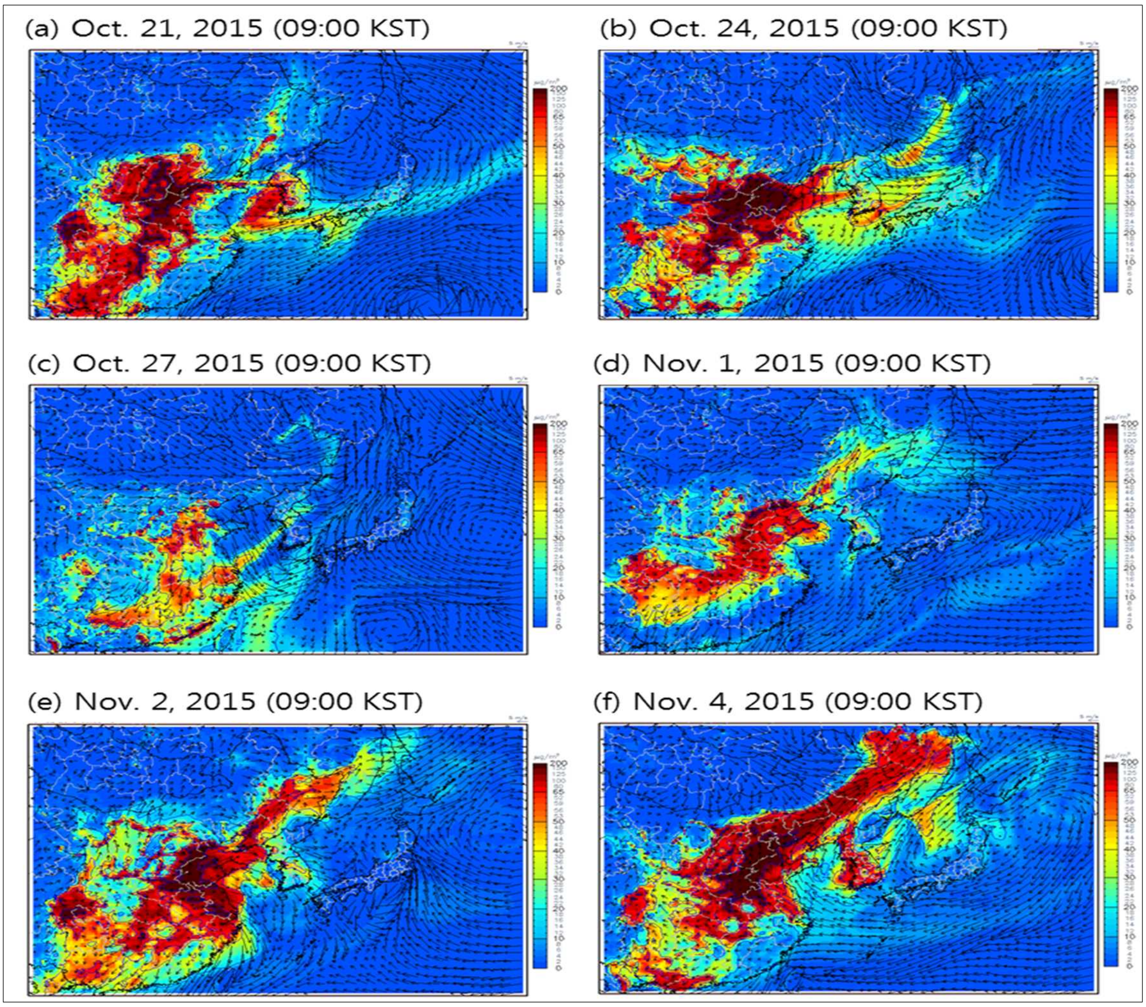


Figure 14. Spatial distributions of surface $PM_{2.5}$ concentrations representing Case 4

3. Case Study of Japan

3-1. Model Configuration

3-1-1. Meteorological and air quality models

For the "bilateral cooperation between Korea and Japan on $PM_{2.5}$," the Japanese side of the working group used the Weather Research and Forecasting (WRF, Skamarock et al., 2008) Model Version 3.9.1, a mesoscale weather model, to simulate the seasonal meteorological fields in the Northeast Asian region for the analysis period under discussion. For the main physical processes applied in the WRF Model, WRF Single Moment 5 Class (WSM5) was used for the microphysics (MP) options. Noah LSM (Chen and Dudhia, 2001; Ek et al., 2003) was used for the land surface options, and the Mellor-Yamada Nakanishi Niino scheme (MYNN, Nakanishi, and Niino, 2006; Nakanishi and Niino, 2009; Olson, Kenyon, Angevine, Brown, Pagowski, and Sušelj, 2019) was utilized for the Planetary Boundary Layer (PBL) physics options. The Kain-Fritsch scheme (Kain, 2002) was applied for the Cumulus Parameterization options.

In addition, the air quality model utilized for simulating $PM_{2.5}$ in the East Asian region was the Community Multi-scale Air Quality (CMAQ, Byun & Ching, 1999) Version 5.1. The aerosol mechanism used was the 6th generation CMAQ Aerosol Module (AERO6, Binkowski, and Roselle, 2003), the Carbon Bond mechanism (CB05, Yarwood et al., 2005), and the advection scheme was the YAMO scheme (Yamartino, 1993). Table 11 itemizes the physical and chemical options by the Japanese side for simulating weather and air quality.

Table 11. Physical and chemical options for WRF and CMAQ model

(a) WRF ver. 3.9.1	
Microphysics	WSM5
Longwave radiation	RRTM
Shortwave radiation	MM5
Land-Surface Model	Noah LSM
PBL physics	MYNN
Cumulus option	Kain-Fritsch
(b) CMAQ ver. 5.1	
Aerosol module	AERO6
Chemical mechanism	Cb05e51_ae6_aq
Advection scheme	YAMO
Horizontal diffusion	Multiscale
Vertical diffusion	ACM2

3-1-2. Model domain establishment

The simulation range for the air quality model used to simulate the $PM_{2.5}$ concentrations in Japan consists of modeling Domain 1 (ASA1) for Northeast Asia, modeling Domain 2 (JPN1) for all of Japan, and Domain 3 (JPN2) for the main region of Japan. The model simulation range, as shown in Figure 15, is organized as a nested grid and centered on 34.0ºN latitude and 139.8ºE longitudes. Moreover, ASA1 has a horizontal grid resolution of 45 km, with 137 parallels of longitude and 87 meridians of latitude. The horizontal resolution for JPN1 is 15 km, with 223 longitudinal parallels and 202 latitude meridians, and the horizontal resolution for JPN2 is 5 km, with 352 longitudinal parallels and 346 latitude meridians. The vertical profile of the atmosphere applied to simulate air quality consists of 18 levels up to 100 hPa.

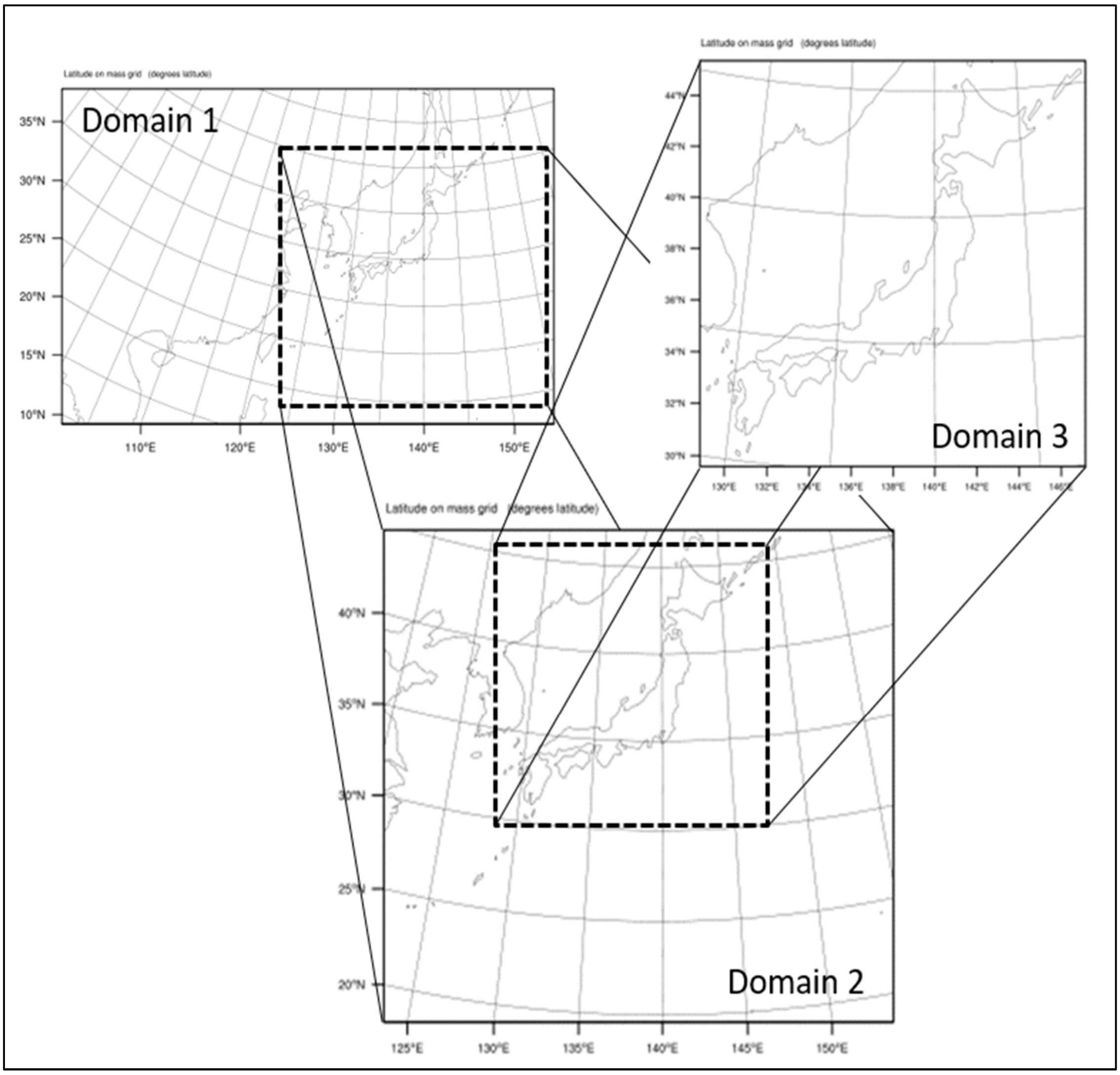


Figure 15. Domains for simulating $PM_{2.5}$

3-1-3. Weather and emission data of the Japanese side for $PM_{2.5}$ simulation

The meteorological input data for the mesoscale weather model is Final Operational Global Analysis (FNL, NCEP 2000) data on 1° × 1° grids provided by the National Center for Environmental Prediction (NCEP). As for the anthropogenic emission data used in the air quality model, the emission figures from outside Japan are from HTAP v2.2 (Janssens-Maenhout et al., 2015), while the emission figures from inside Japan are taken from JEI-DB-AS2014 for vehicles and modified JEI-DB for others. Biomass burning is from GRED v4.1 outside Japan and from modified JEI-DB inside Japan. The Model of Emissions of Gases and Aerosols from Nature Version 2 (MEGAN 2, Guenther et al. 2006) was applied to obtain the amount of natural emissions.

3-1-4. Urban areas in Japan for verifying $PM_{2.5}$ simulation results

Data from the Air Pollution Monitoring Stations operated by MoEJ and local governments in Japan are used to verify the $PM_{2.5}$ simulation results generated by the air quality model. Four urban areas—Tokyo, Nagoya, Osaka, and Fukuoka—are selected, and hourly averaged area $PM_{2.5}$ concentrations are applied for statistical validation.

Figure 16. Areas in Japan for validation.

3-2. Results

3-2-1. CASE 1 (Jan. 21 - Feb. 3 in 2015—Winter)

Synoptic weather analysis

Refers to the description in the section above for the weather analysis (weather map should be discussed commonly).

Validation for simulated $PM_{2.5}$

$PM_{2.5}$ concentrations simulated through the CMAQ model have been validated, with statistical comparison with the concentrations measured in the four monitoring stations of Japanfor the period of Case 1. Because of the validation, model simulation showed correlation coefficient (R) values of 0.37 / 0.49 (hereafter, JPN1 / JPN2) for Tokyo, 0.76 / 0.83 for Nagoya, 0.62 / 0.64 for Osaka, and 0.43 / 0.40 for Fukuoka. Index of agreement (IOA) for the $PM_{2.5}$ concentrations was 0.82 / 0.58, 0.93 / 0.79, 0.91 / 0.71, and 0.47 / 0.46 for Tokyo, Nagoya, Osaka, and Fukuoka, respectively. Regionally, the simulated $PM_{2.5}$ concentrations for Fukuoka and Tokyo showed a relatively low correlation compared to those for Nagoya and Osaka, with R-values about 0.4 and IOA values less than 0.5, respectively—particularly, in Fukuoka.

Furthermore, Mean Bias (MB) and Root Mean Square Error (RMSE) were used for analyzing the simulated $PM_{2.5}$ values. The simulated $PM_{2.5}$ has been underestimated compared to the actual $PM_{2.5}$ having been measured during the Case 1 period in all areas of Japan. Particularly, Fukuoka shows largely negative MB, approximately -10 ㎍/㎥. RMSEs are larger in Tokyo and Fukuoka compared to those in Nagoya and Osaka.

Table 12. Statistical validation of simulated $PM_{2.5}$ concentrations for the Case 1 timeline

CASE 1	**Tokyo**		**Nagoya**		**Osaka**		**Fukuoka**	
	JPN1	**JPN2**	**JPN1**	**JPN2**	**JPN1**	**JPN2**	**JPN1**	**JPN2**
R	0.37	0.49	0.76	0.83	0.62	0.64	0.43	0.40
RMSE	10.54	10.34	6.66	6.59	6.49	6.58	11.38	11.70
MB	-5.76	-6.22	-3.63	-4.25	-4.03	-4.38	-9.75	-10.15
IOA	0.82	0.58	0.93	0.79	0.91	0.71	0.47	0.46

Cause Identification

Figure 17 shows the time series of $PM_{2.5}$ concentration in the four areas. On January 21, observed concentrations show the peak or descending trend from the peak in Japan, but this high concentration is not reproduced by the calculation. Around January 23, high concentration air masses existed on the Korean peninsula, though the concentration around Japan is low. Tokyo displayed the following observational peak on January 26, which the calculation does not efficiently show. This observational peak is considered to be due to local contribution, considering the wind direction around Tokyo (Figure 18, (b)). Nagoya peaked on January 25, while Osaka did not peak until January 25 and 26; these peaks can be attributed to the long-distance transport of $PM_{2.5}$ from China via the Yellow Sea and are well reproduced in the calculations. The peak in Fukuoka was observed on January 27.

Case summary

For the Case 1 period, the Siberian High influence—one of the seasonal characteristics of winter in the East Asia region—was shown, contributing to the long-distance movement and removal of particulate matters. The air pollution model was generally good in simulating trends in concentrations in Nagoya and Osaka. However, the model underestimated $PM_{2.5}$ concentration in Tokyo and Fukuoka.

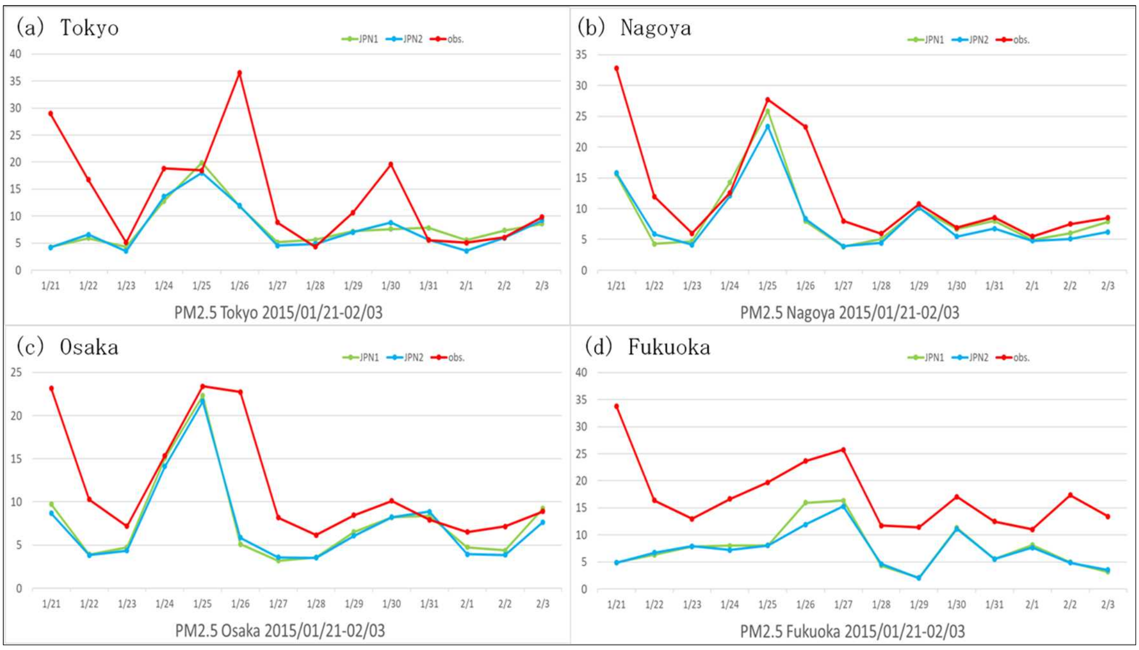


Figure 17. Time series of the observed (red lines) and simulated (JPN1: green lines, JPN2: blue lines) $PM_{2.5}$ concentrations during Case 1

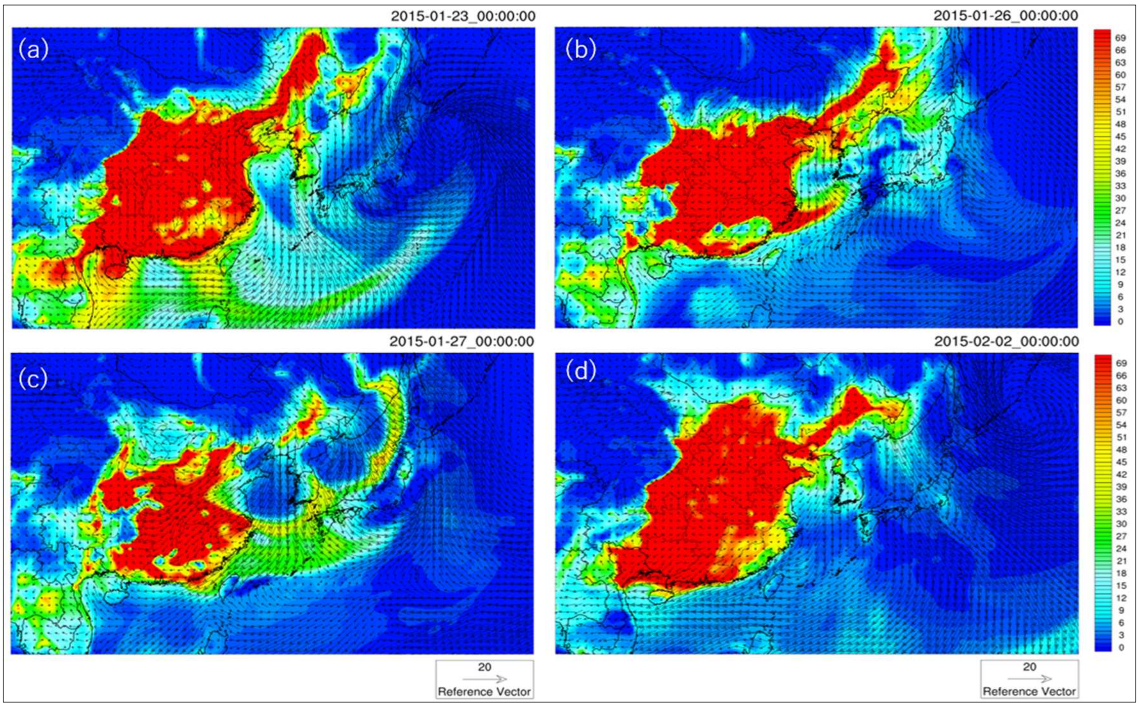


Figure 18. Spatial distributions of surface $PM_{2.5}$ concentrations representing Case 1

3-2-2. CASE 2 (May 7 – 21—Spring)

Synoptic weather analysis

See Korean description for the weather analysis (weather map should be discussed commonly).

Validation for simulated $PM_{2.5}$

Because of statistical analysis using observed $PM_{2.5}$ concentrations data collected from the four areas during Case 2, the simulated $PM_{2.5}$ concentrations through the air quality model showed R-values over 0.8 and IOA values over 0.8 for the all areas except for Fukuoka with R of 0.78 and IOA value of 0.79. The model also showed small MB values ranging -2.51 ㎍/㎥ to 0.58 ㎍/㎥, whose absolute values are smallest among the four cases. RMSEs are relatively small in Case 2 among the four cases.

Table 13. Statistical validation of simulated $PM_{2.5}$ concentrations for the Case 2 timeline

CASE 2	**Tokyo**		**Nagoya**		**Osaka**		**Fukuoka**	
	JPN1	**JPN2**	**JPN1**	**JPN2**	**JPN1**	**JPN2**	**JPN1**	**JPN2**
R	0.83	0.88	0.81	0.84	0.82	0.83	0.78	0.78
RMSE	4.17	4.20	5.67	5.29	5.23	4.69	6.03	5.74
MB	-1.89	-2.51	-0.29	-0.64	0.58	-0.06	0.45	-1.94
IOA	0.99	0.90	0.97	0.83	0.98	0.84	0.79	0.79

Cause Identification

The time series data on the daily mean $PM_{2.5}$ concentrations for all areas shows suitable reproducibility of timings of positive and negative observational peaks, where amplitudes of variations of simulated concentrations are higher than the one of observed concentrations (Figure 19 (a) – (d)). In Japan, $PM_{2.5}$ concentration shows three peaks during Case 2, May 8–10, May 13–14, and May 16.

For the first peak, Tokyo, Nagoya, and Osaka show a local maximum on May 9, though Fukuoka shows it on May 10, where long-range transport brought additional concentrations on nationally wide high concentration (Figure 20 (a) and (b)). For the second peak, three areas—except Tokyo—show local maximum on May 13; Tokyo shows it on May 14, which is supposedly due to local cause for high $PM_{2.5}$ in Tokyo (Figure 20 (d)–(f)).

Case summary

For Case 2, simulation results in Japan show an adequate reproducibility of peaks.

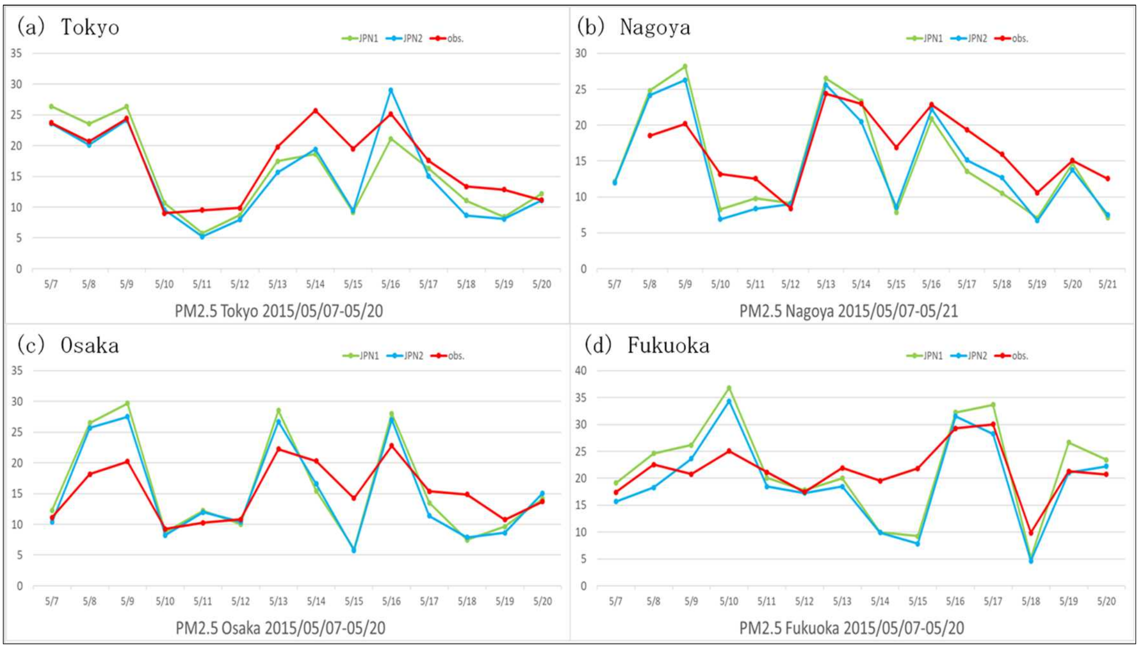


Figure 19. Time series of the observed (red lines) and simulated (JPN1: green lines; JPN2: blue lines) $PM_{2.5}$ concentrations during Case 2

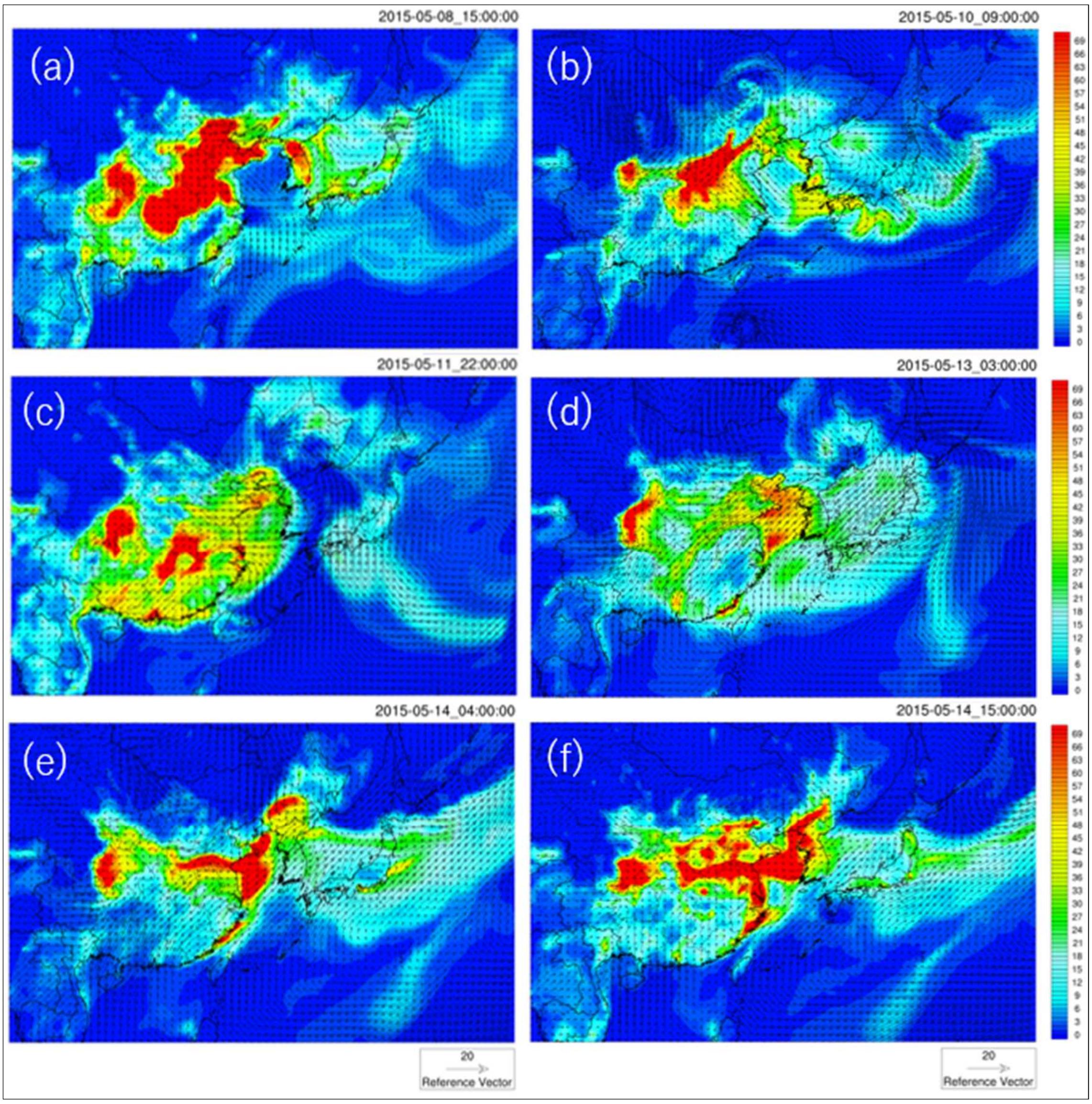


Figure 20. Spatial distributions of surface $PM_{2.5}$ concentrations representing Case 2

3-2-3. CASE 3 (July 22 – Aug. 5 in 2015—Summer)

Synoptic weather analysis

See Korean description for the weather analysis (weather map should be discussed commonly).

