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Study on sulfur dioxide transport from China to Japan using an advection and dispersion model

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Abstract: The current study investigated a series of transport processes of sulfur dioxide, which is an acid material transported from China to Japan in the winter season, through material transport simulations using the advection and dispersion model HYSPLIT4 (Hybrid Single-Particle Lagrangian Integrated Trajectory version 4), which has been developed by Draxler et al. This model assumes materials can be represented by particles or puffs (or both) and calculates their advection, dispersion and deposition processes based on the Lagrangian method. In the current study, experimental simulations based on three scenarios were performed to understand the influence of long-distance transport of the sulfur dioxide released from mainland China in the winter season, and in addition, the validity of the model was examined through the calculation of the contribution ratio of sulfur dioxide from China.

Firstly, it was supposed that the five ministries of Beijing, Hebei, Shanxi, Liaoning and Heilungjiang are one of main sources in China of the sulfur dioxide with the potential for a great influence on Japan. Some simulations were then conducted based on the following three scenarios. The first one is a scenario with the same environmental condition as the situation in February 2000, the second is a pessimistic scenario where environmental measures do not progress sufficiently and the third is an optimistic scenario where environmental measures progress like the current situation in Japan.

Based on the simulation results in each scenario, the deposition amount of the sulfur dioxide after its 12-hour release was examined at some places of the Kanto region in Japan. The deposition amount in the Tsukuba city, for example, was 21.37 $\mu g/m^2$ in Scenario 1 and 24.23 $\mu g/m^2$ in Scenario 2 on the average in 10 days after the release. Thus, the ratio of the deposition amount in Scenario 2 to that in Scenario 1 was 1.134 (=24.23/21.37). Likewise, the ratio of the deposition amount in Scenario 3 to Scenario 1 was estimated to be 0.344. According to the results at some places, if environmental measures will not sufficiently progress by 2010 in China, the deposition amount of the sulfur dioxide transported to Japan will increase to 1.1-1.2 times as much compared to the same environmental condition as the current situation. To the contrary, the deposition amount will decrease to 0.3-0.4 times as much when environmental measures will progress as they do in Japan.

In addition, the current study compared the simulation results of the air concentration of sulfur dioxide with its observation data. The mean air concentration in the lowest layer in Scenario 1 was estimated to be about 0.217 ppb in the Niigata city. According to the report of the National Institute of Science and Technology Policy, the sulfur dioxide emitted from the five ministries of China in 2000 is estimated to be 3,923,000 ton, and that emitted from the whole land of China is 22,086,000 ton. Since the latter is about 5.63 times as much as the former, the concentration of the sulfur dioxide transported from the whole land of China to the Niigata city can be approximated to be 1.222 ppb (=0.217x5.63).

On the other hand, according to the report "Environmental numerical value data base" of the National Institute for Environmental Studies, the sulfur dioxide concentration observed in the Niigata city in the same period is about 2 ppb on average. Thus, the contribution ratio of the sulfur dioxide concentration transported from the whole land of China to the Niigata city is estimated to be 0.611 (=1.222/2.0), namely about 60%, which seems a valid estimate by comparison to estimates in past studies.

Keywords: *acidic oxide, acid rain, sulfur dioxide, advection process, dry deposition, trajectory analysis, advection and dispersion model*

1. INTRODUCTION

The issue of cross-border pollution by sulfur dioxide is growing severe recently in East Asia where economic development is remarkable especially in China. Above all, acid rain problem from which the environment in Europe and the U.S. severely suffered in 1970's to 1990's has begun surfacing in Japan. Rainfall with very high acidity of nearly pH 4 is observed in some regions of Japan.

After 1990's, some models concerning long-distance transport of acid materials have been developed by research laboratories in the world, and some studies on the mechanism of the transport of sulfur dioxide from the Chinese continent to Japan have been conducted based on model simulations.

However, it is necessary to verify the validity of such models since there are some differences in simulation results, and in addition, the current situations including the economic development in China and global warming issues need to be taken into account in the impact assessment on the environment in East Asia.

The current study investigated the transport processes of sulfur dioxide from China to Japan in the winter season, through material transport simulations using the advection and dispersion model HYSPLIT4. In addition, the influence of cross-border pollution by sulfur dioxide in the future is examined in the East Japan, based on the data of sulfur dioxide emissions in the future projected by the National Institute of Science and Technology Policy in Japan.

Table 1. Three scenarios used in the current study.

Scenario 1	the same environmental condition as the situation in February 2000
Scenario 2	pessimistic scenario where environmental measures do not progress sufficiently
Scenario 3	optimistic scenario where environmental measures progress like the current situation in Japan

Table 2. Release rates of sulfur dioxide from the five ministries in China used in the current study.