Validation for simulated $PM_{2.5}$

Averaged data in the four areas of Japan were used to statistically verify the model-simulated values for the Case 3 period. According to the findings, the model showed a high correlation with the observed values for all areas: R-values of 0.88-0.97 and IOA values of 0.80-0.99. MB shows sufficient values in all areas but Fukuoka, where model simulated values underestimated actual observational values. RMSEs are relatively small in Case 3, like Case 2, among the four cases.

Table 14. Statistical validation of simulated $PM_{2.5}$ concentrations for the Case 3 timeline

CASE 3	**Tokyo**		**Nagoya**		**Osaka**		**Fukuoka**	
	JPN1	**JPN2**	**JPN1**	**JPN2**	**JPN1**	**JPN2**	**JPN1**	**JPN2**
R	0.93	0.97	0.94	0.95	0.96	0.91	0.88	0.92
RMSE	4.74	3.80	3.47	4.02	4.32	7.93	5.76	7.49
MB	-2.45	0.75	0.87	2.37	0.47	3.31	-4.68	-6.70
IOA	0.99	0.97	0.99	0.96	0.99	0.92	0.87	0.80

Cause Identification

The time series data on the daily average $PM_{2.5}$ concentrations reveal a high correlation between the simulated results generated by the air quality model and the observed $PM_{2.5}$ concentrations for all areas during the Case 3 period (Figure 21), while the simulated time series in Fukuoka was much lower than the observations. Simulated data in Osaka were higher than the observations from July 27 to August 1.

A peak of $PM_{2.5}$ concentration in Tokyo on July 26 is considered to be locally caused (Figure 22, (a)). As Japan was within the area affected by the North Pacific High, southwesterly wind was prevailing for the period in Japan and the surrounding areas. A peak of $PM_{2.5}$ concentration in Fukuoka on July 28 is likely due to long-range transport from southern China (Figure 22, (b) and (c)). High concentration air mass stayed above western Japan with slow eastwardly movement, according to the air stagnation from July 29 to August 2, which is the case of a gradual upward trend of the concentrations found in Tokyo, Nagoya, and Osaka during the period (Figure 22, (c)–(e)).

Case summary

The Case 3 period mainly demonstrates the effects of the North Pacific High that is typical for this season. The model performed well in simulating overall changes in $PM_{2.5}$ concentrations for all regions except Fukuoka, showing lower simulated concentration than the observations.

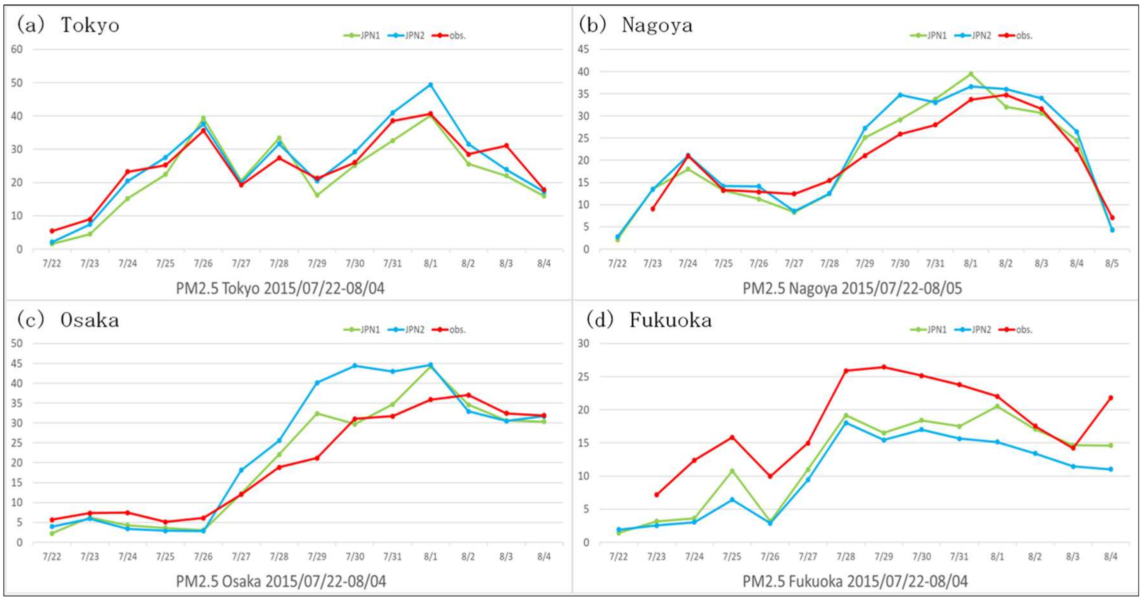


Figure 21. Time series of the observed (red lines) and simulated (JPN1: green lines; JPN2: blue lines) $PM_{2.5}$ concentrations during Case 3

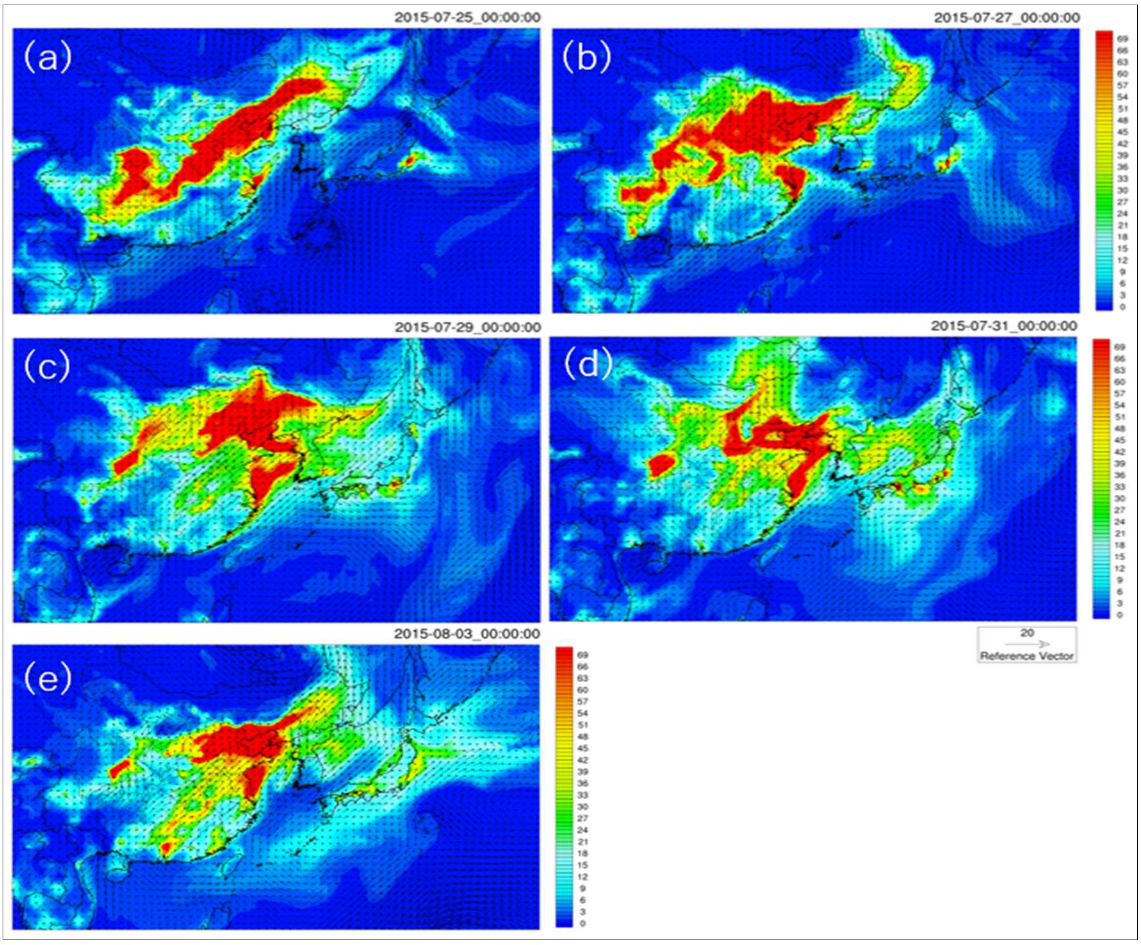


Figure 22. Spatial distributions of surface $PM_{2.5}$ concentrations representing Case 3

3-2-4. CASE 4 (Oct. 21 – Nov. 4 in 2015—Autumn)

Synoptic weather analysis

See Korean description for the weather analysis (weather map should be discussed commonly).

Validation for simulated $PM_{2.5}$

The daily average $PM_{2.5}$ concentrations in the four areas during the Case 4 period were used to statistically analyze the $PM_{2.5}$ figures simulated by the model, and the analysis results are presented in Table 15. The model simulation results for Case 4 show high R-values of 0.86 and higher in Fukuoka and Osaka, and low R-values are seen in Tokyo. RMSEs are small in Tokyo and Osaka but large in Nagoya and Fukuoka, and MB is largely negative, particularly in Fukuoka, while model concentrations are always lower than observed concentrations in all areas (Figure 23, (a)–(d)) except for the first several days of the period. Overall, the concentration timing increases and decreases are well reproduced by the model simulation in all areas, while the amplitude of concentration is much smaller than the observation in most cases.

Table 15. Statistical validation of simulated $PM_{2.5}$ concentrations for the Case 4 timeline

CASE 4	Tokyo		Nagoya		Osaka		Fukuoka	
	JPN1	JPN2	JPN1	JPN2	JPN1	JPN2	JPN1	JPN2
R	0.53	0.59	0.67	0.75	0.86	0.89	0.92	0.93
RMSE	6.19	5.98	11.14	9.55	5.32	5.48	11.06	11.43
MB	-3.65	-4.42	1.04	0.07	-3.47	-4.53	-10.16	-10.63
IOA	0.94	0.61	0.85	0.56	0.97	0.84	0.79	0.77

Cause Identification

On October 21, eastern winds blew across mid- and western Japan, and $PM_{2.5}$ concentrations were decreasing from their peaks in all areas. On October 24, wind was blowing from the Korean Peninsula to mid- and western Japan, and $PM_{2.5}$ concentrations peaked due to long-range transport with the wind. On October 26, it was thought that there was transport to mid- and western Japan, just as on October 24. On November 2, it is believed that trans-boundary transport to western Japan resulted in high concentrations in the three areas except Tokyo, though high concentration in Tokyo was assumed to be due to local causes.

Case summary

During autumn in Japan, the wind system changes every few days due to mobile high and low pressures. According to the wind direction change, $PM_{2.5}$ concentrations also repeatedly increase and decrease. These are similar to the spring case, Case 2, though the model simulation accuracy of Case 4 is poor compared to Case 2. The cause of this needs to be investigated.

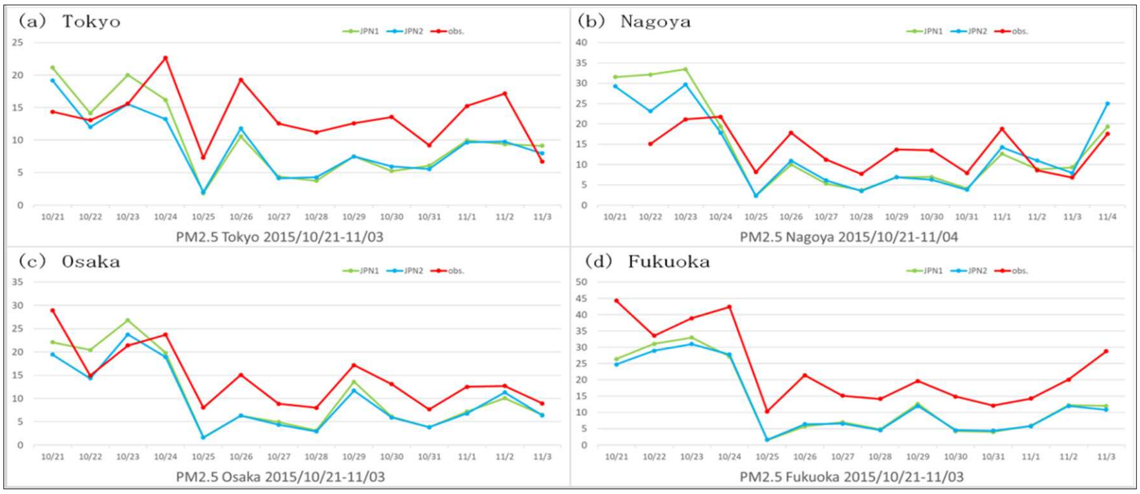


Figure 23. Spatial distributions of surface $PM_{2.5}$ concentrations representing Case 4

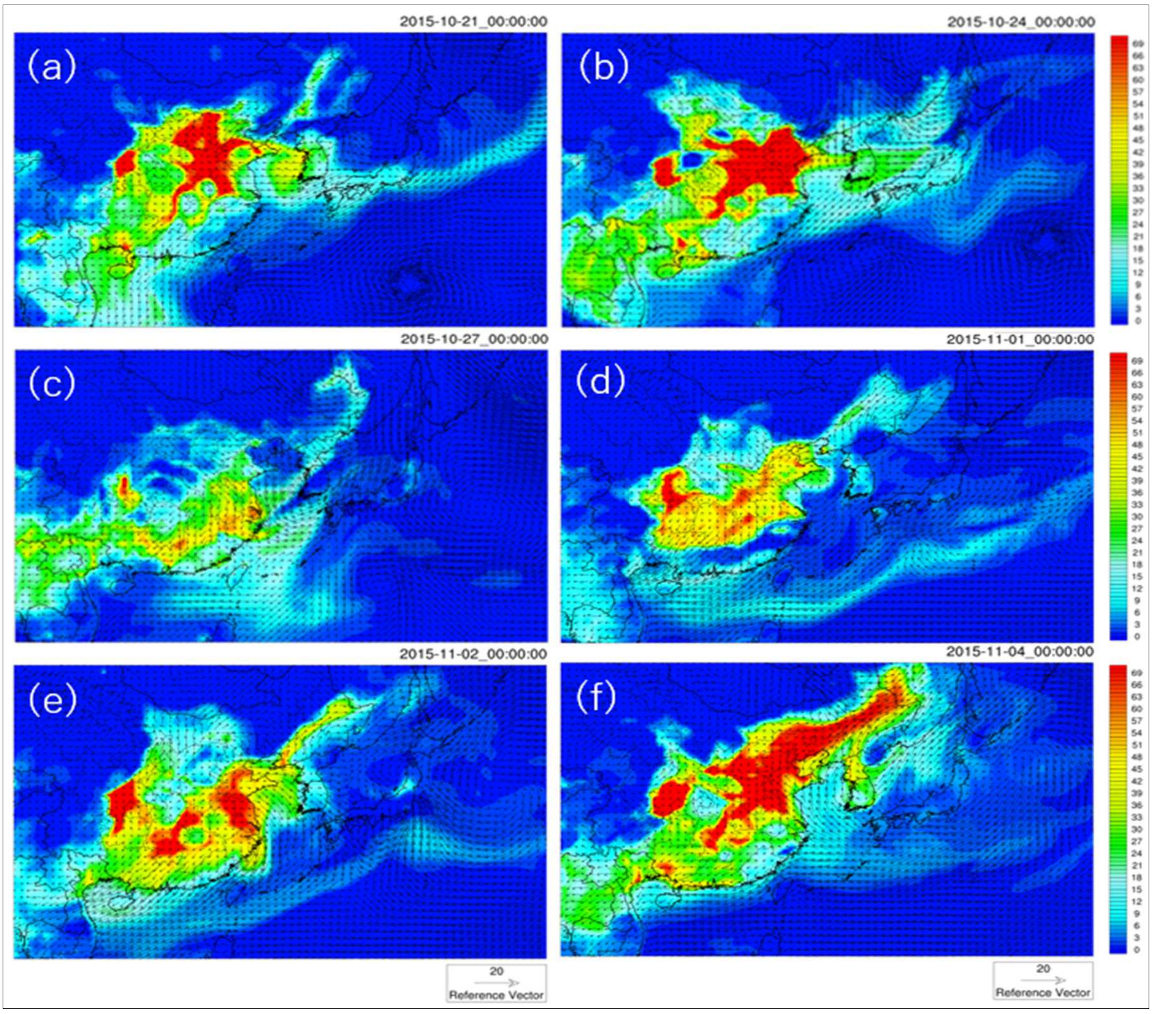


Figure 24. Spatial distributions of surface $PM_{2.5}$ concentrations representing Case 4

4. Conclusions and Discussions

4-1. Korea

Figure 25 arranges the model validation results by season. The air quality model used by the Korean side showed a meaningful correlation, averaging 0.61–0.85 for every intensive monitoring station over all four case periods—except Daejeon in Case 1, when the system utterly failed to simulate the actual $PM_{2.5}$ fluctuations. Thus, the fluctuating characteristics of $PM_{2.5}$ by season were simulated significantly. The average overall R-value by region was 0.62 for Baengnyeongdo, 0.65 for Seoul, 0.61 for Daejeon, 0.70 for Gwangju, 0.75 for Ulsan, and 0.85 for Jeju. These figures indicate that the model's predictability was mainly low regarding South Korea's Midwestern region, which is heavily influenced by $PM_{2.5}$ transported over long distances from China.

In addition, the average MB for each of the six IMS sites ranged between -2.6 and -6.6 over all four case periods, and the model's simulated figures were lower than the observed $PM_{2.5}$ concentrations. The results of the spring and fall case periods indicate that the air quality model lowered the $PM_{2.5}$ concentrations in cloud peripheries and underestimated the volumes of $PM_{2.5}$ transported over long distances to reach South Korea. Additionally, the model overestimated $PM_{2.5}$ levels during times of air stagnation in Seoul and Ulsan in all four case periods. These problems detracted from the model's simulation accuracy.

In future, the findings of this study will serve as the basis for understanding transboundary air pollutant mechanisms through the analysis of case studies on $PM_{2.5}$ transportation over long distances within Northeast Asia, as well as for lowering the pollution levels within the region. Simultaneously, these results indicate the need to analyze and address the causes for the model's overestimations and underestimations of pollution levels.

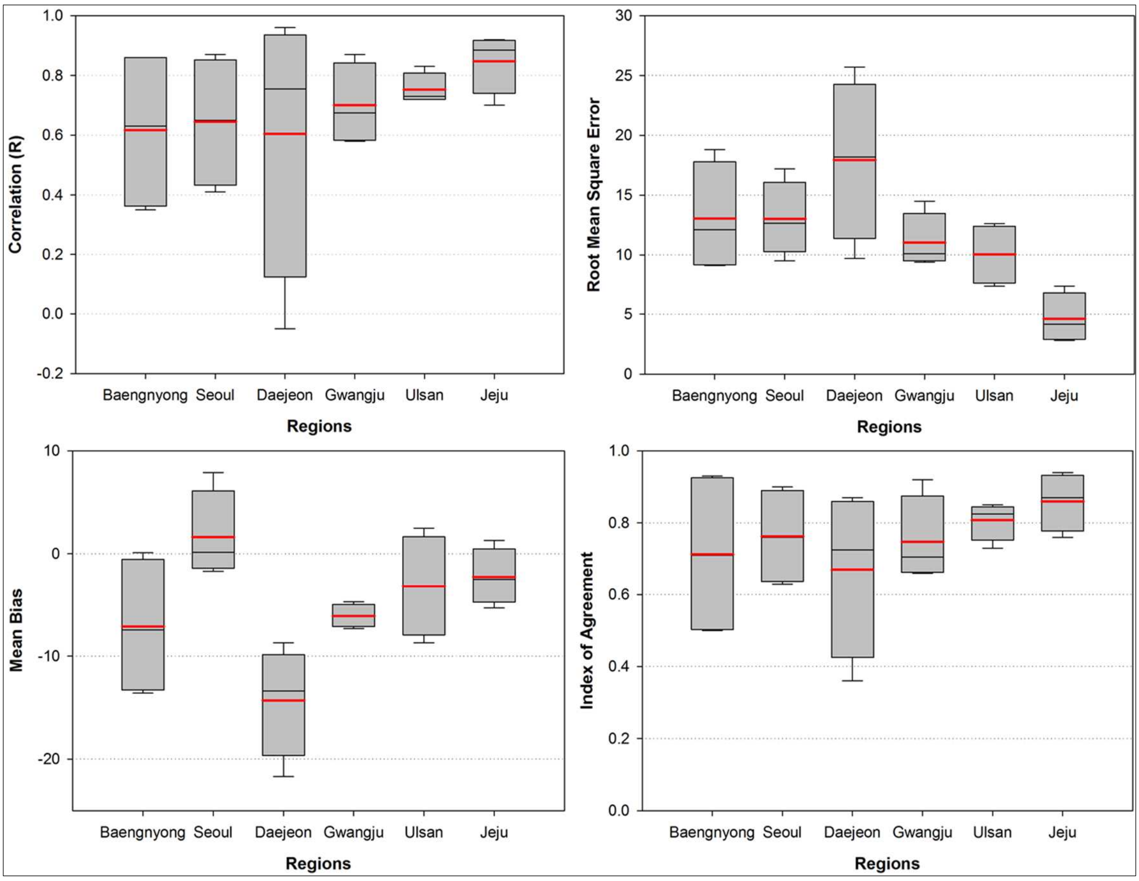


Figure 25. Statistical verification of South Korea's simulated $PM_{2.5}$ values during four case periods in 2015

4-2. Japan

The air quality model used by the Japanese side showed a meaningful correlation averaging 0.73–0.84 for all four urban monitoring areas over all four case periods. Thus, the fluctuating characteristics of $PM_{2.5}$ by season were simulated significantly. The average overall R-value by region was 0.73 for Tokyo, 0.84 for Nagoya, 0.82 for Osaka, and 0.76 for Fukuoka. These figures indicate that the model's predictability was slightly lower in Fukuoka and Tokyo.

In addition, the yearly average MB was -3.1 for Tokyo, -0.6 for Nagoya, -1.4 for Osaka, and -7.4 for Fukuoka. The model underestimated observed $PM_{2.5}$ concentrations, particularly in Fukuoka. As for the season, MB was largely negative in spring and winter.

Results for the Japanese model appear comparable in accuracy to the Korean model's result. At the beginning of this collaboration, the Japanese results showed lower accuracy than the Korean results. Through the collaboration, the Japanese model was improved to catch up to the Korean results.

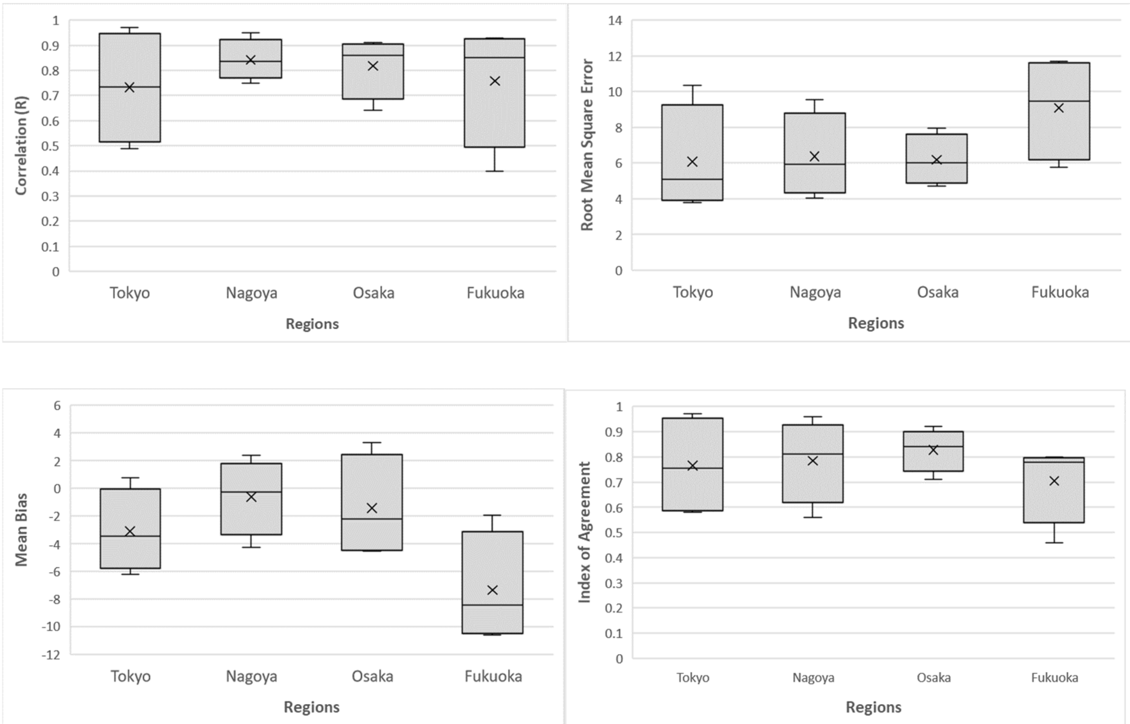


Figure 26. Statistical verification of Japan's simulated $PM_{2.5}$ values during four case periods of 2015

4-3. Outcomes

Through the joint research, the two countries' forecasting models have developed as shown in the figure below.

Korea	Japan
Through the validation of the forecasting model in the joint research, regional/seasonal dependence of the forecast accuracy was confirmed. It was also realized that one of the important problems regarding accuracy was the treatment of wet deposition. These are valuable for improving forecast accuracy in the next step.	Through verification of the forecasting model in the joint research and its comparison between countries, several technical problems for treatment of the model were identified and improved, leading to forecast accuracy comparable to the Korean results.

4-4. Plans Going Forward

Korea and Japan will conduct regular conferences from 2020 to cooperate on the fine dust issue. The meeting agenda will cover (1) joint research topics and (2) ways to improve air quality model predictability, while the two sides share their knowledge and experience. The topics of joint research are expected to include analyzing the characteristics of long-distance $PM_{2.5}$ transport within the Northeast Asian region to determine the following three directions of $PM_{2.5}$ movement:

- China → Korean Peninsula → Japan
- China → Korean Peninsula
- Japan → South Korea

Efforts to improve air quality model predictability will involve research on improving the uncertainties of the models used in the J-K $PM_{2.5}$ Joint Research Project, which was conducted between 2016 and 2018. Major research areas are identified below:

- Analyze and correct the causes of $PM_{2.5}$ simulation uncertainty in cloud peripheries
- Reduce pollution emissions inside and outside of each country

5. References

5-1. Japan

Nakanishi, M., and H. Niino, 2006: An Improved Mellor–Yamada Level-3 Model: Its Numerical Stability and Application to a Regional Prediction of Advection Fog. *Boundary-Layer Meteorology.* **119**, 397–407. doi:10.1007/s10546-005-9030-8
PDF

Nakanishi, M., and H. Niino, 2009: Development of an Improved Turbulence Closure Model for the Atmospheric Boundary Layer. *Journal of the Meteorological Society of Japan. Ser. II.* **87**, 895–912. doi:10.2151/jmsj.87.895

Olson, Joseph B., Jaymes S. Kenyon, Wayne M. Angevine, John M. Brown, Mariusz Pagowski, and Kay Sušelj, 2019: A Description of the MYNN-EDMF Scheme and the Coupling to Other Components in WRF–ARW. *NOAA Technical Memorandum OAR GSD*, **61**, pp. 37.
doi:10.25923/n9wm-be49

Yarwood, G., Rao, S., Yocke, M., Whitten, G.Z., 2005. Updates to the carbon bond mechanism: CB05. Report to the U.S. Environmental Protection Agency, December 2005. (http://www.camx.com/publ/pdfs/CB05_Final_Report_120805.pdf)

5-2. Korea

Benjey, W., Houyoux, M., and Susick, J. (2001). Implementation of the SMOKE emissions data processor and SMOKE tool input data processor in Models-3, U.S. EPA.

Binkowski, F.S., and Roselle, S.J. (2003). Models-3 Community Multiscale Air Quality (CMAQ) model aerosol component 1. Model description, *Journal of Geophysical Research*, 108, 4183, https://doi.org/10.1029/2001JD001409

Byun, D.W., and Ching J.K.S. (1999). Science Algorithms of the EPA Models-3 Community Multi-scale Air Quality (CMAQ) Modeling System. EPA Report, EPA/600/R-99/030.

Carter, W.P.L. (2000). Documentation of the SAPRC-99 Chemical Mechanism for VOC Reactivity Assessment. Contract, 92(329), 95-308.

Chen, F., and Dudhia, J. (2001). Coupling an Advanced Land Surface–Hydrology Model with the Penn State-NCAR MM5 Modeling System. Part I: Model Implementation and Sensitivity. *Monthly Weather Review*, 129(4): 569-585.

Ek, M.B., Mitchell, K.E., Lin, Y., Rogers, E., Grunmann, P., Koren, V., Gayno, G., and Tarpley, J.D. (2003). Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. *Journal of Geophysical Research*, 108(D22).

Guenther, A., Hewitt, C.N., Erickson, D., Fall, R., Geron, C., Graedel, T., Harley, P., Klinger, L., Lerdau, M., Mckay, W.A., Pierce, T., Scholes, B., Steinbrecher, R., Tallamraju, R., Taylor, J., and Zimmerman. P. (1995). A global model of natural volatile organic compound emissions. *Journal of Geophysical Research*, 100: 8873-8892.

Hong, S.Y., Dudhia, J., and Chen, S.H. (2004). A Revised Approach to Ice Microphysical Processes for the Bulk Parameterization of Clouds and Precipitation. *Monthly Weather Review*, 132(1): 103-120.

Hong, S.Y., Noh, Y., and Dudhia, J. (2006). A New Vertical Diffusion Package with an Explicit Treatment of Entrainment Processes. *Monthly Weather Review*, 134(9): 2318-2341.

Kain, J.S., (2004). The Kain-Fritsch Convective Parameterization: An Update. *Journal of Applied Meteorology*, 43(1), 170-181.

Li, M., Zhang, Q., Kurokawa, J., Woo, J.H., He, K.B., Lu, Z., Ohara, T., Song, Y., Streets, D.G., Carmichael, G.R., Cheng, Y.F., Hong, C.P., Huo, H., Jiang, X.J., Kang, S.C., Liu, F., Su, H., and Zheng, B. (2017) MIX: a mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia and HTAP. *Atmospheric Chemistry and Physics*. 17(2): 935-963.

NCEP, (2000). NCEP FNL Operational Model Global Tropospheric Analysis, continuing from July, 1999. Research Data Archive at the National Center for Atmospheric Research. Computational and Information System Laboratory, https://doi.org/10.5065/D6M043C6 (accessed on Sep. 27, 2018)

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G., Huang, X.Y, Wang, W., and Powers, J.G. (2008). A description of the advanced research WRF version 3. NCAR Tech. Rep. TN-475+STR, 113 pp.

Yamartino, R.J. (1993). Nonnegative, Conserved Scalar Transport Using Grid-Cell-centered, Spectrally Constrained Blackman Cubics for Applications on a Variable-Thickness Mesh. *Monthly Weather Review*, 121(3): 753-763.

IV. Emission Inventory Group Report

1. Background and History

At the Ministerial Meeting at COP19 in November 2013, it was agreed to promote information exchange between Japan and Korea on $PM_{2.5}$. In response to this, the Ministry of Environment Japan expressed the promotion of Japan-Korea cooperation for "comprehensive efforts on $PM_{2.5}$ (policy package)" (December 2013). In February 2014, three researchers from Korea visited Japan and exchanged views on the content of cooperation on the $PM_{2.5}$ issue. In April 2014, at the Ministerial Meeting at TEMM 16, the importance and necessity was recognized to promote further cooperation between Japan and Korea for the following five items: "measurement," "prediction," "estimation of emission inventory, contribution from transboundary," "Data sharing," and "countermeasures against sources" for the $PM_{2.5}$ problem. Japan and Korea agreed to cooperate.

In response to this, the first meeting (Korea) in August 2014 and second meeting (Japan) in February 2015 were held to deepen the discussion. In the meetings, the countries agreed to conduct joint research on predictive models and emission inventory. Based on the expert meeting held in June 2015, the third meeting (Korea) in August of the same year discussed the content of concrete collaborative research, and an agreement outline was made. The fourth meeting, held in January 2016, summarized the discussion up to that point, and a concrete three-year research plan was decided on.

[Meeting 4: January 2016]

The countries agreed to discuss mobile and stationary emission sources. Regarding mobile sources, we decided to consider exhaust gas emissions of automobiles. Moreover, evaporative VOC emission and large-scale point sources were selected as stationary sources.

Mobile source

Automobile emission factors (EFs), exhaust emission regulation values, and driving patterns for real driving modes that create EFs were compared between Korea and Japan.

Stationary source

Detailed VOC emission data were compared between Korea and Japan.

Topic

Japan provided Korea volcano emission data from March 2015.

The outline of the National Emission Inventory and the Stage II efforts in Korea were introduced.

[Meeting 5: August 2016]

Mobile source

Data of PM emission from gasoline vehicles were discussed. The decisions at this meeting were as follows:

Research target is PM and NH_3 running emission from gasoline vehicle. Each test vehicle and its conditions and results will be compared. Japan make a table sheet for comparison items by the first week of September in 2016. Korea will check and modify the table sheet and return it to Japan. Both Japan and Korea will complete the table sheet and compare results.

Stationary source

The Detailed Korean National Emission Inventory was introduced. Japanese and Korean emission factors of large point sources (LPS) were compared. We found a direct comparison of emission factors for LPS is difficult. We then discussed individual VOC components believed to be useful for both Korea and Japan.

The decisions at this meeting were as follows:

Individual VOC component data, for both Japan and Korea, will be provided. VOCs data that may have an effect on oxidants and/or $PM_{2.5}$ will be shared.

[Meeting 6: January 2017]

Mobile source

Data of PM emission from gasoline vehicles were discussed. Test conditions (test cycles, etc.) were confirmed for each country. Test data, with the same data format, were exchanged. We confirmed that the data to be surveyed was a gasoline fueled passenger car equipped with a direct injection system (gasoline direct injection: GDI). Japan provided additional 13 GDI data to Korea. Additionally, Japan provided cold start emission data to Korea.

Stationary source

Japan provided evaporated individual VOC data. Korea compared Japanese VOCs with its own. Furthermore, the definition of “VOC” was confirmed. We confirmed the outline of how each data for VOC component were created. Since evaporated VOC has a wide range of components to be surveyed, we targeted the source for paint and printing.

Topic

There was a detailed introduction of the Korean LPS monitoring system, CleanSYS. It addresses specific smoke source with high emissions and was a useful suggestion to Japan.

[Meeting 7: August 2017]

Mobile source

Regarding PM emissions from gasoline vehicles, Japan provided additional measurement results of 13 GDI to Korea. In Korea, with the measurement results of Korea and Japan, the emission factor of GDI PM was created experimentally.

Regarding NH_3 emissions from gasoline vehicles, Japan provided additional measurement results to Korea. Korea reviewed its NH_3 emission factor by comparing with the provided Japanese emission factors.

Stationary source

Since the definition of "VOC" and the way of emission estimations contrast, we reconfirmed the importance of clarifying the difference. Korea updated the VOC EF of its cleaning industry and introduced the estimation method to Japan.

Regarding Condensable Particle Matter (CPM), it was confirmed that Japan had no information to introduce, and it was under research as an important matter in Korea.

[Meeting 8: January 2018]

Mobile source

Efforts related to vehicular emission estimation in each country were introduced. The fourth through seventh meetings were reviewed.

Stationary source

Following Korea's report at the previous meeting, Japan reported a detailed estimation method of VOC emissions by dry cleaning. Korea explained the regulation and countermeasures against VOC emissions.

Topic

A direct comparison between Japan and Korea's national total emissions showed that the difference in CO emissions was particularly large. In order to clarify the cause, Japan decided to provide CO emissions data for each source sector.

[Meeting 9: August 2018]

A summary of the collaborative research was discussed and the way to generate improvements and resolutions for each other's and/or common concerns about emission estimation was also discussed.

2. Stationary Emission Sources

2-1. Combustion Source (Large Point Source)

2-1.1. Calculation method of emission factor in Japan

Emission factors (EF) from large point sources in Japan use the results of the Comprehensive Survey of Air Pollutant Emissions conducted by the Ministry of the Environment, based on the Air Pollution Control Law (Figure 27).

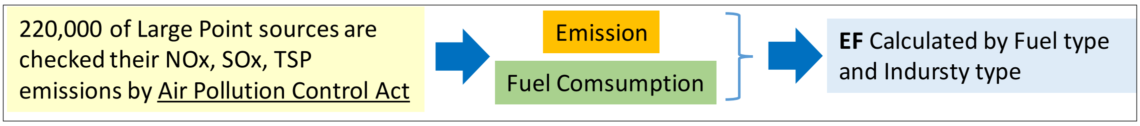


Figure 27. Conceptual calculation diagram of EF of large point sources in Japan

Comprehensive Survey of Air Pollutant Emissions is a questionnaire survey conducted every three years. In the 2014 survey, the target combustion facilities were 217,186, and the obtained responses were 156,715.

Survey items include:

- Fuel type (32 types)
- Fuel property (specific weight, high calorific value, sulfur content)
- Facility type (31 type [subdivided 61 type])
- Industry sector (25 type [subdivided 52 type])
- Exhaust volume (dry and wet)
- O_2 volume %, and H_2O volume % in exhaust gas
- Pollutants amount by facility (SOx, NOx, TSP)
- Yearly operation hours

The results of the survey are shown in Table 16.

Table 16. The result of Comprehensive Survey of Air Pollutant Emissions

Investigation Target Year	Release Year	Number of Facilities	SOx (ton/year)	NOx (ton/year)	TSP (ton/year)
1999	2001	168,477	629,209	837,260	75,086
2002	2003	182,327	595,506	869,113	60,738
2005	2007	184,400	566,773	890,188	57,976
2008	2009	161,496	505,595	731,094	47,660
2011	2013	125,445	410,979	696,404	36,529

2014	2016	156,715	406,735	631,139	35,986

The method of making EF of large point sources in Japan is as follows: With Comprehensive Survey of Air Pollutant Emissions after screening for incomplete records etc., the emission amount per fuel consumption for each point source is obtained (Figure 28). These data are organized by fuel type. If necessary, these are organized by industry category. The average EF for each category is calculated by weighted average of fuel consumption.

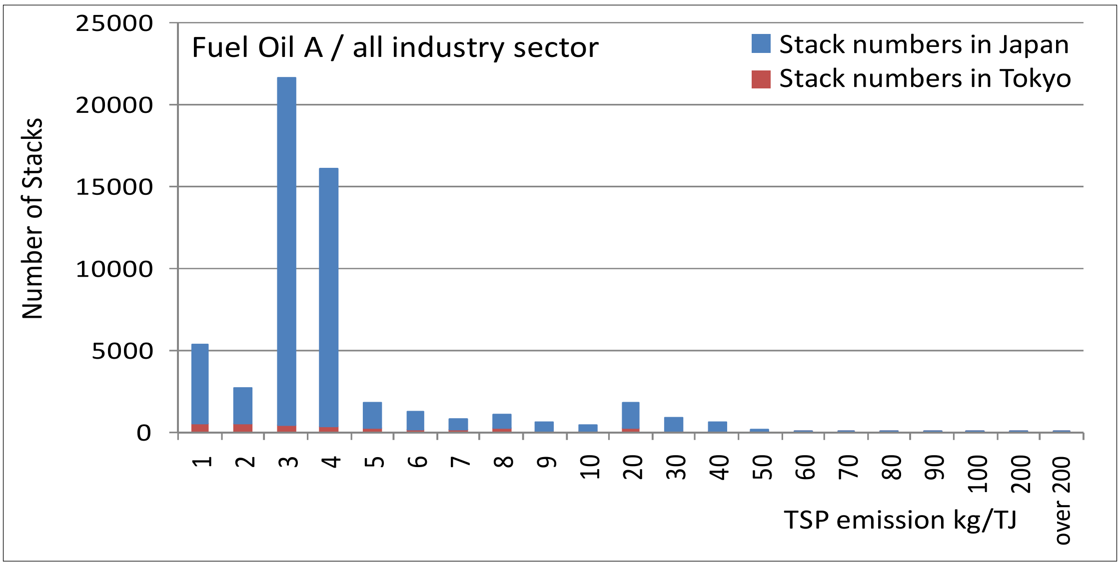


Figure 28. Emission amount per fuel consumption for each point source
(All industry categories using heavy oil A-type)

2-1-2. Calculation method of emission in Korea

To accurately and realistically estimate administrative district level air pollutant emissions in Korea, we developed a Korean Emissions Inventory System, named the Clean Air Policy Support System (CAPSS). In CAPSS, emissions sources are classified into four levels. Emission factors for each classification category are collected from various domestic and international research reports.

We divided the Source Classification Category (SCC) into four levels, based on the European Environment Agency's (EEA) CORe Inventory of AIR emissions (EMEP/CORINAIR), considering the Korean Standard Industrial Classification System (EEA, 2006).

In general, there are two emissions estimation methods for point sources: the direct method and the indirect method. The direct method uses real-time air pollutant emissions released through stacks in industrial sites, whereas the indirect method (also called the emission factor method) utilizes emissions factors and activity data to calculate emissions. We used both the direct and indirect methods for point sources depending on the available real-time emissions data. To estimate emissions from area sources, we used the indirect method, utilizing various ample data from organizations within Korea.

According to the Air Pollution Prevention Law (Korean Clean Air Act) in Korea, large facilities (for example, power plants and cement kilns) should install a Continuous Emission Monitoring System (CEMS) in stacks to continuously monitor air pollutant emissions and report real-time data to the governmental CEMS management center. We collected officially approved CEMS database (DB) information and utilized this to improve accuracy and reliability in estimated emissions for large point sources. Equation 1 below shows the estimated annual emissions from the CEMS DB.

$$E = \frac{Conc \times MW \times FR \times OT \times OD}{22.4 \times 10^6} \qquad \text{(Equation 1)}$$

E represents annual emissions (kg), Conc denotes concentration (ppm)
MW is molecular weight
FR is flow rate (m^3/hour)
OT is operation time (hour)
OD is operation day (day)
10^6 is used for unit conversion

Emissions from area sources or point sources with no CEMS were estimated by multiplying emission factors and relevant activity data considering the removal efficiencies of control devices.

Air pollutant emission factors for each SCC4 category were compiled from a wide range of published sources, for example, Korean research reports published by the NIER, ME, and numerous universities, as well as the EEA's EMEP/CORINAIR and the US EPA AP-42. They were then evaluated and approved by the Committee of Air Pollutant Emission Factors before being used in CAPSS. In principle, domestic emission factors were utilized preferentially to estimate air emissions.

Activity data for point sources were collected by a web-based source data collection system, named the Stack Emission Management System (SEMS). Individual companies input their source information through SEMS, such as fuel consumption, amount of products, and information about stacks and control devices.

Emissions from fuel combustion sources—that include combustion in energy industries, non-industrial combustion plants and combustion in manufacturing industries—were estimated in CAPSS. Emissions of air pollutants from combustion sources were estimated using the following equation.

Uncontrolled emission factors for each species were multiplied by fuel consumptions considering the removal efficiency of air pollutant control devices, as shown in Equation 2.

$$E = EF \times Fuel \times (1-R) \qquad \text{(Equation 2)}$$

E is emissions
EF is emission factor
Fuel is amount of fuel consumption
R is removal efficiency

Emissions from point sources were spatially allocated using information on the locations of point sources, mostly latitude and longitude data of individual industrial sites. If there was no location information, emissions were allocated over the districts containing industrial sites. In the cases of emissions from area sources, emissions were believed to be district level-based, without any spatial allocation, if they were estimated utilizing district level activity data. However, if city-province level activity data were used, emissions were spatially allocated using a spatial allocation index database, such as population data and number of employees.

Table 17. Air pollutant emissions from combustion sources in 2014

(Unit: ton/year)

SCC 1	SCC 2	NOx	SOx	TSP	PM_{10}	CO
Combustion in energy industries	Public power	127,456	73,506	3,976	3,854	41,534
	District heating plants	4,651	1,920	108	85	3,675
	Petroleum refining plants	8,066	13,071	169	104	2,320
	Commercial power	22,644	6,065	481	465	10,327
	Subtotal	**162,818**	**94,562**	**4,733**	**4,508**	**57,856**
Non-industrial combustion plants	Commercial and institutional plants	29,871	6,328	121	112	16,227
	Residential plants	47,055	17,111	1,447	1,206	59,341
	Plants in agriculture, Forestry, and aquaculture	4,216	1,229	340	312	1,026
	Subtotal	**81,143**	**24,668**	**1,908**	**1,629**	**76,594**
Combustion in manufacturing industries	Combustion in boilers, gas turbines, and stationary engines	13,612	3,232	449	323	1,389
	Process furnace	95,197	19,456	3,771	2,282	6,587
	Other	64,852	60,294	98,518	57,370	10,740
	Subtotal	**173,660**	**82,982**	**102,738**	**59,975**	**18,716**
Total		**417,621**	**202,212**	**109,379**	**66,112**	**153,166**

2-1-3. Comparison of emission factors of large point sources in Japan and Korea and its consideration

In comparing the EFs of large point sources in Japan and Korea, it is better to match source category and facility type of each source. For this reason, we decided to compare the EFs of thermal power plants, where the emissions are large and the usage patterns are considered similar between Japan and Korea. Target pollutants are NOx and PM, and EFs for main fuels were arranged and compared.

Figure 29 shows NOx EF, and Figure 30 shows PM EF (Japan shows TSP and Korea shows PM_{10}).

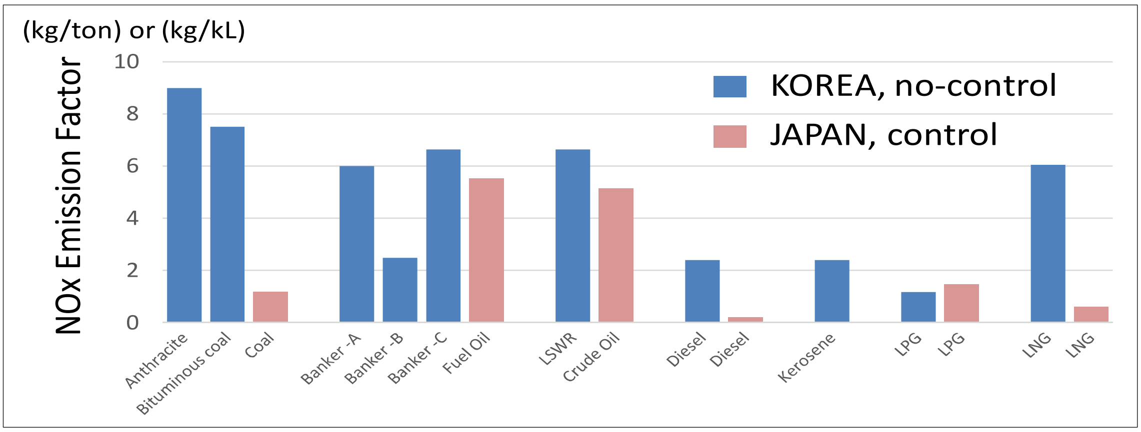


Figure 29. NOx EFs for thermal power plant

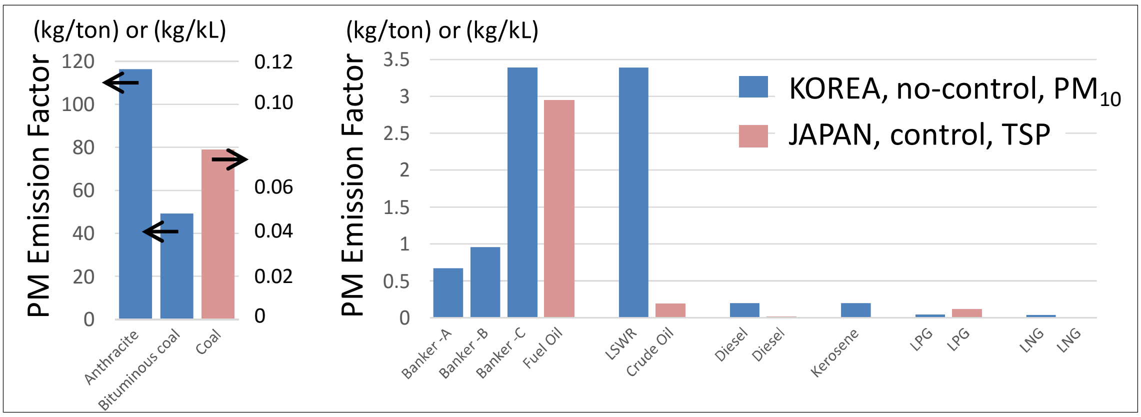


Figure 30. PM EFs for thermal power plant

According to these results, it was confirmed that EFs of Japan and Korea could be divided into two groups. One comprises similar value for both countries, and the other shows trivial Japanese EFs compared to that of Korea.

We verified why Japanese EFs are smaller than Korean EFs in some cases. We confirmed that Korea's EFs were set at the exit of the combustion device, or before the after-treatment device of the exhaust gas, while the Japanese EFs were set after passing through the after-treatment device.

The definition of EF differs is due to the difference of emission estimation procedure.

In Japan, estimating emissions amount E (kg) using EF (kg/kg of fuel consumption), is calculated as per Equation 3.

$$E = EF \times A \qquad \text{(Equation 3)}$$

A signifies activity rate by fuel consumption (kg of fuel), In Korea, considering the emission reduction rate r by various after-treatment devices, E is calculated as per Equation 4.

$$E = EF \times A \times r \qquad \text{(Equation 4)}$$

As a reference, we confirmed the European EMEP EF together (Figure 31).
The EMEP EF was calculated from no SO_2 after-treatment device facilities, and the value is close to the EF of Korea.
Some Japanese EFs are thought to be high with the after-treatment device. The original data were created in 1999, and there was a possibility that emission data with no after-treatment device were mixed in.

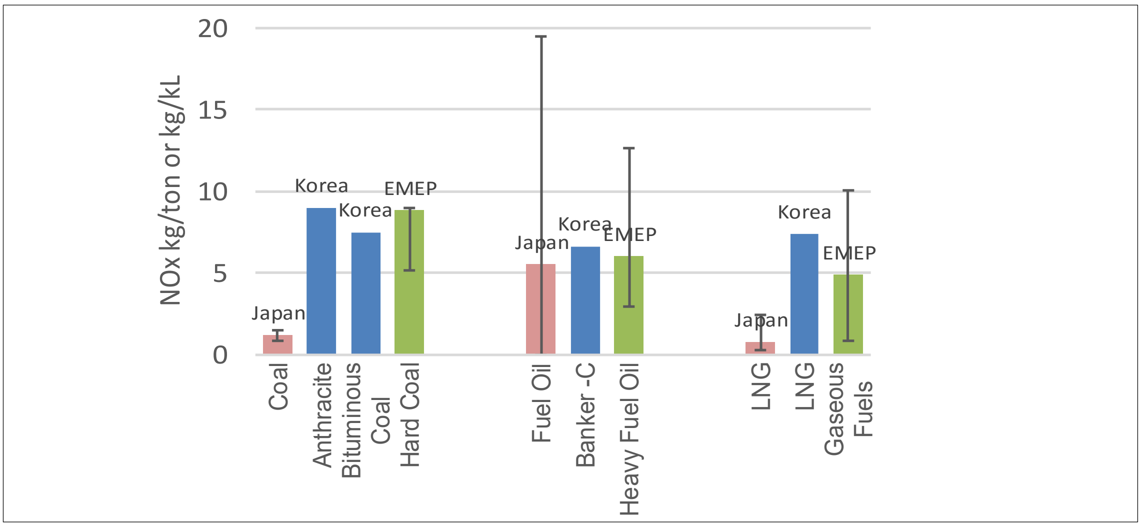


Figure 31. Comparison of NOx EFs for Japan, Korea, and Europe (EMEP)

From the above results, it is difficult to compare EFs of large point sources of the Japan and Korea directly. Therefore, the comparative study on the EF of large point sources was completed once before this finding was obtained.

2. Evaporative VOC Source

2-1. Definition of VOC in Korea and Japan

VOC is important as a precursor of $PM_{2.5}$ and photochemical O_3. There is an issue in realizing VOC in both Korea and Japan. In particular, it is difficult to estimate evaporative VOC emissions compared to VOCs from combustion sources, and it was thought that knowledge of both in Korea and Japan is useful for estimating evaporative VOC emissions.

However, the approach to VOC varies from Korea and Japan, and we realized the importance of sharing information. Figure 32 defines VOC in Korea and Japan.