Release rate (t/h)	Scenario		
	1	2	3
Beijing	52.04	59.29	18.04
Hebei	120.21	137.10	43.26
Shanxi	88.58	101.03	32.65
Liaoning	124.89	140.89	40.75
Heilungjiang	61.76	70.21	30.71

2. MODEL DESCRIPTIONS

HYSPLIT4 (Hybrid Single-Particle Lagrangian Integrated Trajectory Version 4) is an advection and dispersion model developed by Draxler et al. (Draxler and Taylor, 1982; Draxler, 1992; Draxler and Hess, 2004). This model assumes materials can be represented by particles or puffs (or both) and calculates their advection, dispersion and deposition processes based on the Lagrangian method. Air concentration calculations associate the mass of the pollutant species with the release of either puffs, particles, or a combination of both. The dispersion rate is calculated from the vertical diffusivity profile, wind shear, and horizontal deformation of the wind field. Air concentrations are calculated at a specific grid point for puffs and as cell-average concentrations for particles.

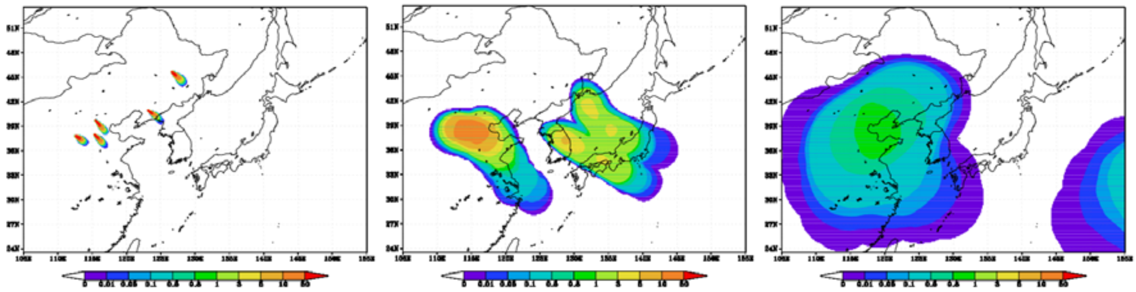
In the current study, the meteorological data used for the initial condition of the model is NOAA re-analysis data in February 2000 with the resolution of 2.5 by 2.5 degrees. The calculation domain was set to be the region with 30 degrees of latitude and 70 degrees of longitude, where Utsunomiya city of Japan is located in the center. The horizontal resolution was set to be 0.15 by 0.15 degrees.

The model was set to be with 5 vertical layers, the first one is the ground level, the 2nd one is 0-500m, the 3rd 500-1000m, the 4th 1000-2000m and the fifth 2000-3000m. The deposition velocity of the sulfur dioxide is assumed as 0.002m/s, referring to Ichikawa and Hayami (1997) and Stohl et al. (2005).

3. MATERIAL TRANSPORT SIMULATIONS OF SULFUR DIOXIDE USING HYSPLIT4

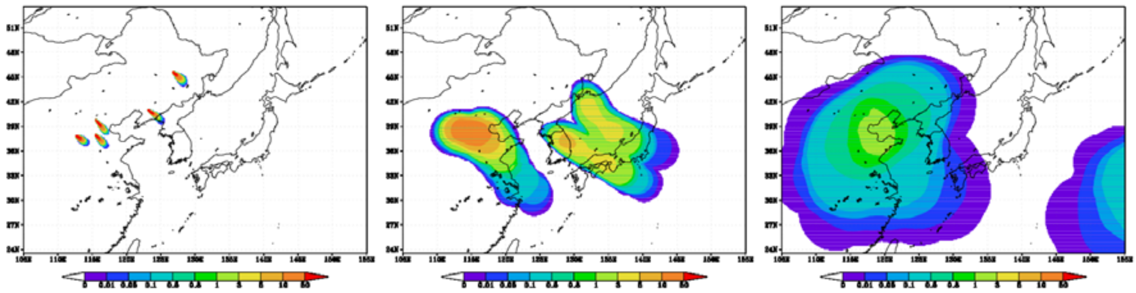
3.1. Calculation conditions and study cases

Firstly, it was supposed that the five ministries of Beijing, Hebei, Shanxi, Liaoning and Heilungjiang are one of main sources in China of the sulfur dioxide with the potential for a great influence on Japan. Some



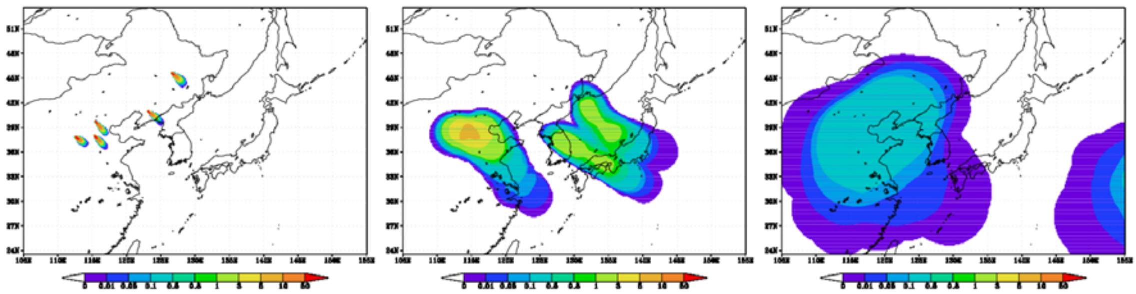
(a) 6 hours after (b) 36 hours after (c) 96 hours after

Figure 1. Air concentration (ppb) of sulfur dioxide in the layer of 0-500m in Scenario 1.