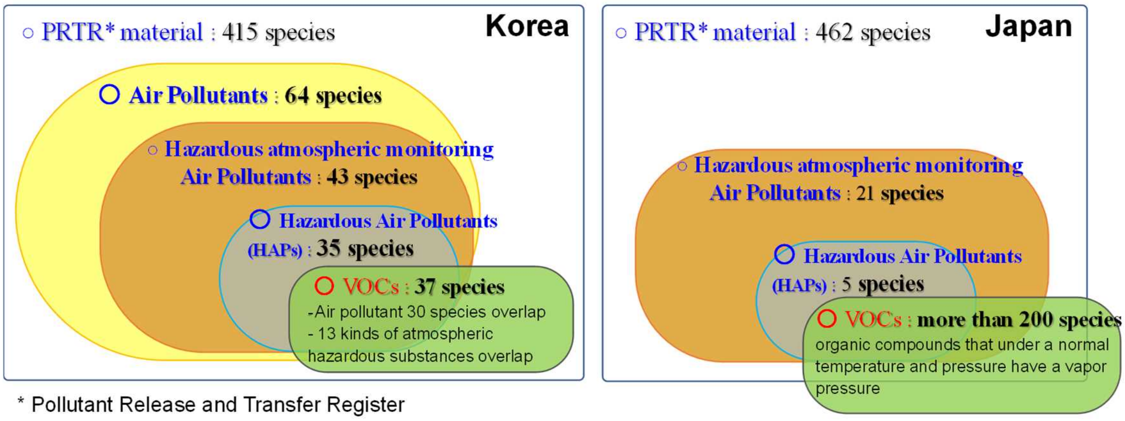


Figure 32. Definition of VOCs in Korea and Japan

In Korea, VOCs are petrochemicals, organic solvents, and other substances among hydrocarbons, which are notified by the minister of Environment in consultation with the head of relevant central administrative agency. Therefore, 37 species of VOCs have been designated and announced as having emission restrictions. Moreover, VOCs for estimating emissions are not limited to these 37 components.

Hazardous Air Pollutants (HAPs) are substances among the hazardous atmospheric monitoring air pollutants considered necessary for managing air emissions, as they can directly or indirectly cause harm to the health of human, animal, and plant life by long-term ingestion or exposure, even at low concentrations, as defined by the Ordinance of the Ministry of Environment. Thus, 35 species of HAPs have been designated and announced. Hazardous atmospheric monitoring air pollutants are also considered necessary for continuous measurement, monitoring, and observation because they can harm human and animals health or plant growth. Thus, 43 species of HAPs have been designated and announced.

An air pollutant is a gas phase and a particulate matter recognized as a cause of air pollution because of evaluated substances present in the atmosphere. Thus, 64 species of air pollutants have been designated and announced.

The definition of VOC is clear in Korea; however, in Japan, it is a vague definition that it is gas at ordinary temperature and pressure, among organic compounds. The evaporative VOCs emitted from industries are estimated using VOC component information. The number of VOC components considered is more than 400 for FY2017.

However, when comparing all VOC emissions, including combustion and mobile sources, the main sources of generation are VOCs by solvent use in Japan and Korea (Figure 33). It is thought that the main components of VOCs can be grasped roughly by the VOC components defined in Korea, which will be discussed in detail later.

We describe the estimation method of VOC emissions and detailed emissions information of Korea and Japan.

Sources	KOREA VOC (ton)	JAPAN VOC (ton)
Energy production	7,697	9,023
Non industry	2,558	59,338
Manufacturing industry	3,280	8,597
Industrial process	180,351	63,552
Storage & Transport	27,645	161,311
Solvents use	549,318	517,346
On-road transport	49,468	175,436
Off-road transport	36,873	16,765
Waste	48,061	13,828
Other area sources	551	723
Total	905,803	1,025,919

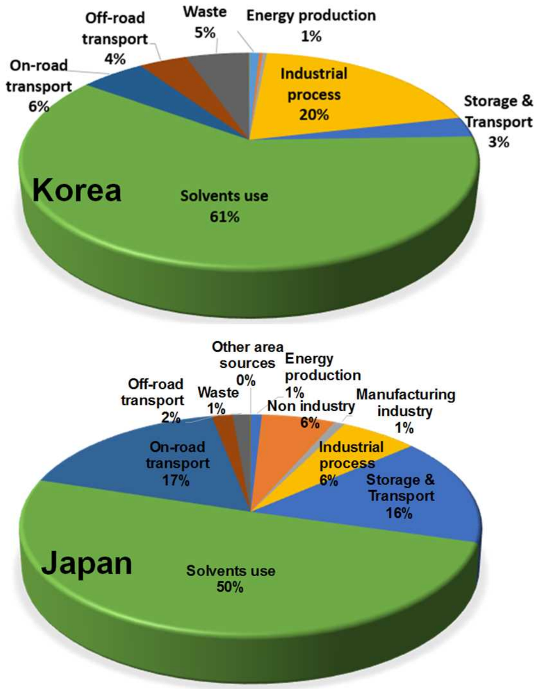


Figure 33. Comparison of VOC emissions in Korea and Japan by source (2012)

2-2. Emission estimation method of evaporated VOC in Japan

Concerning evaporative VOC emissions from industries are difficult to estimate. Thus, in Japan, the total industrial evaporative VOC is estimated by evaluating the emissions—which are mainly estimated by the industrial associations on a voluntary basis—and adjusting the sum as needed (Figure 34).

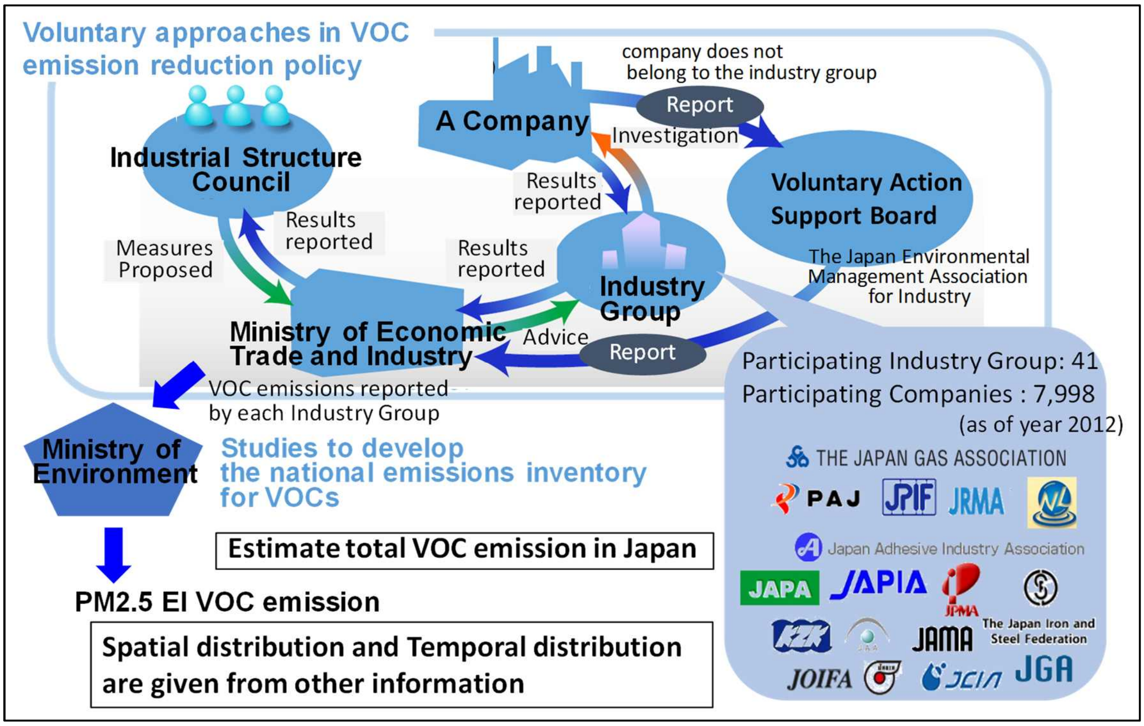


Figure 34. Industrially related evaporative VOC emission estimation

Japanese industries are knowledgeable about the VOC species they use, and it is possible to identify the emission volumes of the main VOC species, to a certain extent.

The information on the emission volumes by VOC species is indispensable when considering the reactions for VOC species' secondary formation. As rough data are available in Japan concerning the species found in the industrial evaporative VOCs, Japan shared them with Korea.

The data included 40 emission sources categories and 151 VOC species. Japan also shared brief explanations about the emission source types of the Japanese evaporative emission sources along with the emission estimates of each VOC species (Figure 35).

As the data for 151 VOC species are cumbersome, Japan reorganized the VOC species data according to the definition of the chemical reaction scheme SAPRC07tc for CMAQ (Figure 36) and shared them with Korea, as well.

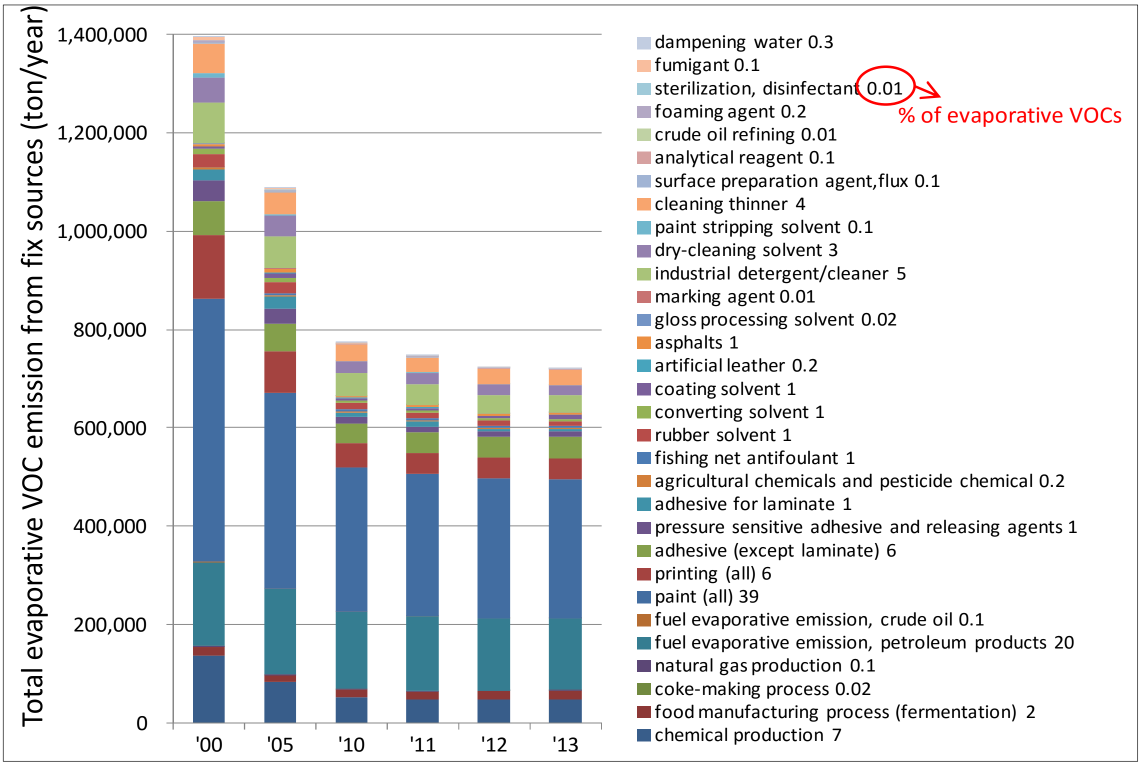


Figure 35. Total VOC amount and short explanation for sources (Numbers mean % of VOC emission to anthropogenic evaporative VOC emission)

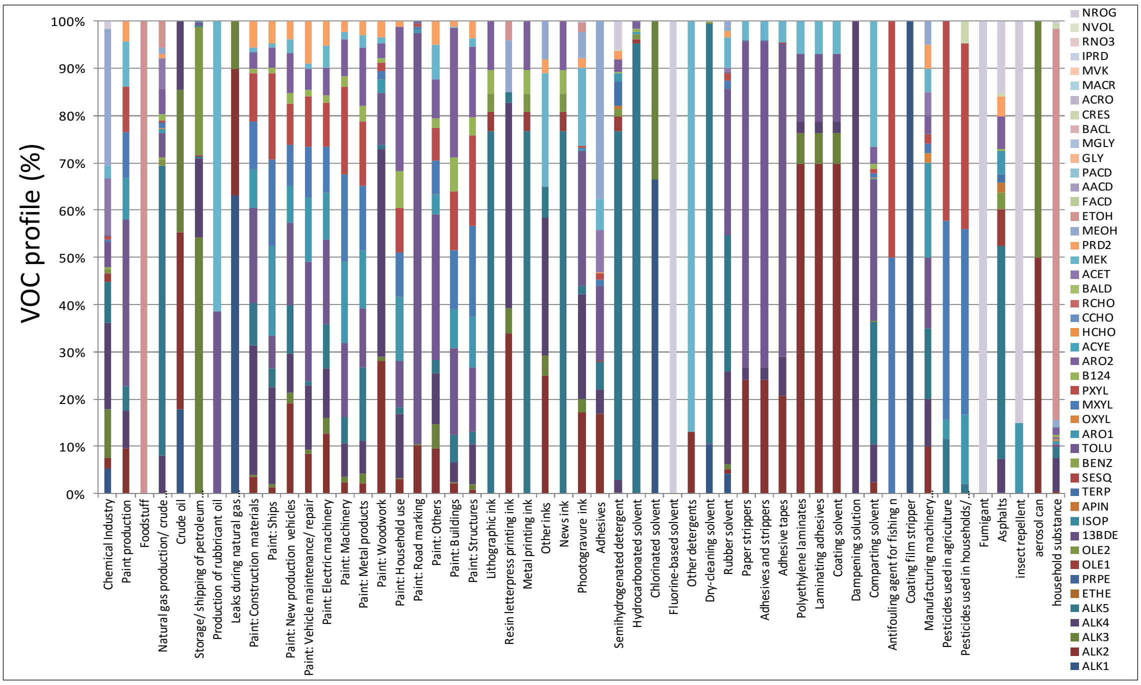


Figure 36. Japanese evaporative VOC profile data by each source, 151 species of VOCs in 40 sources are considered (updated with FY2013 data; Graph shows VOC species as SAPRC07tc chemical mechanism species)

2-3. Emission estimation method of evaporated VOC in Korea

As shown in Table 18, VOCs emissions from solvent use were divided into paint application, degreasing and electronics, dry-cleaning and other use of solvent and related activities.

In the case of solvent use, we used controlled emission factors and the amount of solvent used or alternative statistics corresponding to emission factors, such as the number of employees and corresponding emission factors. This is shown in Equation 5 below.

$$E = EF \times Solvent/Stats \qquad \text{(Equation 5)}$$

E is emissions
EF is emission factor
Solvent is amount of solvent used
Stats is alternative statistics corresponding to EF

Table 18. VOCs Source Classification Category & Emission Factor for Solvent Use

SCC 1	SCC 2	SCC 3	Unit	EF	Reference
Solvent Use	Paint application	Vehicle manufacturing	Kg/ℓ	0.512	USEPA
		Vehicle repairing	Kg/ℓ	0.512	
		Architecture & building	Kg/ℓ	0.512	
		Domestic (except wood, furniture manufacturing)	Kg/ℓ	0.512	
		Coil coating	Kg/ℓ	0.512	
		Marine manufacturing	Kg/ℓ	0.512	
		Wood & furniture manufacturing	Kg/ℓ	0.512	
		Other industrial painting process	Kg/ℓ	0.512	
		Other non-industrial painting process	Kg/ℓ	0.512	
	Degreasing & Electronics	Metal degreasing process	Kg/person/yr	223.1	NIER
		Electronics component manufacturing process	Kg/person/yr	39.463	USEPA
		Other industrial degreasing process	Kg/person/yr	39.463	
	Dry Cleaning	Dry cleaning	Kg/Facilities/yr	610.368	MOE
	Other use of solvent & related activities	Printing facility (master process)	Kg/Facilities/yr	499.6	NIER
		Printing facility (screen process)	Kg/Facilities/yr	1,694.3	
		Printing facility (offset printing)	Kg/Employee/yr	248.3	
		Printing facility (gravure printing)	Kg/Employee/yr	4,443.8	
		Domestic & Commercial use of solvent	Kg/person/yr	2.64	
		Pavement of asphalt road	Kg/Kℓ	600	

2-4. Comparison of VOC emissions between Korea and Japan

Figure 37 shows evaporative VOC emissions of both Japan and Korea. Although the source categories were classified by similarity of the names, this was not confirmed in detail.

According to Figure 37, large differences between Japan and Korea are evident in food fermentation, gas stations, paints, and printing.

We did not conduct a detailed survey on the differences in emissions in those source categories, but we clarified the reason for gas stations being included. Specifically, in Korea, Stage II had been introduced as a control measure for refueling VOC emission at gas stations in large cities, while Japan hadn't introduced such measures against gasoline vapor emissions accompanying refueling in

2012. It was thought that these countermeasures for refueling VOCs could be responsible for difference in VOC emissions from gas stations.

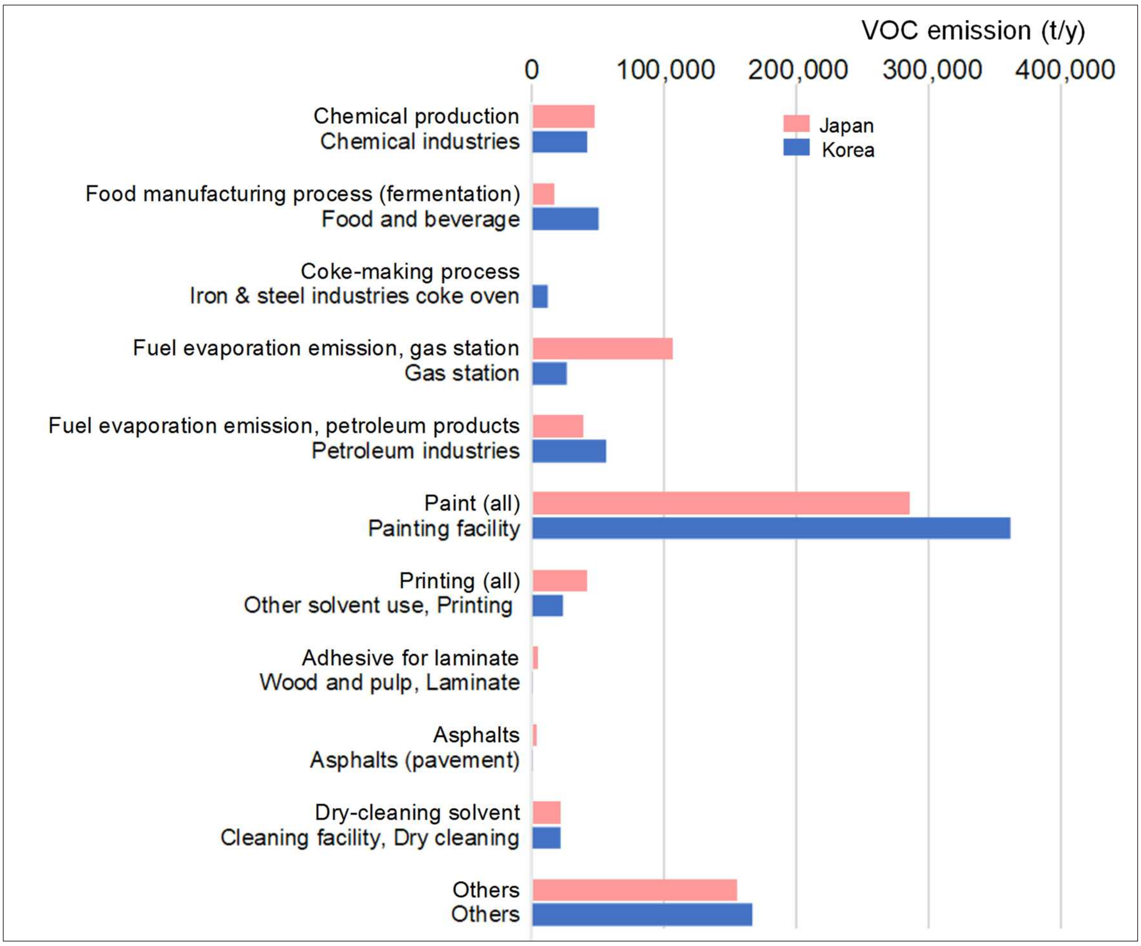


Figure 37. Evaporative VOC emission from main sources in Korea and Japan (2012)

As for VOC emissions from food fermentation, in Korea, the food and beverage processing industry consists of the following emission sources and uses the VOC emission factor based on the subcategories of EU CORINAIR, which does not represent the actual emission characteristics of Korea. The food processing sector estimates emissions from baking, cakes, biscuits, cereals, meat and fish processing, sugar, margarine and cooking fat (solid) processes, and—in the beverage processing sector—emissions from manufacturing of wine, beer, and whiskey.

In Japan, ethanol emissions associated with bread and liquor production are considered. In this estimation, emissions are estimated via EFs and the amount of activity (production of bread or liquor); the EF of EMEP is used.

Additionally, the differences in the printing sector emissions in Korea and Japan can be attributed to the type of printed matter and printing ink used. For example, in Korea, VOC emissions in the printing industry accounted for 52% of gravure printing followed by screen-printing (19%), master printing (15%), and offset printing (14%). In Japan, the following types of ink are considered: planographic, plastic plate, metal printing, gravure, news, and others. Among them, emission from gravure printing accounted for 45%, and other inks accounted for 38%.

Large differences are also seen for paint, and differences in emissions by usage and in VOC components were compared. Figure 38 shows VOC emissions by paint usage; it is interesting to note that the main sources differ, reflecting the differences between industrial structure of both Japan and Korea.

For the detailed VOC component, elements measured varied in both country. There were only 11 common components that could be directly compared (Table 19). Compared to the classification of chemical species, the main components are paraffinic hydrocarbons for both Korea and Japan. However, in Korea the emission amount of ketones is relatively high, while aromatic hydrocarbons are high in Japan.

USEAGE	KOREA	JAPAN
Automobile manufacturing	9,634	41,697
Automobile repairs	8,062	18,217
Construction and building	108,499	100,768
Coil coating	81,828	23,564
Shipbuilding	88,499	32,321
Wood, furniture manufacturing	13,604	9,350
Other (Industrial painting process)	18,275	51,854
Other (Non-industrial painting process)	30,467	7,882
TOTAL	358,870	285,652

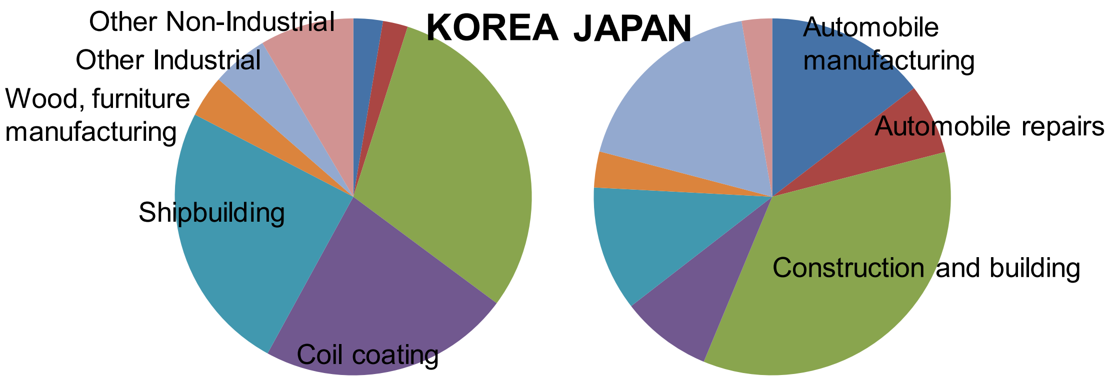


Figure 38. VOC emissions by paint usage (2012)

Table 19. Common VOC components in paint and their emissions between Korea and Japan (2012)

Chemical	KOREA (ton/yr)	JAPAN (ton/yr)	Chemical	KOREA (ton/yr)	JAPAN (ton/yr)
TOLUENE	29,302	27,426	ETHYL ACETATE	6,386	15,720
ISOMERS OF XYLENE	50,963	47,812	N-BUTYL ACETATE	10,972	18,074
ISOPROPYL ALCOHOL	1,903	4,502	CELLOSOLVE	1,040	1,943
ISOBUTYL ALCOHOL	6,563	1,6445	BUTYL CELLOSOLVE	12,694	12,887
ACETONE	9,886	7,466	CELLOSOLVE ACETATE	1,540	2,046
METHYL ETHYL KETONE	11,928	2,617	ETHYLENE GLYCOL	15,356	3,682
METHYL ISOBUTYL KETONE	9,865	8,912			

Detailed data has been given in Annex 1.

3. Introduction of Countermeasures to Reduce Emissions that are Useful in Both Countries

3-1. CleanSYS (Air Pollutant Monitoring System for Stationary Sources) System in Korea

CleanSYS is an advance remote monitoring system that enables pollutants data of stacks from facilities to be automatically measured and transmitted from the sites to the control center via a telecommunication line, thus preventing environmental pollution.

The purpose of CleanSYS is to transform a regulation-driven into a prevention-oriented system, as well as for scientific utilization of statistic data about air pollution for the environment policy decision, improvement of management efficiency of air pollution source facilities, and improvement of air quality by inducing air pollution reduction from CleanSYS facilities.

Target facilities are power plants (50 MWh), incinerators (0.4–1 ton/hour), chemical manufacturers & cement facilities (10,000 m^3/hour), and 1^{st} to 3^{rd} class large-scale air pollutant emission facilities. It corresponds to 1,531 stacks of 578 companies in December 2015.

The monitoring items include concentrations of 7 air pollutants (dust, SOx, NOx, HCl, HF, NH_3, CO) and flow, temperature, and O_2 concentration (Figure 39).

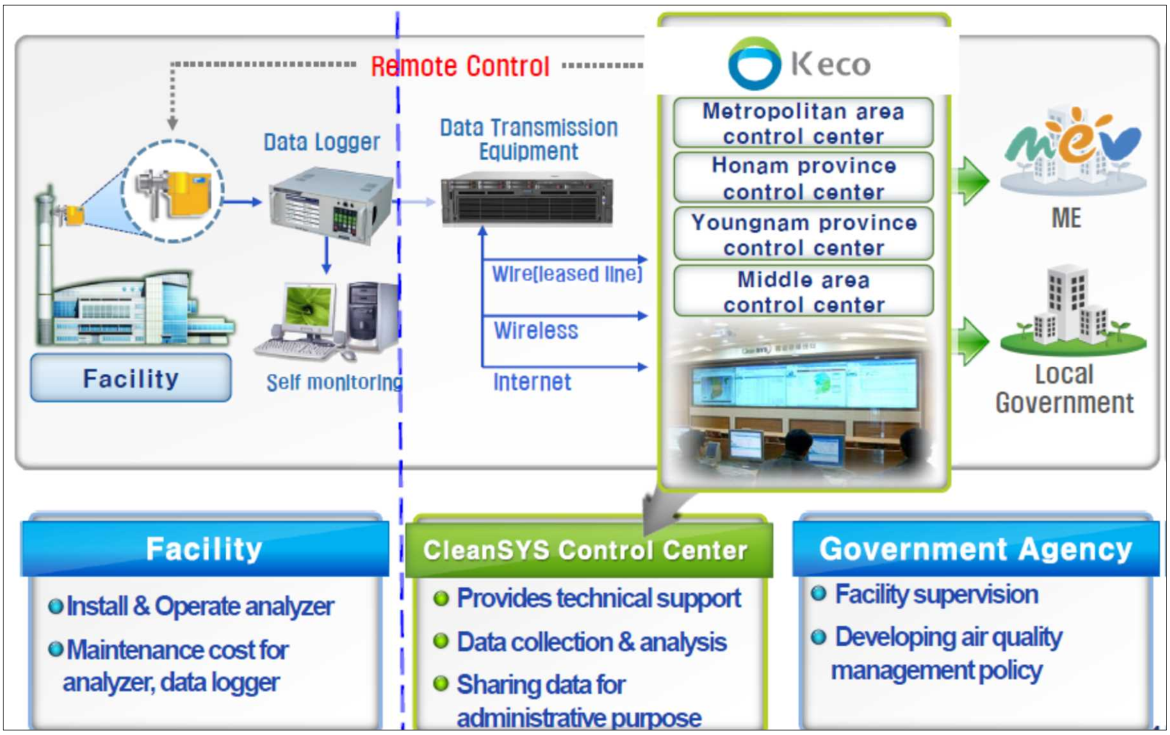


Figure 39. CleanSYS Configuration for Stationary Sources

Using the CleanSYS System, various real-time data, including trend chart and status of analyzer operation, can be checked. Therefore, facilities can properly manage their emissions and prevent excessive amounts. In addition, officials can inspect whether facilities comply with emission standards. Emission charges based on the CleanSYS data are calculated and imposed on the source facilities.

If the emission level is near or over the limit, facilities and local government are informed through an automatic SNS transmission, so that they can take proper action to control their excessive emissions.

If the CleanSYS control center orders a remote check, a sample gas test is automatically injected into the analyzer. It shows a measured concentration level of the gas. Based on the measured concentration level of the gas, we can assume the analyzer is being properly operated.

The number of CleanSYS is 15% of major facility (1st to 3rd class), and it covers 85% emission volume of all major facilities nationwide. Figure 40 shows the contribution rate of CleanSYS to the major facilities.

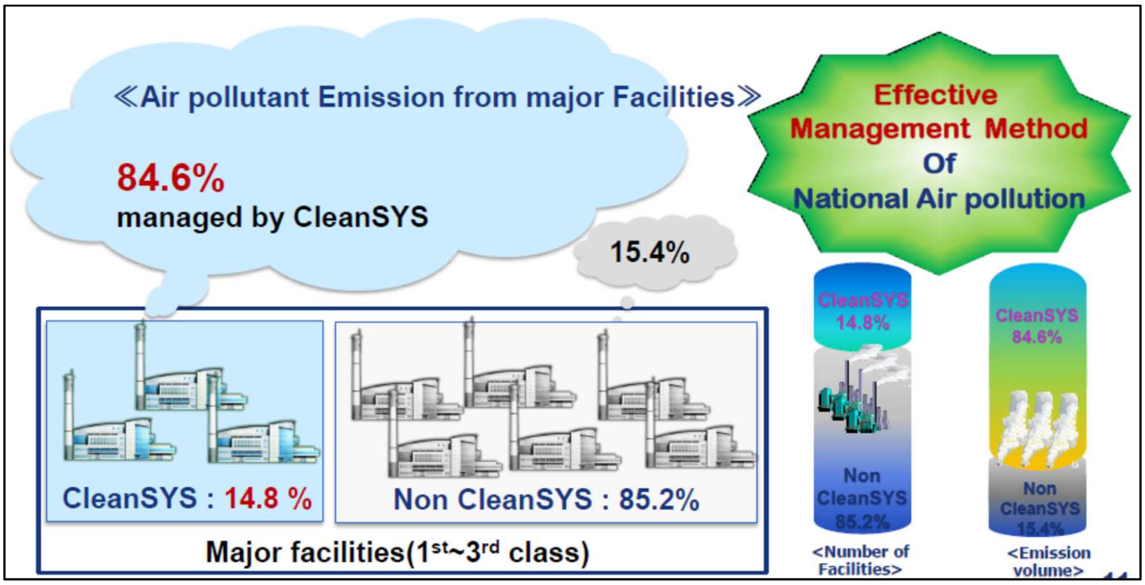


Figure 40. Contribution rate of CleanSYS to the major facilities (1st to 3rd class)

3-2. Management of VOCs in Korea

Gas stations emit VOCs, such as gasoline vapors, and they were in high need of management as they are often located close to residential areas. To address this matter, prevention facilities were installed in gas stations situated in air conservation special countermeasure areas and air quality control areas (Figure 41).

Installation was completed for Stage I (from manufacturing facilities to gas station storage facilities) by 2004 and for Stage II (from gas station storage facilities to filling vehicle fuel tanks) from 2007 to 2020.

VOCs emitted from a gas station when supplying oil to a vehicle should not be directly discharged to the atmosphere; a vapor recovery system attached to the gas station should be made use of. The recovery efficiency of the recovery equipment should be above 90%. The law requires that the recovery efficiency test be conducted annually with the whole recovery system inspected.

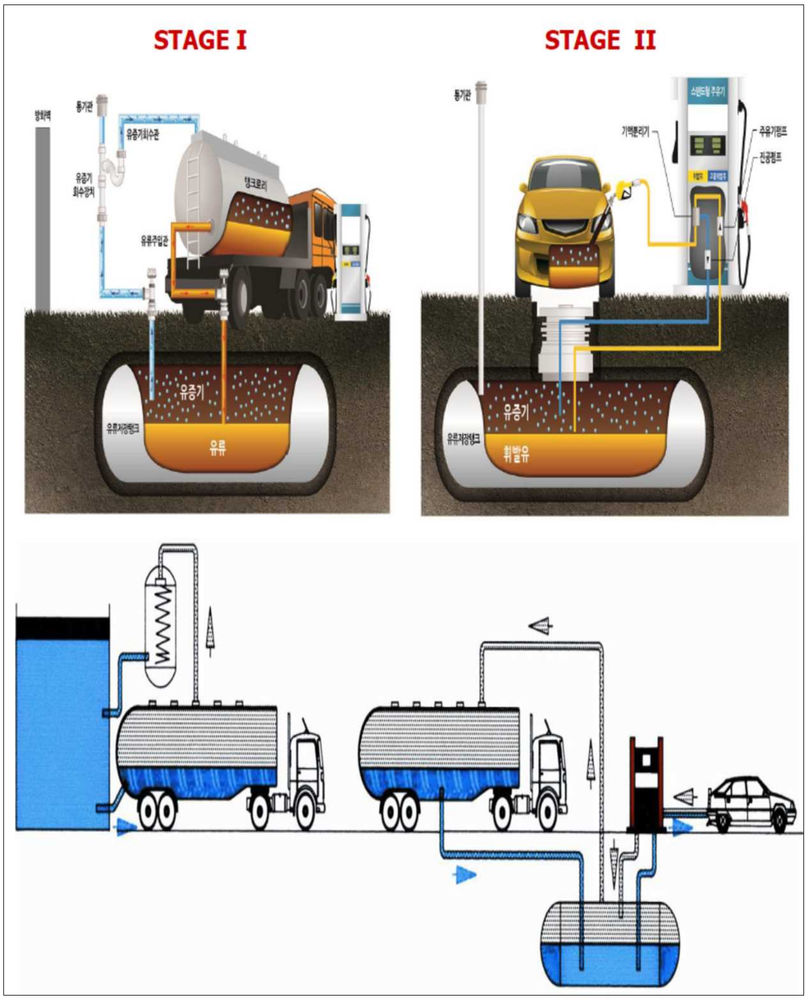


Figure 41. Oil-vapor recovery equipment from service station (Stage I and Stage II)

Oil-vapor recovery equipment was regulated mainly in Seoul and metropolitan cities; however, the installation will be expanded to 10 cities with a population of 500,000 or more. Furthermore, the gas stations to be installed in Stage II are based on the annual sales volume, as shown in Table 20.

Table 20. Stage II installation deadline by annual sales of gas station

	Facilities	Deadline
A	Annual sales volume over 2,000 m^3	January 28, 2019
B	Annual sales volume of more than 1,000 m^3 and less than 2,000 m^3	December 31, 2019
C	Annual sales volume of more than 300 m^3 and less than 1,000 m^3	December 31, 2020
D	Annual sales volume less than 300 m^3	2 years from the next year when annual sales volume exceeds 300 m^3

As shown in Figure 42, because emissions from non-point sources are about twice as much as the emissions from point sources, we can understand that the air quality cannot be improved only by the concentration regulation from stack emissions.

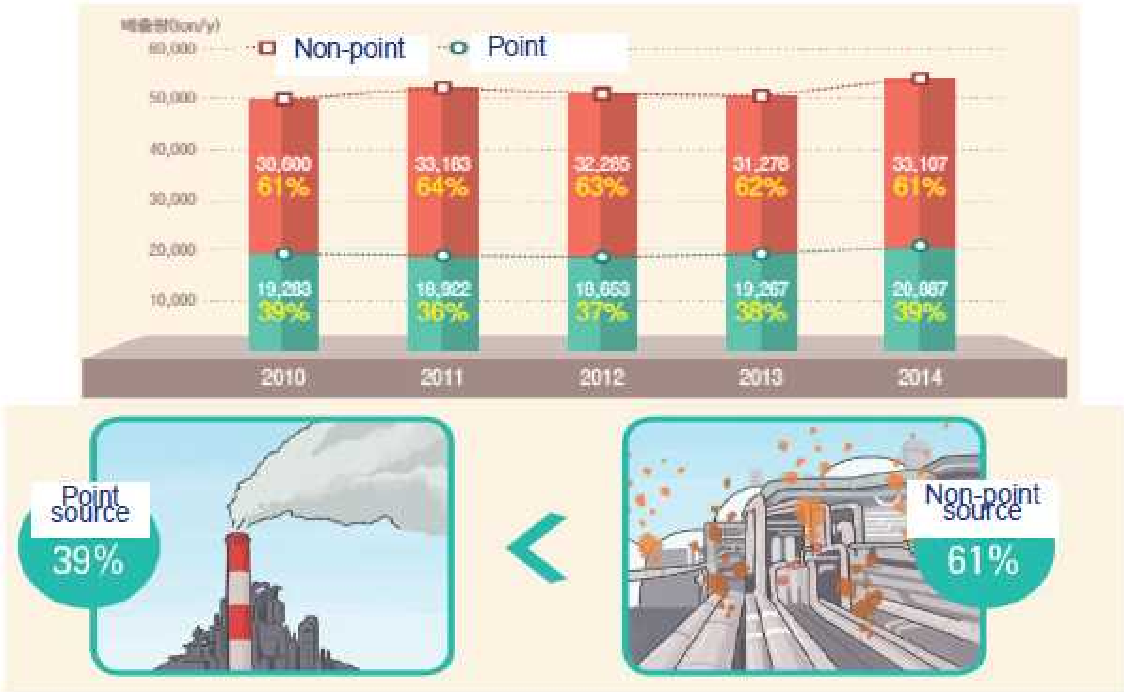
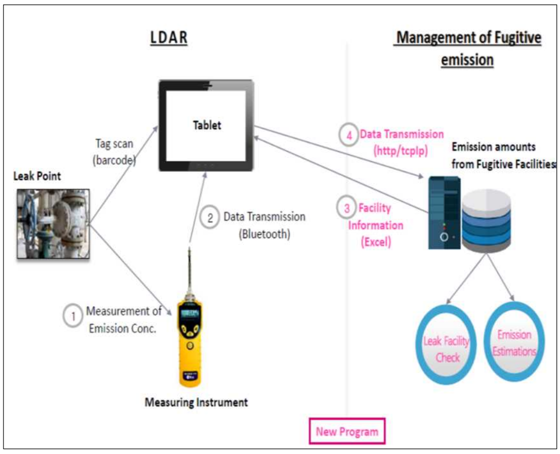


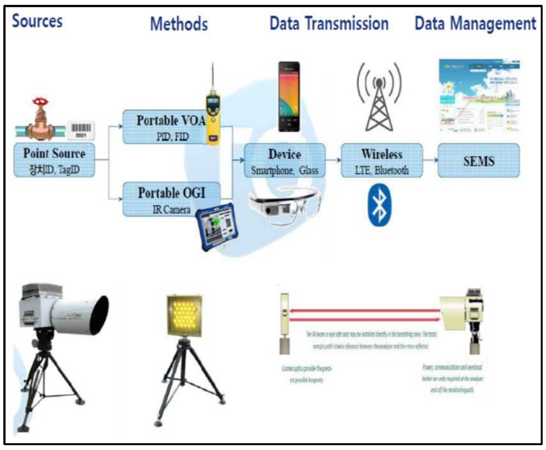
Figure 42. Annual Trend of VOCs Emissions between point sources and non-point sources

In Korea, many attempts have been made to introduce the fugitive emission reduction program since 2005. Since 2015, standards for facility management have been introduced in the petroleum refining industry to reduce fugitive emissions. Prior to this, the process facility was improperly managed or only the main facility was managed. However, the newly introduced fugitive emission reduction program required completely sealing off the pollution facility, strict management of all facilities, periodic inspection of the leak facility, and installation of double valves.

In future, the LDAR system—which is applied only to some petroleum refining facilities—is planned to be expanded and applied to all types of industries. Thus far, we have been manually measuring and managing the data at the workplace, but we will build the measurement data management system and link it with the VOCs emission inventory in the future.

In order to reduce the VOC emissions from fugitive emission sources, we plan to introduce the optical technique, such as portable OGI Camera and construct the data transmission and management system (Figure 43).





<Expanded application of LDAR system> <Introduction of optical techniques>

Figure 43. Policy direction on fugitive VOCs emission regulations

3-3. VOCs Emission Regulations in Japan

To help reduce air pollution, especially relating to Suspended Particulate Matter (SPM) and photochemical oxidants, the Air Pollution Control Law was revised in May 2004 to control VOC emissions from factories. By combining legal control of VOC emissions and voluntary actions by business operators, the revised law provided an effective solution for curbing VOC emissions since 2005 (Best Mix policy for VOC reduction, Figure 44). The regulated VOC emission processes are listed in Table 21.

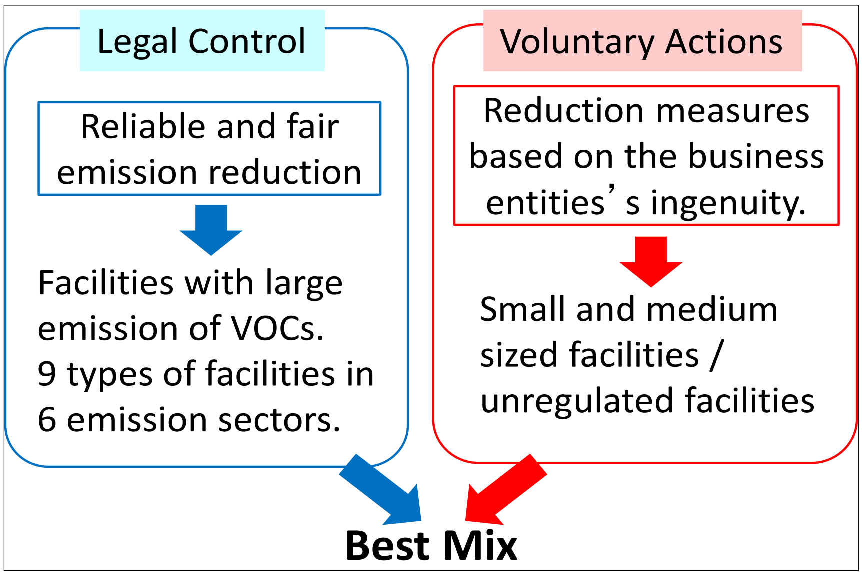


Figure 44. Best Mix policy for VOC reduction

Table 21. 9 VOC emission processes regulated by the law and their regulation values

Facility	Ventilation Capacity (m^3/hour), Area (m^2)[1] or Tank Volume (kL)	Emission Standard[2] (ppmC)	
Drying facilities for manufacture of chemical products	≥ 3,000 (m^3/hour)	600	
Painting facilities for spray coating	≥ 100,000 (m^3/hour)	Automobile mfg., existing	700
		Automobile mfg., new	400
		Others	700
Drying facilities for painting (other than spray coating and electrostatic painting)	≥ 10,000 (m^3/hour)	Wood products mfg.	1,000
		Others	600
Drying facilities for manufacture of adhesive bonding of copper-clad laminate for printed circuit board, adhesive tape or sheet, release coated paper or wrapping material	≥ 5,000 (m^3/hour)	1,400	
Drying facilities for adhesive bonding	≥ 15,000 (m^3/hour)	1,400	
Drying facilities using rotary offset printing	≥ 7,000 (m^3/hour)	400	
Drying facilities using gravure printing	≥ 27,000 (m^3/hour)	700	
VOC cleaning facilities	≥ 5 (m^2)	400	
VOC storage tanks[3]	≥1,000 (kL)	60,000	

Notes:
1. Area is the VOC accessible surface area exposed to the air.
2. Emission standards are calculated in cubic centimeters per cubic meter (parts per million by volume) and converted as carbon (i.e., ppmC). Sampling method is JIS K0095. Analysis is by JIS K0114 or JIS K0151, with correction for non-VOC compounds.
3. VOC storage tanks: volatile organic compounds (e.g., gasoline, crude oil, or naphtha) with a vapor pressure of more than 20 kPa at a temperature of 37.8°C (except enclosed type and floating roof type (including internal floating roof)).
4. Monitoring Frequency: Once a year

The initial goal of VOC reduction by the "Best Mix" was 30% reduction by 2010 compared to 2000. However, 45% reduction was achieved in 2010, dropping from 1,410,412 tons (2000) to 774,957 tons (2010). The reduction rate of VOC emissions through voluntary action plans was approximately 56% in 2010[1]. These measures are still being implemented, and VOC emissions in 2017 were 671,567 tons—a 52% reduction from emissions in 2000.

4. Mobile Emission Sources

4-1. Introduction

On-road vehicles are an important source of air pollutant emissions. In urban areas without large stationary pollutants, it can be most influential emission source. Therefore, it is important to develop or establish the "mobile source emission inventory."

An emission inventory is an accounting of the amount of pollutants discharged into the atmosphere. For mobile source, an emission inventory usually contains the total emissions for specific air pollutants, originating from various types of vehicles in a certain geographical area and within a specified time span, usually a specific year. An emission inventory is compiled for both scientific applications and for use in policy processes. By organizing data, inventories permit the individuation of pollution sources and their localization. By quantifying emissions, they permit the best feasible allocation of emitted pollutants to the originating sources, or vehicles, in this case. Air quality management and the necessity of imposing effective limits to pollutant emissions into the atmosphere require the availability of that kind of quantitative information of emissions.

This importance of emission inventory may explain why this "Korea-Japan Bilateral Cooperation on $PM_{2.5}$" has prepared a working group for emissions inventory. Japan and Korea have their own mobile source emissions inventories. Enhancing mutual understanding of each other's emissions inventory through collaborative research is one of the significant steps to achieve environmental policy improvement.

One common approach used for estimating emission inventories is the use of EFs and associated activities. This method is based on a linear relation between source activity and emissions that can be generally outlined, as Equation 6 displays.

---

[1] N. Matsumoto and A. Ogihara. "Voluntary approaches in VOC emission reduction policy in Japan - architecture and participation,"-In Paper submitted to Earth System Governance Tokyo Conference, January 28-31, 2013 (2013)
https://pub.iges.or.jp/pub_file-80/download

$$EM_{i,j} = EF_{i,j} \times Act_j \quad \text{(Equation 6)}$$

$EM_{i,j}$: Emission of the pollutant i that emitted source vehicle j (g/year)
$EF_{i,j}$: Emission factor for the pollutant i from vehicle j (g/km)
Act_j : Activity of vehicle j (km/year)

EFs represent emission characteristics of vehicles, and activities quantify vehicular operation from the emission-causing perspective. Both Japan and Korea use EFs that express emissions per unit distance driven (g/km) as a function of vehicle speed (km/h). This form is often used in other parts of the world and is an effective way to evaluate vehicle speed as an important variable affecting the emission of pollutants by vehicles.

EFs and activity levels will vary depending on various situations in each country. First, as the EFs express the pollutant emission characteristics of a vehicle, these are influenced by the regulations or standards for vehicle emissions. Japan and Korea have different emission regulations, emission limits, and implementing schedules. Therefore, the EFs of vehicle pollutants in Japan and Korea will reflect such differences in regulations.

The same is true for activity. For example, the number of registered vehicles classified by fuel type would be one of the most representative activities for vehicle emission inventory. Japan does not have a large number of passenger cars using diesel fuel, while Korea has many diesel passenger cars and light-duty vehicles. This difference in activity can significantly affect the contribution of individual EFs to total emission inventory.

Considering the differences in the circumstances of each country, it may not be beneficial for both countries to unconditionally implement the outcome of a collaborative research into existing emission inventory framework. The results of the joint research should be selectively applied to the current systems of the two countries under careful consideration.

Therefore, before describing the results of joint research on vehicle emission inventory, this chapter will compare vehicle emission managing system of both countries. This comparison may be too broad to describe briefly, so we have focused on two items that majorly affect the vehicle emissions inventory: vehicle emission standard and vehicle classification.

4-1-1. Vehicle emission standard

Vehicle emission standards are legal requirements governing air pollutants released from vehicles into the atmosphere. Vehicles must comply with their applicable emission standards. Both Japan and Korea are regulating the species and amounts of pollutants. The Japanese emission standard is based on the Air Pollution Control Act, and Korea's emission limit is based on the Air Quality Preservation Act.

For the objective of this chapter, the topic of emission standards could be separated into three subparts: (1) regulated pollutants, (2) limit value, and (3) test method.

Regulated pollutants in Japan and Korea are similar. In the case of gasoline passenger cars, both Japan and Korea regulate same pollutants: carbon monoxide (CO), hydrocarbon (HC)[2], nitrogen oxide (NOx), and particulate matter (PM). For light-duty diesel vehicles, however, Korea regulates the number of particles (PN) in addition to PM. Korea also regulates ammonia emission from heavy-duty vehicles.

The emission limit values vary widely. Japan has its own limit value. Recent regulations, as of 2018, require gasoline and liquefied petroleum gas (LPG) fueled passenger cars to meet 2.03, 0.16, 0.08, and 0.007 g/km for CO, NMHC, NOx, and PM, respectively. Regulations for diesel passenger cars are 2.03, 0.037, 0.23, and 0.007 g/km for CO, NMHC, NOx, and PM, respectively. The vehicle emission tests are conducted on a 48 in. (118 cm) chassis dynamometer over the driving cycles. A driving cycle is quantified based on second-by-second speed versus time. In the tests, vehicle emissions were measured while the test vehicle was operated on a chassis dynamometer according to each of selected driving cycles. The Japanese standard driving cycle is the cold state WLTC mode, aside from the extremely high-speed portion of the 2018 regulation.

In Korea, emission standards are separately specified for each fuel type. For gasoline and LPG vehicles, emission limits and driving cycles are similar to those of United States. There are four to six sets of emission limits, under Fleet Average System (FAS), which means the different vehicle models with the same model year can have different emission limits despite being categorized into same vehicle classification. Driving cycle is FTP-75 cycle. For diesel vehicles, emission standards of the European Union have been adopted for the Korean standard. Emission limits are similar to the European Euro Standard. The standard driving cycle is NEDC or WLTC.

As we have seen, vehicles in both Japan and Korea are subject to different emission limits and different driving cycles. Thus, the emission factors of two countries are not necessarily the same.

[2] Hydrocarbon is regulated as total hydrocarbon (THC), non-methane hydrocarbon (NMHC), or non-methane organic gas (NMOG), depending on the vehicle type, fuel type, etc. In the case of recent gasoline passenger cars, Korea regulates as NMOG. In Japan, hydrocarbons were regulated as THC before 2005, when the regulation changed to NMHC.

4-1-2 Vehicle classification

Regarding the regulation, “Passenger Car” mentioned in the section above might be defined differently in Japan and Korea. A vehicle category—"Passenger Car," for example—is based on the classification of vehicle specification, such as the displacement of the engine, number of passengers, weight of the vehicle, usage, and appearance.

Vehicle classification is particularly important for emission inventory calculation. Equation 6 implies that the EF and activity information have to be properly associated, which means that those two variables should be categorized under same definition. For example, the number of small-sized gasoline passenger cars, which meets the Post New Long Term regulations, must be multiplied by the EF of that specific vehicle category.

This classification standard (definition) is not necessarily the same for both Japan and Korea. The detailed discussion of this topic may be too broad for the purpose of this report. However, some examples are given for a clear comparison.

Example 1: Small-Sized Passenger Car

Item	Japan	Korea
Category name	Small-sized passenger car and Passenger car	Small-sized passenger car
Description	Carriage of passengers	Carriage of passengers
Number of passengers	Up to 10 persons	Up to 8 persons
Vehicle mass limit	No more than 3.5 ton gross vehicle weight (GVW)	No more than 3.5 ton gross vehicle weight (GVW)
Engine size limit	No less than 660 cc engine displacement	No less than 1,000 cc engine displacement
Remarks	Same emission regulation	

Example 2: Light-Duty Truck

Item	Japan	Korea
Category name	Truck and bus, Light-duty vehicles	Light-duty freight vehicle
Description	Carriage of goods	Carriage of goods
Number of passengers	n/a	n/a
Vehicle mass limit	No more than 1.7 ton gross vehicle weight (GVW)	No more than 2 ton gross vehicle weight (GVW)
Engine size limit	n/a	No less than 1,000 cc engine displacement
Remarks		

4-2. Vehicle Emission Inventory Estimation System of Japan and Korea

As we have seen in the previous chapter, both countries' vehicle emission managing systems influence the two key elements of emission estimates: EFs and activity. Despite this inherent difference, there are many interesting aspects in each country's emission inventory framework that can be set as benchmark examples for the other country. Researchers in both countries have gained a better understanding of each other's emission estimating systems over the period of the collaborative research and have gained valuable insights for further improvement of emissions estimating systems. In this chapter, we briefly describe the Japanese and Korean mobile emission inventory calculation system. Key subparts are the EF and activity. Activity is addressed separately for the topics of the number of vehicles and traffic volume.

4-2-1. Emission factors

An EF is a representative emission quantity associated with vehicle activity. Japan and Korea use a speed-dependent type function for EF. The EF implies that the representative emissions from a given vehicle are estimated by vehicle speed, as illustrated in Figure 45. The Japanese EF has a fixed function form (polynomial). In Japan, the Ministry of the Environment of Japan determines the EFs coefficient of average travelling speed by vehicle type and regulation. These EFs are based on the results from chassis dynamometer tests of actual driving cycles, performed by different research institutes in Japan. To note, the actual driving cycles vary depending on the research institutes. Concerning the EFs, they are available by vehicle type but are not as detailed as the vehicle type subcategories shown in Figure 46. For instance, trucks and buses have common EFs, because their regulations are the same. An overview of the EFs is shown in Figure 47.

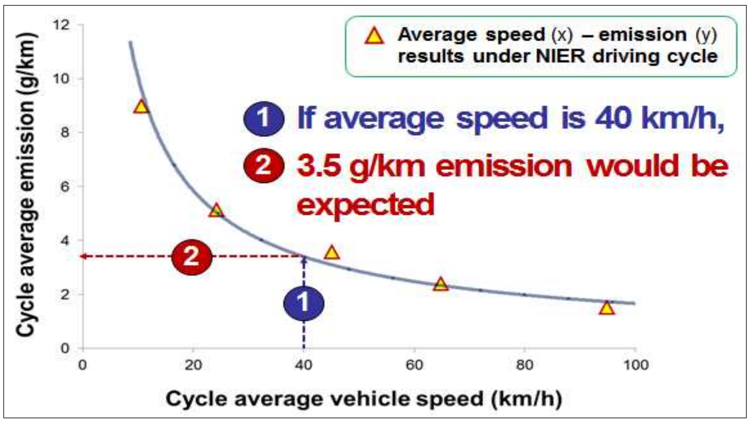
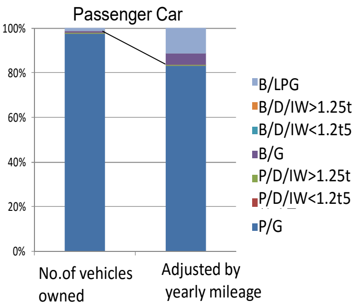


Figure 45. Illustration of the nature of Korean vehicle emission factor

No.		Vehicle Type	Usage	Fuel Type	Weght Class	No. of vehicles owned (2010)
1	1	Light Passenger Car	Private	G	–	17,482,451
2			Buisiness	G	–	12,377
3	2	Passenger Car	Private	G	–	39,099,930
4				D	IW≦1.25t	64,869
5					IW＞1.25t	988,354
6			Buisiness	G	–	29,908
7				D	IW≦1.25t	109
8					IW＞1.25t	6,342
9				LPG	–	229,064
10	3	Bus	Private	G	1.7t＜GVW≦2.5t	183
11					2.5t＜GVW≦3.5t	5,173
12					3.5t＜GVW	2,839
13				D	1.7t＜GVW≦2.5t	159
14					2.5t＜GVW≦3.5t	11,543
15					3.5t＜GVW≦5.0t	32,059
16					5.0t＜GVW≦8.0t	51,959
17					8.0t＜GVW≦12t	10,746
18					12t＜GVW	5,743
19			Buisiness	G	1.7t＜GVW≦2.5t	10
20					2.5t＜GVW≦3.5t	303
21					3.5t＜GVW	1,154
22				D	1.7t＜GVW≦2.5t	2
23					2.5t＜GVW≦3.5t	932
24					3.5t＜GVW≦5.0t	1,796
25					5.0t＜GVW≦8.0t	16,920
26					8.0t＜GVW≦12t	21,433
27					12t＜GVW	65,324
28	4	Light Truck	Private	G	–	8,849,122
29			Buisiness	G	–	321,561
30	5	Small Truck	Private	G	GVW≦1.7t	742,543
31					1.7t＜GVW≦2.5t	661,320
32					2.5t＜GVW≦3.5t	439,134
33					3.5t＜GVW	5,515
34				D	GVW≦1.7t	60,161
35					1.7t＜GVW≦2.5t	281,843
36					2.5t＜GVW≦3.5t	850,984
37					3.5t＜GVW≦5.0t	676,136
38					5.0t＜GVW	112,786
39			Buisiness	G	GVW≦1.7t	5,235
40					1.7t＜GVW≦2.5t	5,527
41					2.5t＜GVW≦3.5t	7,084
42					3.5t＜GVW	413
43				D	GVW≦1.7t	716
44					1.7t＜GVW≦2.5t	3,150
45					2.5t＜GVW≦3.5t	19,304
46					3.5t＜GVW≦5.0t	28,272
47					5.0t＜GVW	6,731
48	7	Truck	Private	G	GVW≦1.7t	2,849
49					1.7t＜GVW≦2.5t	28,890
50					2.5t＜GVW≦3.5t	77,197
51					3.5t＜GVW	19,083
52				D	GVW≦2.5t	14,511
53					2.5t＜GVW≦3.5t	125,887
54					3.5t＜GVW≦5.0t	183,660
55					5.0t＜GVW≦8.0t	838,205
56					8.0t＜GVW≦12t	11,062
57					12t＜GVW≦25t	133,933
58					25t＜GVW	4,892
59			Buisiness	G	GVW≦1.7t	4
60					1.7t＜GVW≦2.5t	70
61					2.5t＜GVW≦3.5t	3,762
62					3.5t＜GVW	20,108
63				D	GVW≦2.5t	93
64					2.5t＜GVW≦3.5t	3,222
65					3.5t＜GVW≦5.0t	63,791
66					5.0t＜GVW≦8.0t	360,008
67					8.0t＜GVW≦12t	9,487
68					12t＜GVW≦25t	318,786
69					25t＜GVW	84,067
70	8	Special Purpose Vehicle	Private	G	–	149,027
71					GVW≦1.7t	7,148
72					1.7t＜GVW≦2.5t	38,911
73					2.5t＜GVW≦3.5t	106,463
74					3.5t＜GVW	10,323
75				D	–	24,543
76					GVW≦1.7t	4,479
77					1.7t＜GVW≦2.5t	15,499
78					2.5t＜GVW≦3.5t	102,555
79					3.5t＜GVW≦5.0t	91,118
80					5.0t＜GVW≦8.0t	286,917
81					8.0t＜GVW≦12t	17,886
82					12t＜GVW	57,803
83			Buisiness	G	–	11,648
84					GVW≦1.7t	681
85					1.7t＜GVW≦2.5t	3,076
86					2.5t＜GVW≦3.5t	4,040
87					3.5t＜GVW	4,430
88				D	–	348
89					GVW≦1.7t	19
90					1.7t＜GVW≦2.5t	591
91					2.5t＜GVW≦3.5t	5,273
92					3.5t＜GVW≦5.0t	9,379
93					5.0t＜GVW≦8.0t	122,641
94					8.0t＜GVW≦12t	4,353
95					12t＜GVW	109,115
96	9	Motorcycle	Private	G	Less than 50cc, 2st	3,511,593
97					Less than 50cc, 4st	4,019,079
98					Less than 125cc, 2st	423,593
99					Less than 125cc, 4st	1,087,847
100					Less than 250cc, 2st	359,859
101					Less than 250cc, 4st	1,633,080
102					Over 250cc, 2st	0
103					Over 250cc, 4st	1,524,176

Note: Weight Class — Emission factor contains vehicle weight



Traffic volume of each vehicle type is devided in detail categoly by the ratio of number of vehicle owned, which adjusted by yearly mileage.

Figure 46. Vehicle Categories Considered in JEI-VEM, Vehicle Emission Estimation Program

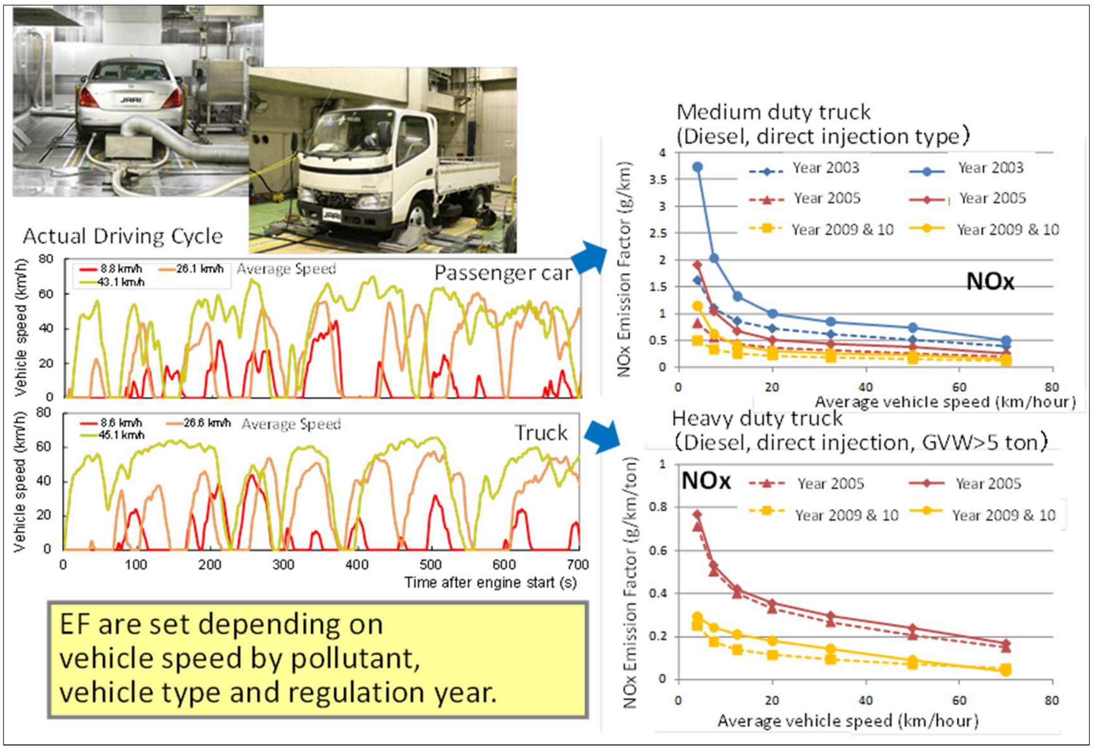


Figure 47. Emission Factors of On-Road Vehicles by Ministry of the Environment (The actual driving cycle test modes from C/D tests means JARI modes)

The EF estimating method in Korea is similar to that in Japan. One key difference is the driving cycle. Korea uses the NIER suite, which is a set of 15 sub-cycles that have been used as the Korean standard for EF development since 2001 (NIER, 2001). Each of the sub-cycles has a different cycle-average vehicle speed. In Korea, the functional relationship between the emission result (g/km) and the average vehicle speed (km/h) of the NIER cycles—for example, a least-squared regression curve–is suggested as the EF of a given vehicle category. The form of the EF function is not fixed as a polynomial type. The exponential type function is often combined with the polynomial type. In practice, Korea tested seven to nine sub-cycles to build an EF instead of testing the whole package from the NIER suite. Korea also used type-approval test results measured under the WLTP or FTP-75, depending on the availability of measurement data.

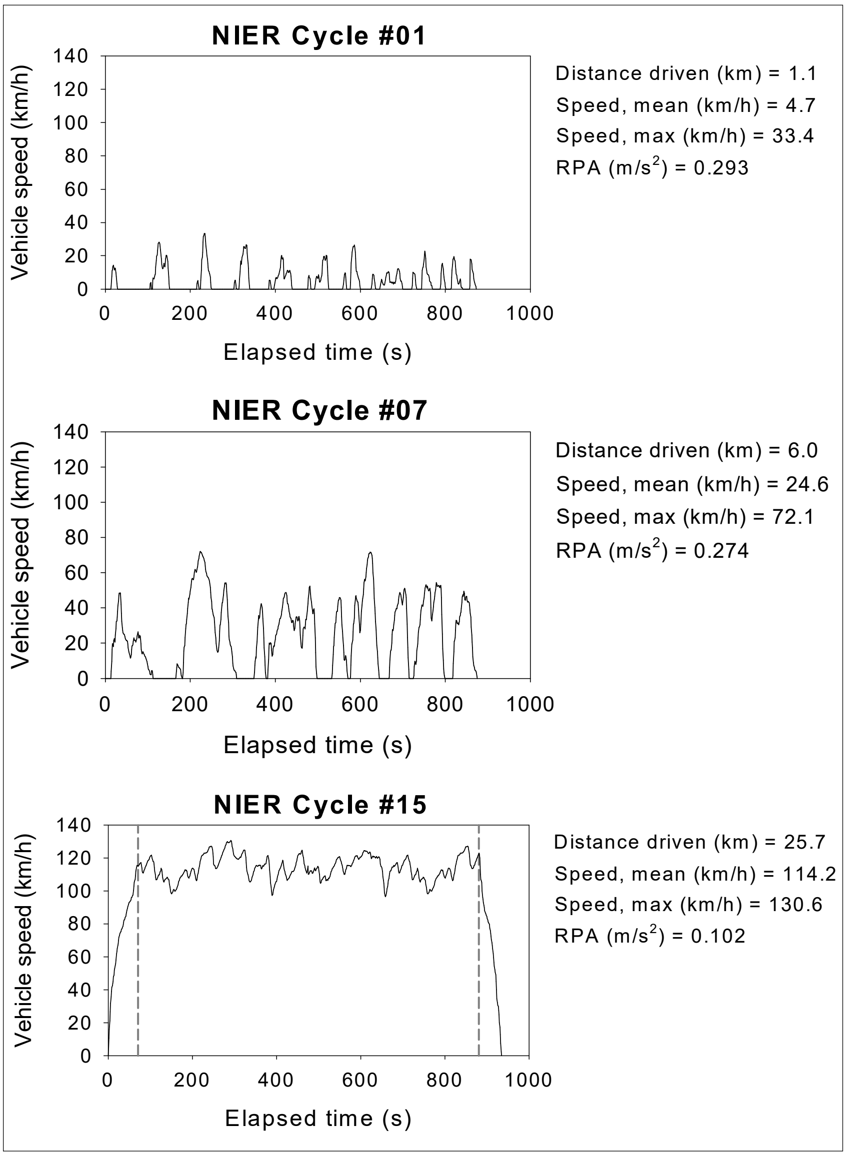


Figure 48. Speed profiles and selected characteristics for NIER driving cycle (3 selected examples)

In recognition—and quantitative consideration—of the difference between the two countries, we have examined the effects of driving cycle acceleration levels through introducing Relative Positive Acceleration, RPA (m/s^2). The RPA can be interpreted as the specific acceleration of the trip (Demuynck et al., 2012) and is often used as a factor to compare different test cycles or trips (Barlow et al., 2009; Lee et al, 2013). It is calculated as the integral of the product of instantaneous speed and positive acceleration over the time spent on each trip, as shown in Equation 7 below.

$$RPA_j = \frac{1}{x_j}\int_0^{t_j}\left(v_{i,j} \times a_{i,j}^{+}\right) dt \qquad \text{(Equation 7)}$$

RPA_j : relative positive acceleration of averaging window j (m/s^2)

x_j : travel distance of averaging window j (m)

t_j : time duration of averaging window j (s)

$v_{i,j}$: instantaneous speed at time i in averaging window j (m/s)

$a^{+}_{i,j}$: instantaneous positive acceleration at time i in averaging window j (m/s^2)

We have compared the average speed and RPA of selected driving cycle (Figure 49). Korean NIER 7 has a higher RPA than the Japanese JC08 (test mode of emission regulation until September 2018) and PN03 (an actual driving cycle test mode of the Public Works Research Institute, Japan), although average speeds of the three cycles are similar.

In this way, it has been confirmed that each driving mode to create EFs has its own characteristics. Emissions are expected to increase as RPA increases. Therefore, it was considered necessary to check not only the average vehicle speed of the driving test cycle but also the RPA value to compare the EFs obtained in different driving test cycles.

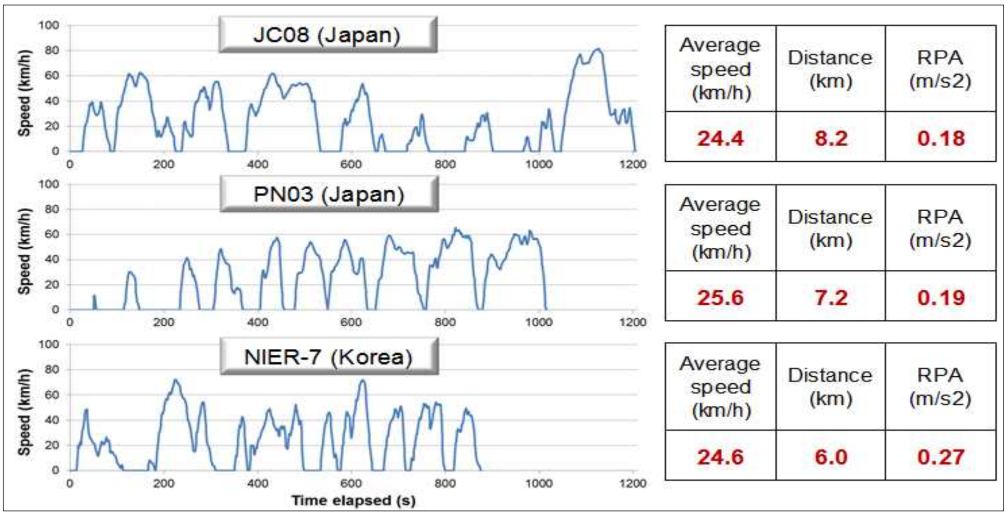


Figure 49. Average speed and RPA of Japanese JC08, PN03, and Korean NIER 7 driving cycle

Most of the above discussion is for the EF for fully warmed-up, new vehicles in running condition. In an actual situation, however, pollutants can be emitted through different processes. Cold start emissions from vehicles differ from the aforementioned example; evaporative emission is another mechanism. Table 22 shows the pollutants and emission process by fuel type. The Japanese and Korean inventories have their own procedures to incorporate these phenomena. Researchers from both countries have thoroughly discussed this practical research task and found that the schemes have different conceptual models. For example, the Japanese model uses "the number of engine starts and soaking time" as primary variables for cold start emissions, while the Korean model uses "the representative driving distance after engine start."

Table 22. The pollutants and emission process of gasoline and diesel vehicle inventories

Japan		CO	NOx	Hydro-carbon	PM	NH_3	SO_2	CO_2
Tailpipe emission	Running emission	G/D	G/D	G/D	G/D	G	G/D	G/D
	Start emission	G/D	G/D	G/D	G/D	G	G/D	G/D
Evaporative emission	Running loss			G				
	Diurnal breathing loss			G				
	Hot soak loss			G				

Korea		CO	NOx	Hydro carbon	PM	NH_3	SO_2	CO_2
Tail pipe emission	Running emission	G/D	G/D	G/D	G/D	G/D	G/D	n/a
	Cold running emission	G/D	G/D	G/D	D	n/a	G/D	n/a
Evaporative emission	Running loss							
	Diurnal breathing loss			G				n/a
	Hot soak loss							

Consideration and development of correction coefficients are another important aspect of EF. The correction coefficients have been adopted to produce estimated emission volumes realistic to those of actually running vehicles. They correct the estimated values according to air temperature, humidity, deterioration from travel distance, and deterioration of DPF. All these correction coefficients need updating according to the changes in circumstances. One common interest has been found on remote sensing device (RSD). RSD measurement has been contributing to the Japanese deterioration factor development. Korea has used RSD for its roadside emission surveillance program. Utilizing RSD on the emission inventory perspective is a possible corporation topic in the future.

4-2-2. Vehicle registration status

The number of vehicles is an important element for vehicle emission calculations. The number of registered cars in Japan is 78,267,177 (as of July 2018)[3], and the number of cars in Korea is 22,943,994 (as of July 2018). The important classification criteria regarding emissions would be vehicle age and fuel type. Recent years are expected to show lower pollutant emissions, because they are subject to stronger emission limits. Since the type of combustion of the internal combustion engine largely varies depending on the fuel used, there may be a difference for emissions caused by this difference.

3 Excluding motorcycles, trailer, large special vehicles (construction machines).

Table 23. The number of registered vehicles in Japan and Korea by vehicle age

	0-5 years	6-10 years	11+ years	Total
Japan (as of March 2018, excluding light passenger cars & trucks)	16,600,093 (35.4%)	12,698,264 (27.1%)	17,566,560 (37.5%)	46,864,917
Korea (as of March 2018)	8,641,178 (38.1%)	6,738,598 (29.7%)	7,314,026 (32.2%)	22,693,802

Note: 1. Data is for March 2018, for both countries

Table 24. The number of registered vehicles in Japan and Korea by vehicle fuel type

	Gasoline	Diesel	LPG	Others	Total
Japan (as of March 2018)	63,378,029	6,051,055	197,697	7,794,972	77,421,753
Korea (as of July 2018)	10,528,521	9,802,385	2,066,241	546,847	22,943,994

Note: 1. Data is for March 2018 for Japan and July 2018 for Korea

2. "Others" includes CNG, Hybrid, Electric, Fuel Cell, etc.

4-2-3. Vehicle traffic volume

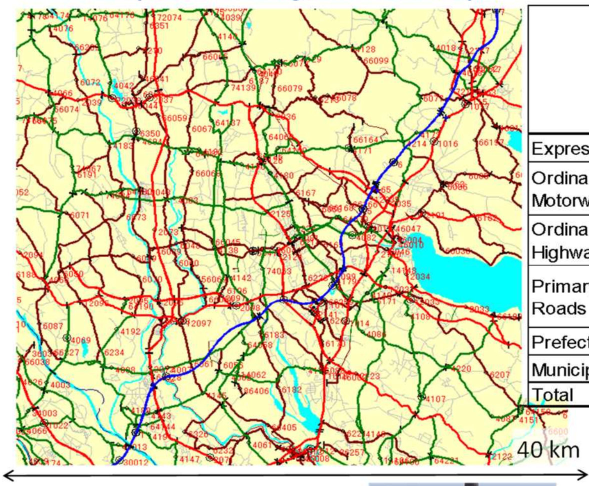
(1) In Japan, the total vehicle traffic volumes are available by month from the statistical survey on vehicle fuel consumption of the Ministry of Land, Infrastructure, Transport and Tourism. It includes national data, as well as data from nine regions: Hokkaido, Tohoku, Kanto, Hokuriku Shinetsu, Chubu, Kinki, Chugoku, Shikoku, and Kyushu. Regional data excludes certain vehicle types in which only the national data are available.

(2) For the main roads, the Ministry of Land, Infrastructure, Transport and Tourism conducts the road traffic census every five years (Figure 50). This census surveys road traffic volume at a unit distance between 2 and 10 km, by vehicle, for 12 to 24 hours. The Japanese emission inventory uses these census data to consider road traffic volumes at unit distance by hour of the day and vehicle type (Figure 51).

(3) As for narrow streets, the Japanese emission inventory defines its emission as the difference between the national totals available from the vehicle fuel consumption survey and emissions from

main roads available from the road traffic census. The vehicle speed on the narrow streets is fixed at 20 km/h, uniformly. The narrow streets' traffic volumes by hour of the day are referenced to the narrowest main road of the road traffic census. Until 2005, the road traffic census published the data by weekday and holiday. The Japanese emission inventory, therefore, reflects the weekday/holiday ratio of 2005 in its activity rates.

Example of investigative road map



Investigative road and length

	Total Investigated Length (km)	Number of Investigated Sections	Average Investigated Distance (Average Link) (km)
Express Ways	6457	787	8.2
Ordinary National Motorways	604	118	5.1
Ordinary National Highways	53669	9,469	5.7
Primary Prefectural Roads	57340	9,831	5.8
Prefectural Road	69964	14,902	4.7
Municipal Roads	698	331	2.1
Total	188731	35438	5.3

Survey Items

For weekday, 24hrs or 12hrs
- ✓ Traffic volume by vehicle type
- ✓ Traffic congestion

With average vehicle speed at rush hours and non-rush hours, each 1hr average vehicle speed is calculated.

Figure 50. Traffic Volume Surveys Road Traffic Census by Ministry of Land, Infrastructure and Transport (MLIT) since 1928

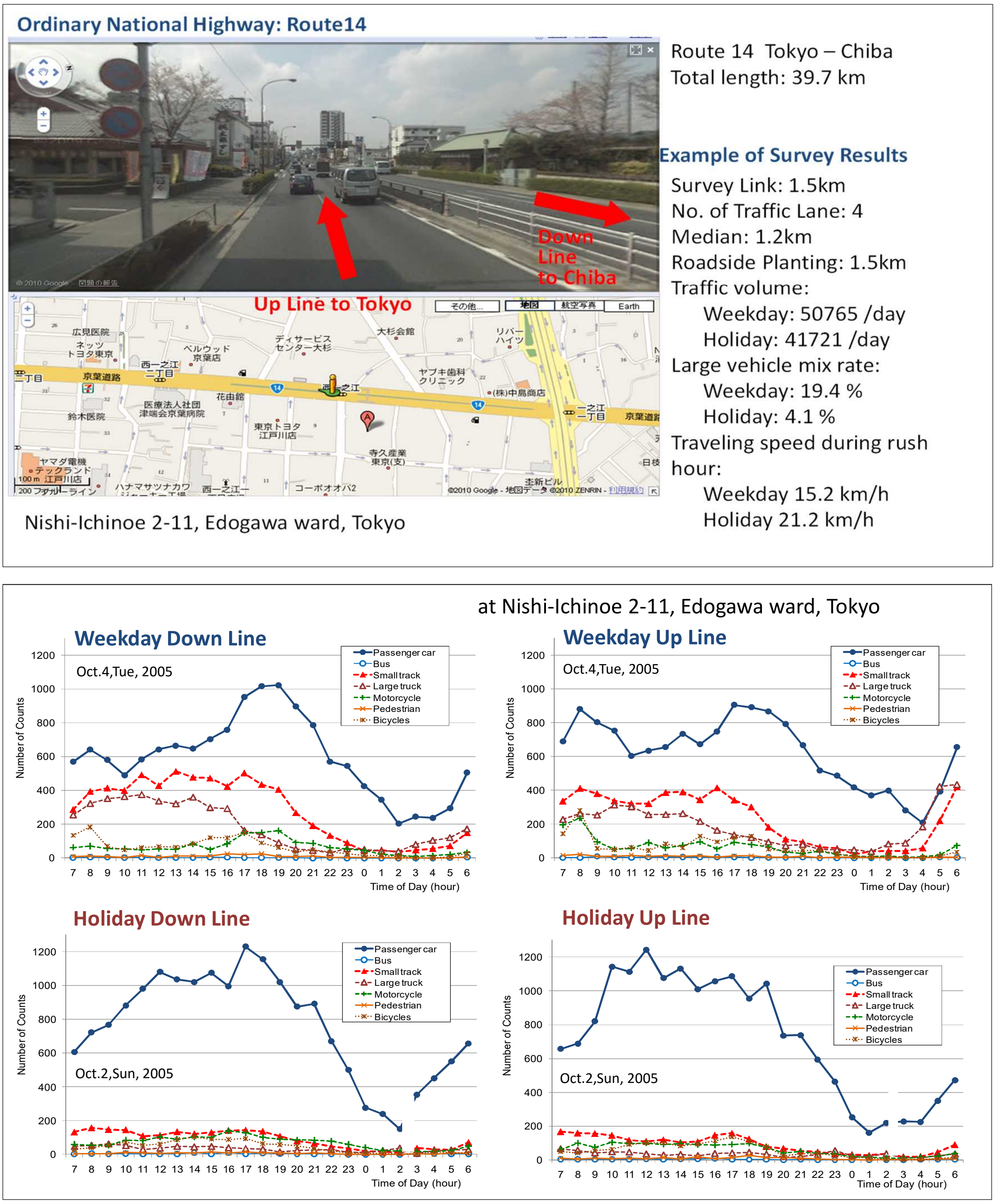


Figure 51. Example of 24-hour Traffic Volume Survey

In Korea, nationwide traffic volume is estimated based on the vehicle kilometer travel, or VKT (km/vehicle), information. VKT data is gathered from a vehicle inspection program. Around 9 million valid samples have been selected from the inspection record of the previous year by the refinement process, such as removing missing data. The data represents more than 40% of all registered vehicles in Korea. To calculate VKT, the daily average vehicle-kilometer from the previous vehicle inspection until the last inspection is calculated. In 2015, the average daily VKT was 39.8 (km/day-vehicle).

Average VKT of each vehicle category can be obtained. The nationwide annual VKT is obtained as shown in Equation 8 below.

$$VKT = \sum_{i=1}^{n}(N_i \times VKT_i \times 365) \qquad \text{(Equation 8)}$$

VKT : annual nationwide vehicle kilometer travel (km/year)
VKT_i : daily vehicle kilometer travel for vehicle category i (km/day-vehicle)
N_i : the number of registered vehicles in vehicle category i (-)
n : the number of vehicle category (-)

Then, the total VKT should be distributed spatially. Korea uses two concept of VKT. One is theoretical VKT, which is expressed by Equation 9, shown below. Nationwide VKT in Equation 8 is an example of theoretical VKT. The other is observed VKT, which is measured by various traffic volume measuring systems.

$$VKT_{i,j} = \sum_{i=1}^{n}\left(N_{i,j} \times VKT_i \times 365\right) \qquad \text{(Equation 9)}$$

$VKT_{i,j}$: theoretically calculated annual vehicle kilometer travel for vehicle category i in region j (km/year)
VKT_i : daily vehicle kilometer travel for vehicle category i (km/day-vehicle)
$N_{i,j}$: number of registered vehicles in vehicle category i in region j (-)
n : number of vehicle category (-)

For nationwide data, theoretical VKT is always greater than the observed VKT. However, for some administrative districts with numerous traffic measurement points, the observed VKT may be greater than the theoretical VKT in that area. In this case, the actual measured traffic volume is used as that area's traffic volume.

4-2-4. Comparison of mobile emission inventory

The estimation results of vehicle emissions and the total emissions of the country are shown in Table 25, for both Japan and Korea.

Table 25. Air pollutant emissions from vehicles in 2015 in Japan and Korea

Japan

	Total (t/y)	On-road mobile (t/y)	Ratio (%)
$PM_{2.5}$	63,592	10,799	17.0
NOx	1,199,871	417,536	34.8
CO	3,011,594	1,208,142	40.1
VOC	906,843	126,666	14.0
NH_3	353,050	15,744	4.5
SOx	345,955	917	0.3

NOTE: 1. The total excludes natural sources (biogenic VOCs, soil, and volcanos).
2. "On-road mobile" does not include road dust (including brake dust) no tire wear.
3. VOC of "On-road mobile" includes evaporative emission from gasoline vehicles.
4. The total excludes ship emissions in the Japanese port and on major Japanese domestic routes.

Korea

	Total (t/y)	On-road mobile (t/y)	Ratio (%)
PM	98,806	8,817	8.9
NOx	1,157,728	369,585	31.9
CO	792,776	245,516	31.0
VOC	1,010,771	46,145	4.6
NH_3	267,167	10,078	3.4
SOx	352,292	209	0.1

NOTE: 1. The total excludes natural sources (biogenic VOCs, soil, and volcanos).
2. "On-road mobile" does not include road dust (including brake dust) or tire wear.
3. VOC of "On-road mobile" includes evaporative emission from gasoline vehicles.

4-3. Estimation of PM Emission Factor of Gasoline Cars

The emissions estimating systems of the two countries already have a robust system. The knowledge exchange allows us to draw implications to improve our own inventories. At the same time, there is a practical limit to incorporating the results of this collaborative research into the existing system.

Based on this recognition of the reality and understanding of the above-mentioned conditions of vehicle emission management in the two countries, the joint research theme, "Estimate emission factor of gasoline car PM," was selected. This topic is consistent with the study's intent in dealing with $PM_{2.5}$, which is a major concern of this joint research. On the regulation perspective, gasoline PM is a relatively new pollutant for both countries. Thus, the difference in legal regulation systems, mentioned in Chapter 3-1, may not have a strong effect the gasoline PM cooperation. Finally, Korea had not prepared gasoline PM EFs at that time. Meanwhile, in Japan, the PM emission measurement from gasoline vehicles began in 2014. Therefore, the outcome of the collaboration could be mutually beneficial.

4-3-1. PM emission factor for gasoline direct injection (GDI) vehicles

At the sixth meeting, Korea had emission results of 11 individual vehicles over CVS-75 mode (driving cycle), which is the driving cycle identical to U.S. EPA's FTP-75, and another set of measurement data over speed-dependent driving cycle suite (NIER set) for five vehicles. The average GDI PM of 11 vehicles over CVS-75 is 1.2 mg/km. Japan provided Japanese speed-dependent GDI PM results for two vehicles. Considering GDI PM is a relatively new pollutant, there were not sufficient experiences on the speed-dependent characteristics of GDI PM. Thus, it is difficult to derive a regression function using these results; therefore, Korean researchers introduced the European JRC's proposal as a reference, which shows emissions of 1 mg/km in the vehicle speed range below 85 km/h.

Since the sixth meeting, Korea has been supplementing this content in two respects. The first is for high-emission vehicles in the high-speed range. These findings were confirmed—in both Korean and Japanese results—and it was necessary to judge to what extent this phenomenon should be reflected in the EFs (Figure 52). Korea tested three cars over the US03 cycle, which is a high-power driving pattern used in the United States, and compared the emissions under normal driving conditions using CVS-75 mode (Figure 53). The comparison confirmed that two of the three vehicles had a large amount of emissions under a high load condition, while the other had a higher amount of emissions under normal conditions. This reveals a characteristic of increasing the emission under high load conditions. However, it also implies that there are possibilities of different behaviors depending on the emission control technique, or other factors, for each vehicle.

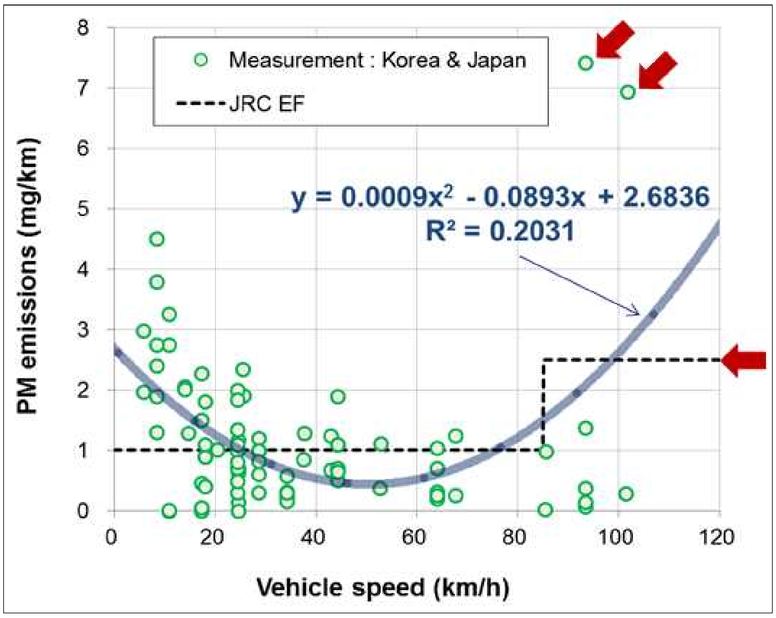


Figure 52. PM emissions for gasoline direct injection (GDI) vehicles

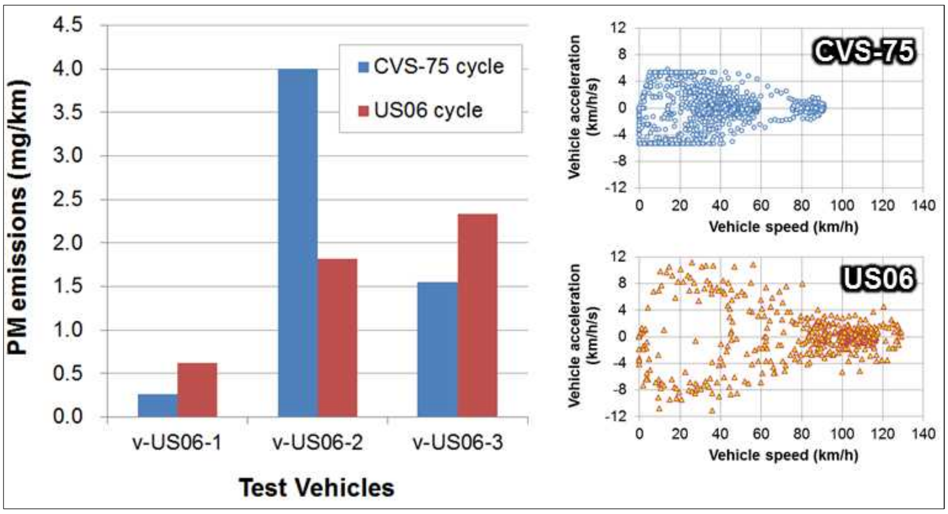


Figure 53. GDI PM emissions over normal driving cycle (CVS-75) and higher load driving cycle (US06)

Korea has also learned how to use Japanese measurement results for its own emission factor development. The Japanese colleagues shared additional results of 12 GDI vehicles since Meeting 6, allowing us to further analyze the results of six vehicles that could be identified based on their year of production, or vehicle model year. Additional results are valuable for recognizing emission characteristics in the medium to low speed range of less than 50 km/h—an important indicator of speed-emission trends of the EF. However, strictly speaking, the results provided by Japanese colleagues are obtained from Japanese driving patterns that differ from the Korean NIER cycle suite for Korean EF development. After Meeting 6, we attempted to calibrate or adjust each country's measurement values, using any possible explanatory variable, to convert the Japanese results into driving conditions comparable to the Korean measurement, or vice versa. The selected key variable is the RPA of the driving cycle, described in Chapter 3-1. In this attempt, however, we could not find a consistent dependency of GDI PM emissions on RPA of test cycles. Thus, we decided to use the Japanese result for supporting the speed-emission trends qualitative approach, without any quantified value correction for adjusting cycle differences.

Korea considered several aspects to use the measurement results as national official EFs. An important consideration was the type of EF function. The variation of GDI PM measurement results was relatively large in low-speed driving condition, and high emission characteristics of GDI PM were confirmed in high-speed driving conditions. Since Korea had not previously had GDI PM EFs, there was not much accumulation of experience in form of function by vehicle speed. Another factor is that the technology and emissions characteristics are relatively large in that GDI PM related technologies are still in development and the emission allowance standards are also steadily increasing. Considering these various factors, the emission coefficient of the staircase function type, which assigns a constant number of emission factors of the medium- to low- speed vehicle range and the high-speed vehicle range, was adopted instead of the conventional function type.

Korea decided to use this EF as the official national EF, and it was proposed and approved by the "Emission and Emission Factor Control Committee." The type of step function is somewhat disadvantageous to reflect the characteristics of vehicle speed, but it can be regarded as a stable approach, considering it is the first emission coefficient.

4-3-2. Emission characteristics for GDI PM under Hot/Cold start condition

This is a research topic proposed by the Japanese colleagues at the sixth meeting. Normally, vehicle emissions are affected by a vehicle's condition at the starting point of a driving cycle. There are two conditions: cold start and hot start. In a cold start, a vehicle is soaked under a specified temperature condition for some time without engine firing. “Hot start” means a warmed-up vehicle start. Previously discussed EFs are all hot start, unless specifically mentioned. Among Japanese provided data, we have found hot/cold-start emission results for six vehicles (model year identified vehicle) on the JC08 cycle. Korea measured hot/cold-start emission results for three vehicles. We have selected a driving cycle (NIER-7) of average speed 24.6 km/h, which has similar average speed of JC08 (24.4 km/h) (Figure 54).

Overall, cold was higher than the hot results but did not always show the same trend. Korea accounts for cold-start emission characteristics when estimating emissions inventory, together with typical warming-up required time and the number of vehicle starts per day. The suggested cold/hot condition GDI PM emission ratio is 2.4, based on the results of this measurement set (Figure 55).

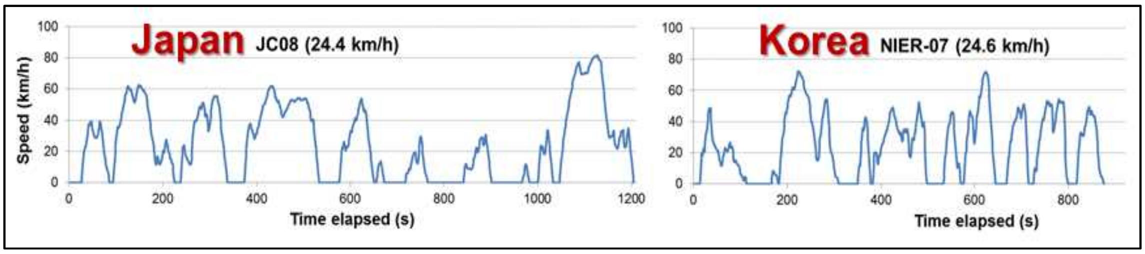


Figure 54. Test driving cycles for GDI PM emissions under Cold- and Hot-start conditions in Japan (Japanese JC08, average speed 24.4 km/h) and Korea (Korean NIER-7, average speed 24.6 km/h).

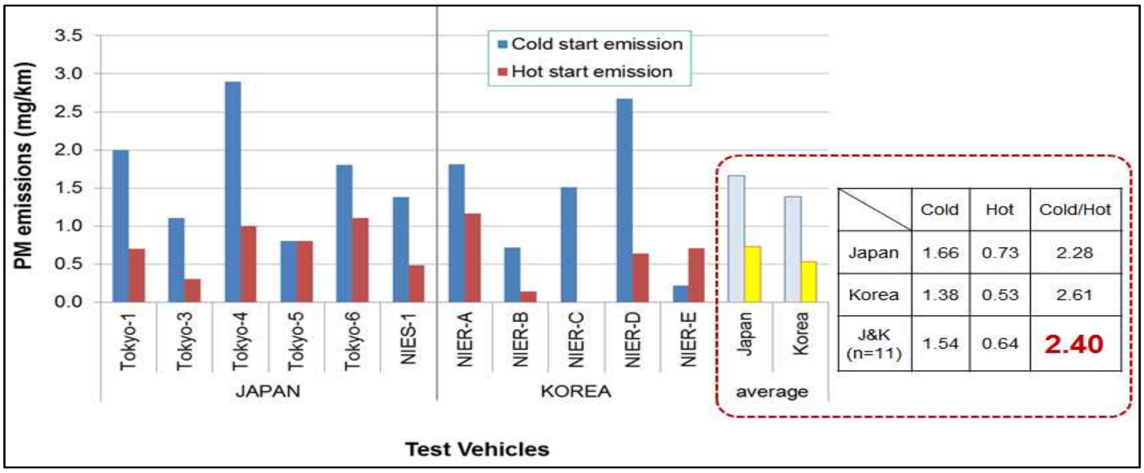


Figure 55. GDI PM emissions under Cold- and Hot-start conditions. Japanese test cycle is JC08 and Korean is NIER-7.

4-3-3. PM emission factor for multi-point injection (MPI) vehicles

Based on GDI PM experience data sharing and EF development experience, data sharing has been extended to PMI data of intake manifold multi-point injection (MPI) method. The MPI PM emission factor developed through this study was 30% lower than the GDI PM coefficient, and the form of the EF function adopted a step function similar to the GDI PM coefficient.

By studying the PM emission characteristics of gasoline cars (GDI and MPI technology vehicles), we obtained various practical benefits. By sharing data, a meaningful database can be constructed with minimal temporal and cost burden. This efficiency of the joint research has been especially important for Korea, because it has a relatively large amount of research capacity in solving light vehicle problems, such as "excessive emission of NOx during the actual road driving of small and medium sized light rail vehicles." It was possible to successfully develop the GDI PM emission factor even in a situation with a lack of test results on GDI gasoline vehicles in Korea.

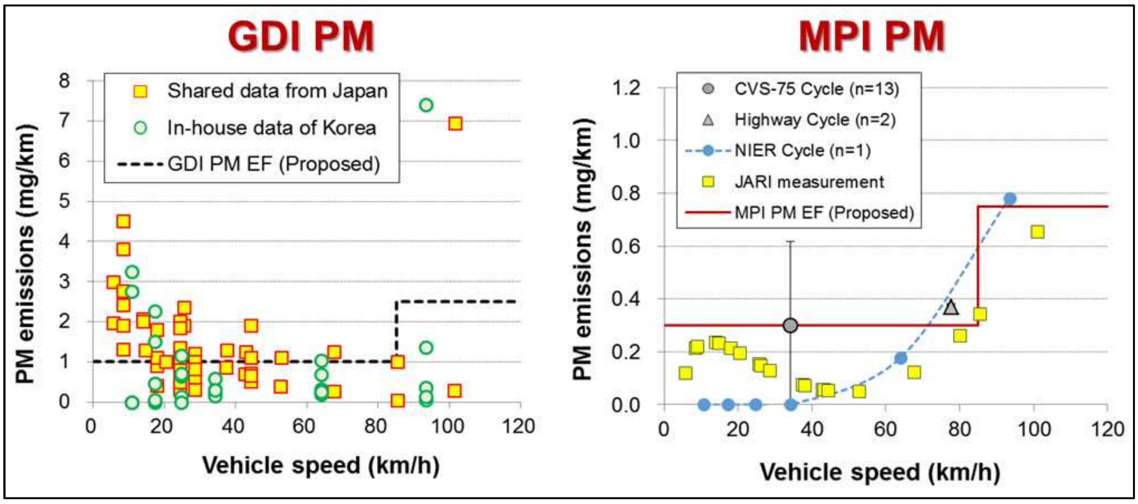


Figure 56. PM emission characteristics of gasoline cars (GDI and MPI technology vehicles)

5. Outline of National Air Emissions

5-1. National Air Emissions in Korea

Table 26 summarizes the 2015 national air pollutant emissions regarding SCC1 sectors, and Figure 57 shows the sectoral contribution of emissions for the six air pollutants of CO, NOx, SOx, $PM_{10,}$ VOCs. and NH_3

In 2015, CO emissions in Korea totaled 560 thousand tons. The road transport sector was the dominant source, with 245 thousand tons of emissions and a 43.8% contribution rate to total emissions. The second-largest sector for CO emissions was “other mobile sources,” which emitted 135 thousand tons of CO emissions with 24.2% contribution rate. In this sector, emissions from ships were the major contributor (60 thousand tons). The third-largest sector was “non-industrial combustion plants,” with 72 thousand tons of emissions and a 12.9% contribution rate.

Table 26. Sectoral air pollutant emissions in 2015 in Korea

(Unit: ton/year)

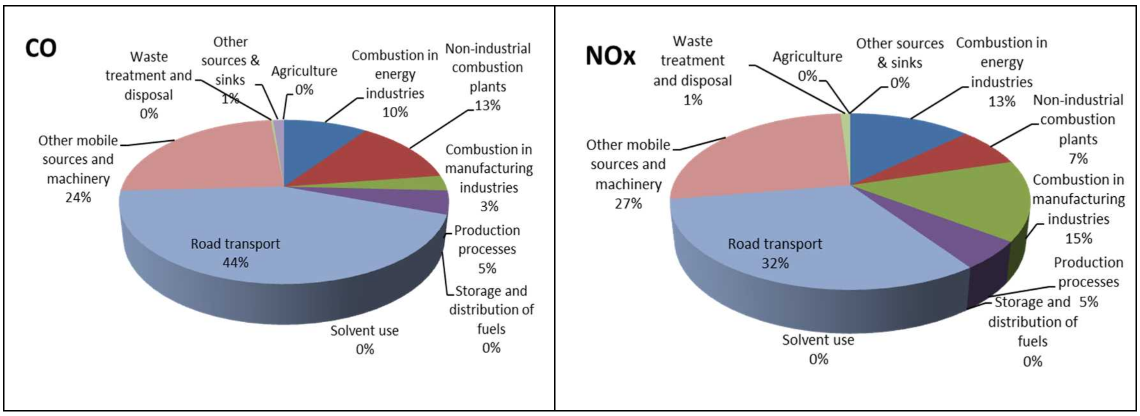
SCC1	CO	NOx	SOx	PM_{10}	$PM_{2.5}$	VOC	NH_3
Combustion in energy industries	55,138	150,818	91,243	4,394	3,607	7,464	1,379
Non-industrial combustion plants	72,299	82,948	28,736	1,582	1,025	2,622	1,351
Combustion in manufacturing industries	16,854	169,139	85,098	70,893	36,317	3,101	627
Production processes	26,069	59,830	105,385	6,658	5,132	182,899	39,432

Storage and distribution of fuels	0	0	0	0	0	29,137	0
Solvent use	0	0	0	0	0	555,359	0
Road transport	245,516	369,585	209	9,583	8,817	46,145	10,078
Other mobile sources and machinery	135,700	304,376	39,424	15,317	14,106	40,311	117
Waste treatment and disposal	1,548	11,977	2,119	246	209	57,074	22
Other sources and sinks	7,197	172	0	317	285	648	12,882
Agriculture	0	0	0	0	0	0	231,263
Combustion total	**144,291**	**402,905**	**205,077**	**76,869**	**40,949**	**13,187**	**3,357**
Mobile total	**381,216**	**673,961**	**39,633**	**24,900**	**22,923**	**86,456**	**10,195**
Total	**560,321**	**1,148,845**	**352,214**	**108,890**	**69,498**	**924,760**	**297,151**

NOTE:

1. Incineration of agricultural residues (biomass burning) is classified as "Other sources and sinks." "Agriculture" contains NH_3 emissions from livestock manure management and fertilizer use.

In Korea, various policies have been implemented to reduce PM_{10} emissions. For PM_{10} emissions in 2015, combustion in the manufacturing industries sector was the dominant source, with 70 thousand tons of emissions and a 65.0% contribution rate to total emissions. For the combustion in manufacturing industries subsectors, other sectors were primary sources, with 68 thousand tons of emissions. The second-largest sector for PM_{10} emissions was "other mobile sources and machinery," which emitted 15 thousand tons of PM_{10} emissions with a 14.1% contribution rate. In this sector, emissions from ships were the major contributor (7 thousand tons). The third-largest sector was "road transport," with 9 thousand tons of emissions and an 8.8% contribution rate. PM_{10} emissions in Korea for 2015 totaled 108 thousand tons.



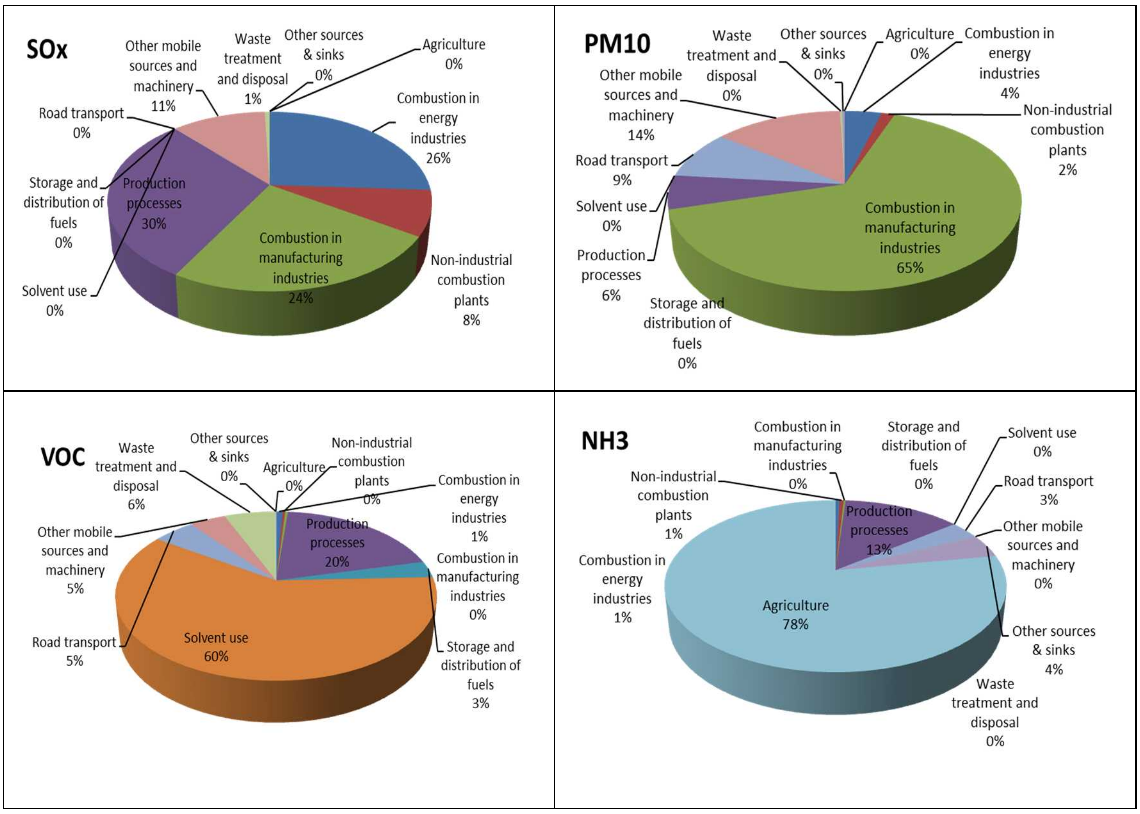


Figure 57. Contribution rate by source category for CO, NOx, SOx, PM_{10}, VOCs and NH_3 in Korea

5-2. National Air Emissions in Japan

Table 27 summarizes the amount of national air pollutant emissions for FY 2015 in Japan, in the classification according to Korea's SCC 1 sector shown in Table 26. (Note: The Japanese fiscal year begins in April and ends in March. Thus, in this case, the estimated emissions are from April 2015 to March 2016.). In Japan, PM_{10} is not estimated.

Table 27 shows ship emission, but it covers the port area and some main routes of coast of Japan. Figure 58 shows the sectoral contribution of each air pollutant— CO, NOx, SOx, $PM_{2.5}$, VOC, and NH_3 emissions.

The total CO emissions in Japan in FY2015 was 3,034 thousand tons. Emissions from the road transport sector have been the main source of emissions. However, due to the strengthened automobile emissions regulations, emissions from the road transport sector have been decreasing every year, and 2015 was the first time it fell below fixed source emissions.

Although the proportion of NOx emissions from mobile sources is decreasing, it is still being emitted more from these sources than from the stationary sources. Approximately 55% of NOx emission from mobile sources is generated by automobiles. Subsequently, the second-largest contributor of NOx emission is ships, with about 32% of NOx from this mobile source, but the emissions vary greatly depending on the area estimated. For stationary sources, the largest emission is from the manufacturing industries.

SOx is emitted from the sulfur contained in fuel, and emissions from stationary sources are emitted mainly from thermal power plants and manufacturing industries. As for emission from automobiles, both gasoline and diesel oils are regulated to 10 ppm or less for sulfur content and lead to nearly 0% SOx emission compared to stationary sources. On the other hand, the sulfur content in residual oil is 2.6%, and SOx from mobile sources mostly derives from ships. Although not listed in Table 27, it should be noted that SO_2 emission from volcanos is more than twice as much as the anthropogenic SO_2 emission in Japan.

For $PM_{2.5}$, as well as NOx, the mobile source emission is slightly larger than the stationary sources. $PM_{2.5}$ emitted from mobile source includes road dust emissions that accompanies running of vehicle engines. Since $PM_{2.5}$ emitted from the tailpipe of vehicles are decreasing due to exhaust gas emission regulations, the ratio of $PM_{2.5}$ emissions of road dust increases. In FY2015, the $PM_{2.5}$ emission from road dust exceeds $PM_{2.5}$ emissions from tailpipe emission.

The main source of anthropogenic VOC is solvent use, accounting for 56% of the total. Among the solvent applications, the largest emission relates to paints. Subsequently, leakage from fuel and VOC emission from vehicles are the same. Regarding fugitive fuel emission, those related to automobiles—such as refueling gasoline—are the main culprit of emission, accounting for 73%.Then automobile-related VOCs are 25% of total VOC emission.

Many of the NH_3 emissions are from agriculture activities, specifically farming and fertilization. The next largest NH_3 emissions are from the human body and pets. The three-way catalyst equipped on gasoline vehicles generates NH_3. NH_3 leakage from urea SCR devices used for NOx reduction can be considered in calculating NH_3 emissions. However, it is considered low, as the latest diesel vehicles are equipped with an additional oxidation catalyst for purifying NH_3 leakage. For stationary combustion sources, the leaked NH_3 emission during denitrification device usage is considered.

Table 27. Sectoral air pollutant emissions in 2015 in Japan

(Unit: ton/year)

SCC1	**CO**	**NOx**	**SOx**	**$PM_{2.5}$**	**VOC**	**NH_3**
Combustion in energy industries	31,261	216,731	177,780	4,196	8,807	2,712
Non-industrial combustion plants	127,284	53,868	7,702	3,996	19,854	0
Combustion in manufacturing industries	1,268,951	341,998	123,504	8,543	8,445	3,434
Production processes	0	0	0	0	60,523	4,408

Storage and distribution of fuels	0	0	0	0	138,299	0
Solvent use	0	0	0	0	512,895	0
Road transport	1,208,142	417,536	917	23,714	126,666	15,744
Other mobile sources and machinery	187,826	340,716	125,278	16,819	24,458	0
Waste treatment and disposal	91,670	63,563	31,743	4,561	2,585	0
Other sources and sinks	119,459	7,987	1,235	14,588	14,816	63,280
Agriculture	0	0	0	0	0	263,472
Combustion total	**1,519,166**	**676,160**	**340,729**	**21,296**	**39,691**	**6,146**
Mobile total	**1,395,968**	**758,252**	**126,195**	**40,533**	**151,124**	**15,744**
Total	**3,034,593**	**1,442,399**	**468,159**	**76,417**	**917,348**	**353,050**

NOTE:

1. Excludes natural sources (biogenic VOCs, soil, volcanos)

2. "Road transport" includes road dust (including brake dust) and tire wear.

3. "Other mobile sources and machinery" includes ship emissions in the Japanese port and on major Japanese domestic routes.

4. Incineration of agricultural residues (biomass burning) is classified as "Other sources and sinks." "Agriculture" contains NH_3 emissions from livestock manure management and fertilizer use.

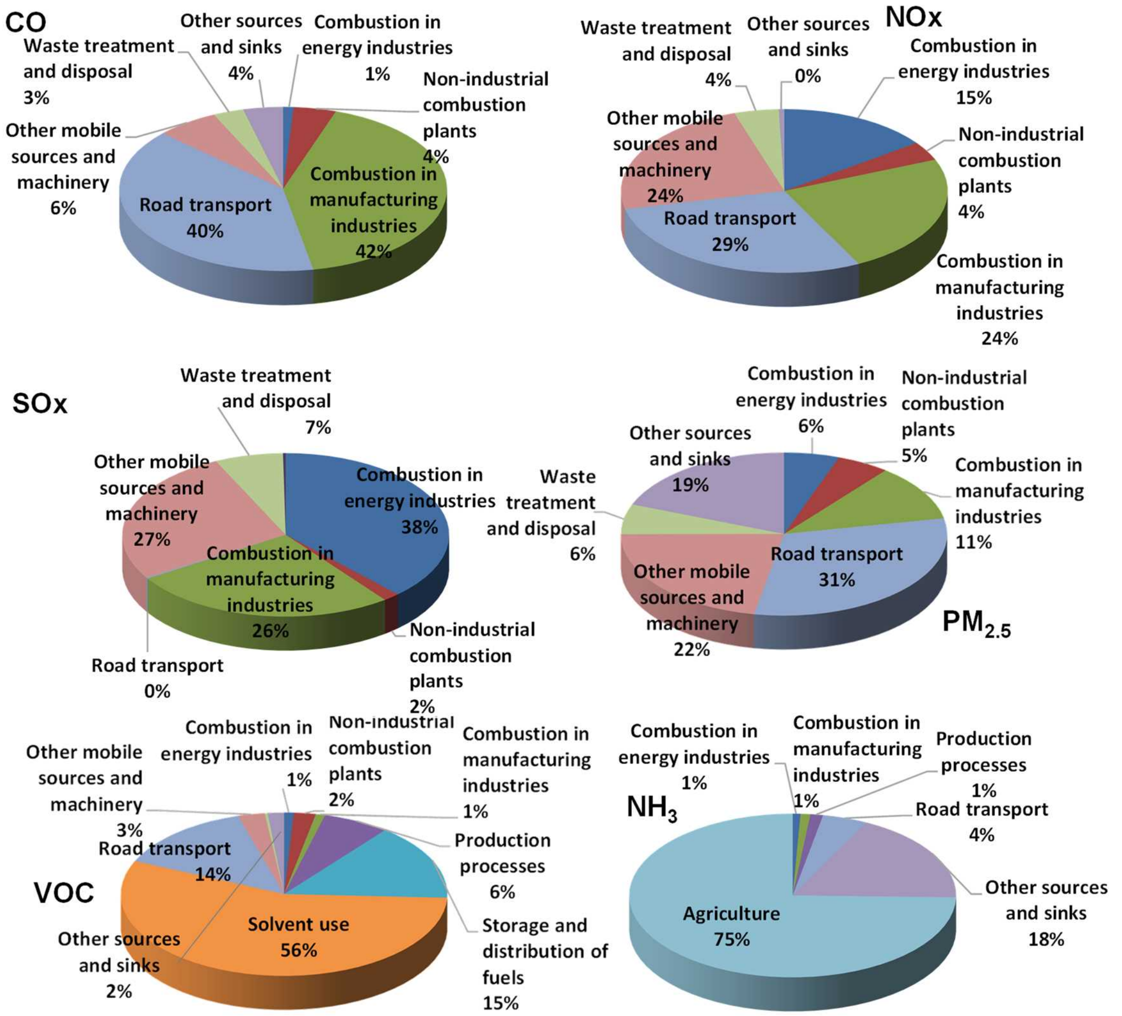


Figure 58. Contribution rate by source category for CO, NOx, SOx, $PM_{2.5}$, VOCs, and NH_3 in Japan.

6. Conclusions

To improve the emission inventory required for $PM_{2.5}$ measures, we exchanged knowledge about the method of creating the emission inventory and specific source measures. In this series of surveys, comparison of emission inventory of Japan and Korea is also included as basic information.

Since there are various kinds of emission sources, we decided to limit our investigation subjects as follows:

Stationary emission sources:

Combustion sources (large point sources) and evaporative VOCs.

Mobile emission sources:

Tail pipe emission from gasoline passenger cars.

By carrying out detailed comparisons and expanding the data obtained in each country, knowledge accumulation has not only led to improvement in the accuracy of the emission inventory itself, but also reflection on implemented measures.

It can be said that sufficient results were obtained, but the difference between Japan and Korea was larger than expected. In the Emission Inventory Gr, it is not only important to compare each data numerically; we needed to confirm definitions of target substances with one another to understand the estimation logic (including the details) and the meaning of the data (including the background). The work required some time, and it is noted that the results of this study are based on careful surveying.

The main contents are as follows.

6-1. Stationary Emission Sources

6-1-1. Combustion sources (large point sources, LPS)

After a detailed comparison of the estimated emissions method of large point sources in Japan and Korea, a discussion on EF was held. EF in Korea was set up before the exhaust gas post-treatment system to reflect the effects of the system separately. Alternatively, in Japan, it has been confirmed that the EF is considered including the post-processing device. Therefore, it is not possible to directly compare the EFs of Japan and Korea, resulting in the interruption of the comparative study of EF of a large-scale smoke source.

6-1-2. Evaporative VOCs

The knowledge of Korea and Japan was considered useful, because evaporative VOCs cannot easily be estimated, unlike the combustion sources that are proportional to the amount of fuel used.

However, it was found that the definition of VOC varies in Japan and Korea. Therefore, shared information was considered essential.

Large differences in VOC emissions between Japan and Korea are attributed to food fermentation, gas stations, paints, and printing. In particular, the VOC emissions from paint reflect the differences in industrial structure between Japan and Korea, and they manifest as the differences in VOC components. It was found that the VOC emission from gas stations clearly showed the difference between Japan without measures and Korea with measures.

6-1-3. Introduction of countermeasures useful to both countries in reducing emissions

Korea introduced the CleanSYS, which is an advanced remote monitoring system of large point sources and management of VOCs, including Stage II. In particular, the experience the Stage II introduction, a gasoline vapor recovery system, was helpful for Japan. It had not previously been introduced.

From Japan, the regulation of VOC sources and their regulatory values were mentioned. This is a reference example for VOC regulations in Korea.

6-2. Mobile Emission Sources

6-2-1. Comparison of vehicle emission inventory estimation systems

Japan and Korea have their own individual Vehicle Emission Inventory Estimation System, each of which is robust. As it was thought that exchanging both findings could contribute much to emission inventory improvement in each country, the emission estimation methods of both countries were compared in detail. The comparison targets are specifically about the method of creating the EF, vehicle type composition, and traffic volume. No direct comparisons were made for EFs. Specifically, we conducted a detailed comparison of two items: vehicle emission criteria and vehicle classification, which greatly affect emissions.

6-2-2. PM emissions from gasoline vehicles

To examine the "PM emissions from gasoline vehicles" in detail— the object of relatively new air pollutants for Japan and Korea—the raw test results were exchanged, respectively. As Korea has only recently begun investigating PM emission behavior from direct injection gasoline vehicles, Japanese data and experiences were helpful to create PM emission factor. Korea decided to use the emission factor created based on this joint research as the official emission factor.

6-3. Outline of National Air Emissions

The total amounts of major air pollutants by source sector in 2015, for Korea and Japan, are respectively compared. It can be seen that the measures of each country are reflected in the emission ratio of each source sector.

The three-year joint research will end here, but stationary and mobile sources still require consideration in each country. In the future, the issues considered suitable for implementation within this joint research framework of this cooperative meeting are as follows:

Stationary emission sources

Condensable particles from combustion sources

-Discussion on measurement methods

-Findings by facility, fuel type and after-treatment device

-Consideration of measurement results

Mobile emission source

RSD (Remote Sensing Device) research

-Discussions on survey methods

-Measurement results and analysis of results

RDE (Real Driving Emission) research

-A discussion about the method

-Measurement results and analysis of results

Exchange of information on electrification of automobiles

1. Reflecting the Joint Research Outcomes in the Policy Areas

Japan

A general improvement in air pollution concerning $PM_{2.5}$ has been observed in Japan. This is because of the domestic policy efforts, as well as international cooperation.

The Japan-Korea bilateral cooperation on $PM_{2.5}$ started with the kick-off meeting in August 2014, followed by the joint researches in two groups beginning in 2016. The government officers and researchers have shared information and exchanged opinions over the last five years.

A number of insights have been obtained for promoting future $PM_{2.5}$ countermeasures by sharing the two countries' latest scientific knowledge, good practices, experiences, etc., through introducing each country's policy systems and the latest policy trends/research programs, the sharing of data related to monitoring and emission inventories, and comparing simulation models.

The main outcomes achieved through the bilateral cooperation so far are as follows:

1. Aiming to control $PM_{2.5}$ emissions from stationary sources in Japan, much effort has been made concerning the VOCs stationary sources through a policy matrix, called "the best-mix," combined with the private sectors' voluntary efforts and regulatory restrictions based on the Air Pollution Control Act, which was amended in April 2006. Consequently, continuous emission reductions have been achieved.

As for the policy measures, in order to curve VOCs emissions further, Japan introduced the "SS Certificate System" in February 2018, designed to promote Stage II [4] by granting a certificate to the environmentally-friendly fuel stations as a counter measure for the fuel gas evaporation from fuel retailers. In introducing this system, a reference was made to the example of the Korean counter measures for the fuel gas evaporation at fuel stations.

2. It is important to identify the $PM_{2.5}$ secondary formation mechanisms and emission sources to promote the $PM_{2.5}$ counter measures. To this end, continuous monitoring of the various species comprising $PM_{2.5}$ is essential.

[4] Measures to control the fuel gas evaporation, which leaks while fueling the vehicles (fuel stations counter measures).

Regarding reinforcing the Japanese air quality-monitoring network for $PM_{2.5}$, ten sites around the country started automatic monitoring in 2017. The example of the Korean monitoring supersites was suggestive at that time.

It is planned in the future to analyze the variety of data accumulated to date, the emission sources' contributions to $PM_{2.5}$, and the causes of the high concentration events.

3. The comparative studies between the Japanese and Korean simulation models have led to improved accuracy of the Japanese air environment simulation model, which reproduces the behavior of long-range transporting pollutants. Additionally, a number of insights have been obtained through the information and opinion exchanges concerning emission inventories.

Efforts will be continuously made to sophisticate the air quality simulation models, as well as to update and elaborate the emission inventories of air pollutants, with a vision of supporting the policy assessment for the measures undertaken so far and consideration of additional countermeasures.

Korea

The government of the Republic of Korea established air quality standards under the "Clean Air Conservation Act," enacted in 1990, which require managing $PM_{2.5}$ through emission controls. However, as of 2015, the $PM_{2.5}$ concentration is still higher than those of developed countries.

With a growing demand for clean air, the Ministry of Environment of Korea announced a series of "Special Countermeasures on Fine Dust" (on June 3, 2016), after consulting with stakeholders and reviewing with experts from National Institute for Environment Research, among others. The countermeasures plan to control emissions beyond the government's focus of primary sources by including secondary pollution. The countermeasures were formulated on the foundation of analysis for emission sources and contribution of each.

Despite extraordinary efforts, it was still falling short of satisfying citizens' expectation toward clean air. With the inauguration of the new government in May 2017—putting response actions to fine dust at the top of its agenda—the Intergovernmental Task Force Team was established to announce the "Masterplan for Fine Dust Reduction."

The Masterplan requires stricter reduction targets, compared to those from the Special Countermeasures of June 2016, aiming at a full range of emissions reduction across all sectors—from industry and generation to transportation. In the short-term, it plans to enforce emergency measures to reduce fine dusts during episodes of high $PM_{2.5}$ concentration, as well as prioritizing the implementation of actions to protect sensitive groups from air pollution. In the mid- to long-term, it intends to significantly reduce emissions from all sectors across the country, described as follows.

First, regarding the generation sector, coal-fired power plants under operation will be subject to stricter control. Ultimately, the share of coal-fired power in the Korean energy portfolio will decrease, pursuing transformation to the sustainable energy mix scheme.

Second, for the industry sector, the government will expand the intensive control targets from the greater capital metropolitan area to heavily polluted areas.

Third, for the transportation sector, strict measures will be implemented for early scrapping of old diesel vehicles manufactured before 2005 and for managing blind spots.

Finally, for the daily surroundings, the government will secure twice as many dust-cleaning vehicles to reduce on-road fugitive dusts and tighten control of fugitive dusts and biological combustion (for example, by carrying out special instructions on construction sites and prohibiting illegal incineration).

The government has also shown a great commitment to strengthening cooperation with neighboring countries to determine a practical solution for transboundary air pollution, which is crucial to achieving its first and most important goal of protecting public health, especially for the sensitive groups.

For Korea to lay the foundation for planning and implementing the countermeasures explained above, this cooperation body—"Korea-Japan Cooperation on $PM_{2.5}$"—has played an important role since the first meeting held in Aug 2014 to provide a forum to share experiences and promote bilateral collaboration. This is particularly true regarding improving emission inventories and modeling, respectively, for both countries to clearly identify emission sources and their contribution, as well as forecasting, alarming, or warning citizens of increasing air pollution levels. It is also worth mentioning that the two countries' collaboration on automobile emission inventory has made remarkable progress. The joint research significantly contributes to improving the accuracy of emission inventories and air quality forecasting, which ultimately will form the strong scientific basis for carrying forward our fine dust countermeasures.

2. Future Bilateral Cooperation between Japan and Korea

Toward a full achievement of Environmental Quality Standard for $PM_{2.5}$, the members of the joint research confirmed our willingness to continue and develop our cooperation based on new demands of the two countries.

Annex I. Evaporative VOC emission by source category of Japan and Korea

JAPAN		KOREA	
Source	**Emissions (t/y)**	**Source**	**Emissions (t/y)**
Chemical production	47,990	Industrial process –chemical industries	41,914
Food manufacturing process (fermentation)	17,122	Industrial process –food and beverage	50,509
Coke-making process	167	Industrial process –iron & steel industries coke oven (door leakage & extinction)	12,689
Natural gas production	653		
Fuel evaporation emission, gas station	107,082	Gas station	26,985
Fuel evaporation emission, petroleum products, Crude oil refining	39,277	Industrial process – petroleum industries	55,919
Fuel evaporation emission, crude oil	429		
Paint (all)	285,652	Solvents use –painting facility	358,870
Printing (all)	41,612	Solvents use –other solvent use, printing	23,576
Adhesive (except laminate)	42,683		
Pressure sensitive adhesive and releasing agents	11,080		
Adhesive for laminate	4,539	Industrial process – wood and pulp-laminate	1
Agricultural chemicals & pesticide	1,736		
Fishing net antifoulant	4,151		
Rubber solvent	10,414		
Converting solvent	4,232		
Coating solvent	4,610		
Artificial leather	1,434		
Asphalts	4,023	Solvent use – asphalts (pavement)	968
Gloss processing solvent	184		
Marking agent	67		
Industrial detergent / cleaner	37,200		
Dry-cleaning solvent	21,890	Solvents –cleaning facility –dry-cleaning	22,115
Paint stripping solvent	1,165		
Cleaning thinner	30,565		
Surface preparation agent, flux	620		
Analytical reagent	722		
Foaming agent	1,215		
Sterilization, disinfectant	109		
Fumigant	603		
Dampening water	1,827		
		Others	165,601
TOTAL	**725,053**	**TOTAL**	**759,147**

Annex II. VOC component in paint of Japan and Korea

JAPAN (2012)	t/y	KOREA (2012)	t/y
TOLUENE	27,426	TOLUENE	29,302
M-XYLENE AND P-XYLENE	47,470,342	ISOMAL OF XYLENE	50,963
ISOPROPYL ALCOHOL	4,502	ISOPROPYL ALCOHOL	1,903
ISOBUTYL ALCOHOL	16,445	ISOBUTYL ALCOHOL	6,563
METHYLETHYL KETONE	2,617	METHYLETHYL KETONE	11,928
METHYLISOBUTYL KETONE	8,912	METHYLISOBUTYL KETONE	9,865
ETHYL ACETATE	15,720	ETHYL ACETATE	6,386
N-BUTYLACETATE	18,074	N-BUTYLACETATE	10,972
ETHYLENE GLYCOL	3,682	ETHYLENE GLYCOL	15,356
ACETONE	7,466	ACETONE	9,886
BUTYL CELLOSOLVE	12,887	BUTYL CELLOSOLVE	12,694
ETHYLBENZENE	31,941		
1,3,5-TRIMETHYLBENZENE	5,222		
1,2,4-TRIMETHYLBENZENE	9,845		
NONANE	2,740		
3-METHYLOCTANE	86		
N-DECANE	4,709		
2-methylnonane	771		
3-methylnonane	856		
DIMETHYLOCTANES	171		
ISOMERS OF DECANE	2,654		
N-UNDECANE	2,996		
ISOMERS OF UNDECANE	3,510		
N-DODECANE	171		
C10 OLEFINS	685		
n-butylcyclopentane	86		
C9 CYCLOPARAFFINS	428		
c-Paraffin, C10	1,113		
ISOMERS OF ETHYLTOLUENE	10,530		
ISOMERS OF PROPYLBENZENE	1,883		
ISOBUTYLBENZENE	1,627		
ETHYLDIMETHYLBENZENE	4,794		
C10 AROMATIC	7,705		
Unknown C11 Aromatics	6,592		
BUTYLBENZENE	86		
1,2,4,5-tetramethylbenzene	514		
Unknown C12 Aromatics	599		
Methyl acetate	3,273		
Isophorone (3,5,5-trimethyl-2-cyclohexenone)	1,330		
Ethylene glycol monoethyl ether acetate	2,046		
methyl cellosolve acetate	102		
ETHYLENE GLYCOL MONOETHYL ETHER	1,943		
HEXANE	1,227		
CYCLOHEXANE	205		
STYRENE	7,671		
		S-BUTYL ALCOHOL	11,008

1,1,1-TRICHLORO ETHANE	750
MINERAL SPIRITS	125,385
ETHYL ALCOHOL	2,467
PROPYLENE GLYCOL	6,237
MONOMETHYL ETHER DIPROPYLENE GLYCOL	1,301
DIACETONE ALCOHOL	9,673
BUTYL CARBITOL	2,325
CARBITOL	499
METHYL CARBITOL	499
CELLOSOLVE ACETATE	1,540
CELLOSOLVE	1,040
N-PROPYLE ACETATE	5,901
PROPYLENE GLYCOL MONOMETHYL ETHER ACETATE	2,587
1-METHOXY-2-PROPANOL	1,301
KETONES - GENERAL	1,445
OXYGENATES	1,960
UNC PEAKS TO CBM XYLENE	15,982
UNDEFINED VOC	1,240

There are 110 active volcanoes in Japan, and the SO_2 emission was confirmed from 12 volcanoes among them; this SO_2 emission data were shared with Korea (Fig. A1). Initially, Korea requested the data covering March and December of 2015 (Fig. A2). Later, the data from 2010 through 2015 were shared per Korea's additional request.

To note, no active volcano has been found in Korea.

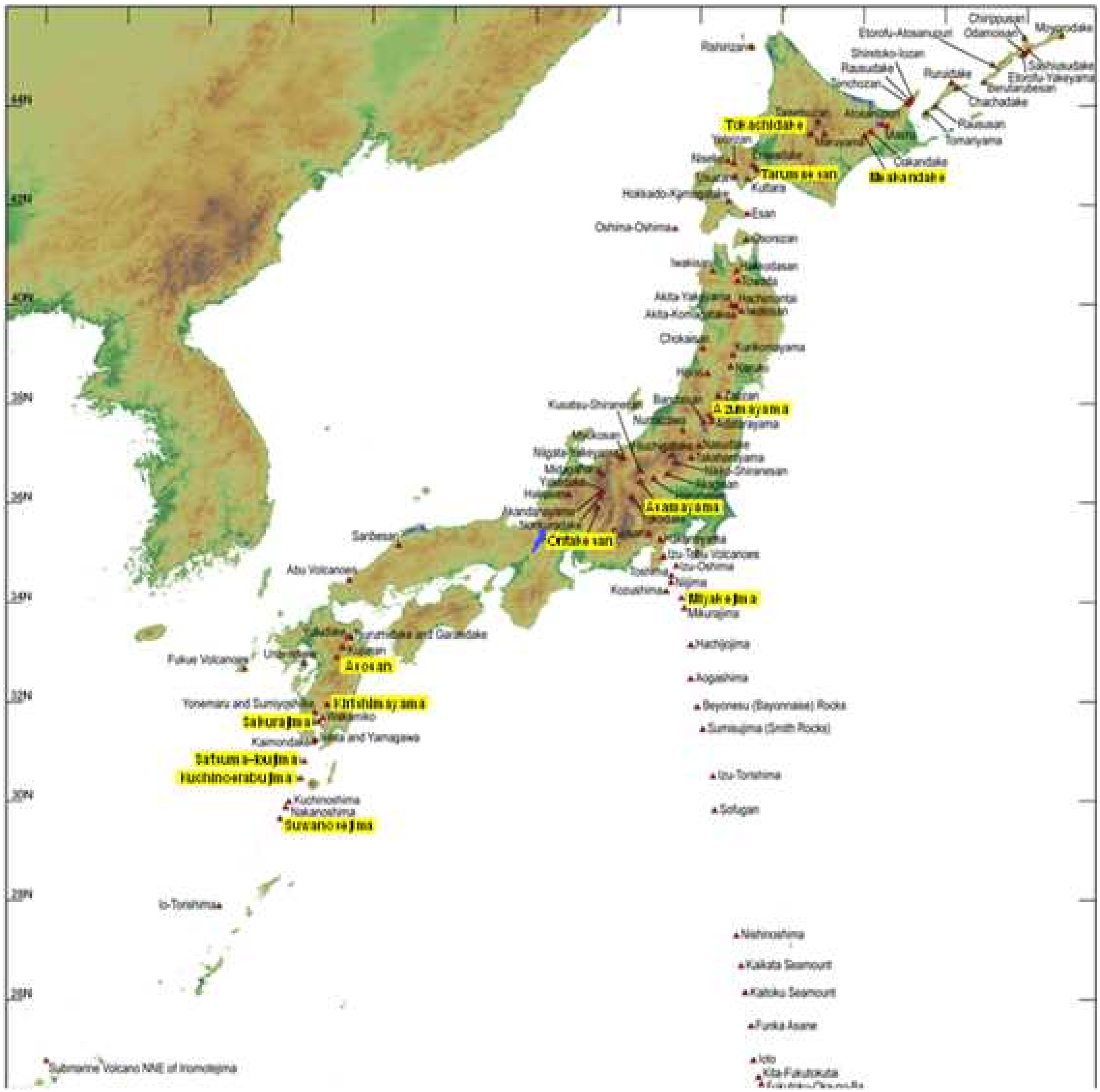


Fig. A1 Japanese Active Volcanos: volcanoes that have erupted within the past 10000 years, and/or volcanoes with current fumarolic activity*. Text highlighted in yellow signifies volcanos in which SO_2 emission concerned.

* http://www.data.jma.go.jp/svd/vois/data/tokyo/STOCK/souran_eng/intro/distribution.pdf

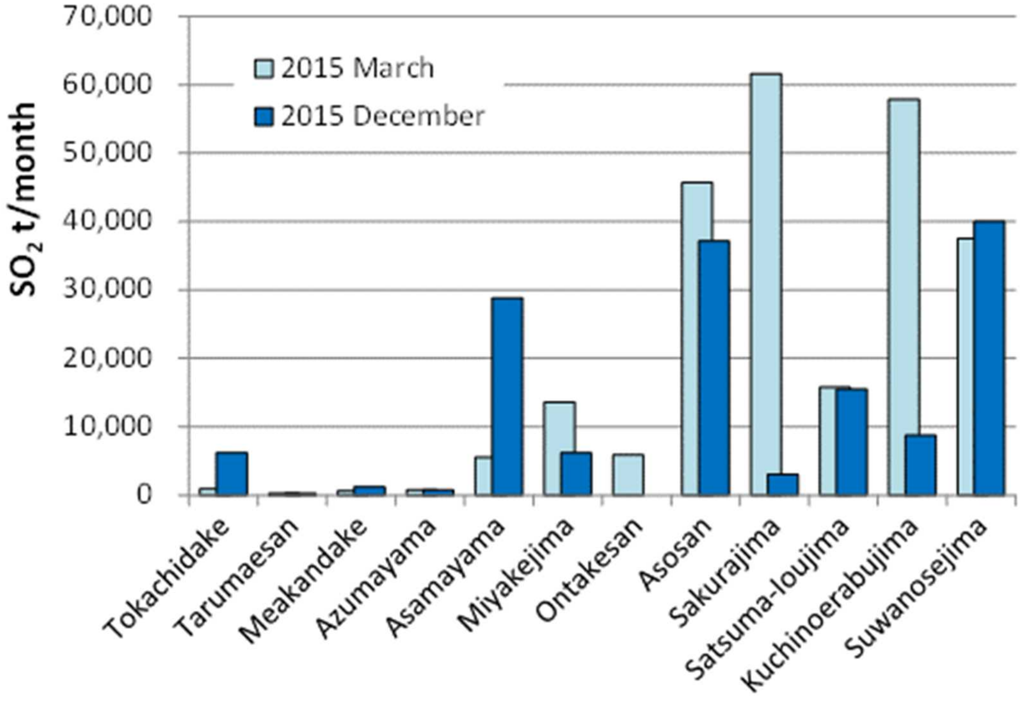


Fig. A2 Japanese volcanic gas (SO_2) for March and December 2015