(a) 6 hours after (b) 36 hours after (c) 96 hours after

Figure 2. Air concentration (ppb) of sulfur dioxide in the layer of 0-500m in Scenario 2.



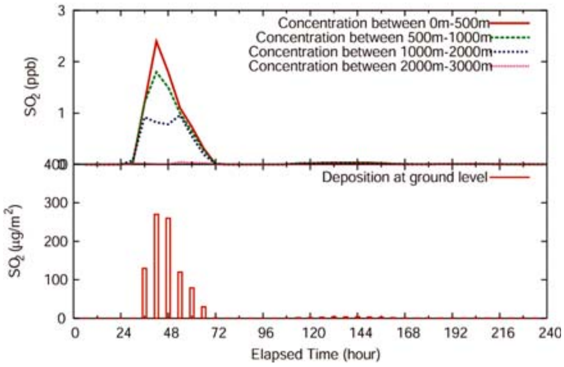
(a) 6 hours after (b) 36 hours after (c) 96 hours after

Figure 3. Air concentration (ppb) of sulfur dioxide in the layer of 0-500m in Scenario 3.

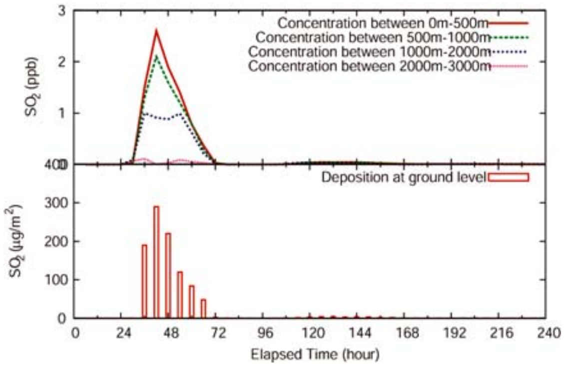
simulations were then conducted based on the three scenarios in Table 1, adopted by the National Institute of Science and Technology Policy in Japan (Goto et al., 1993). The first one is a scenario with the same environmental condition as the situation in February 2000, the second is a pessimistic scenario where environmental measures do not sufficiently progress by 2010, and the third is an optimistic scenario where environmental measures progress until 2010 like the current situation in Japan. The same degree of industrialization and population growth is expected in the second and third scenarios.

In Scenario 3, environmental measures in China for the reduction of sulfur dioxide were assumed to be taken at the power stations constructed in and after 1997 in the Southern district where acid rains are frequent, in case of burning coal or heavy fuels with the sulfur contents of 1.5% or more. The rates of the reduction were assumed to be 90% for 3% or more in the sulfur content, 70% for 2-3% sulfur, and 50% for 1.5-2% sulfur. No particular environmental and other measures would be taken for the other districts and facilities. Fuel oil consumption for the newly constructed plants after 1997 was assumed to be 3/13 of the increase of fuel oil consumption from 1987 to 2000 on the assumption that the fuel oil consumption would increase evenly for these 13 years.

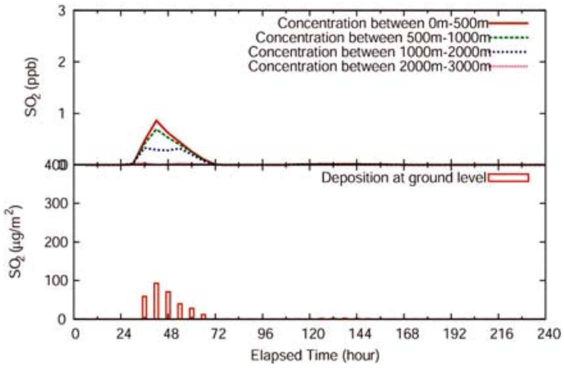
Based on the report of the National Institute of Science and Technology Policy in Japan (Goto et al., 1993), the release rate of sulfur dioxide from the five ministries in China can be estimated to be the values shown in Table 2 in each of the three scenarios. Using these data, the current study conducted experimental simulations using HYSPLIT4 to understand the influence of long-distance transport of the sulfur dioxide released from mainland China in the winter season. In the simulations, the air mass release of sulfur dioxide begins at 12:00 on February 15th, 2000 and lasts for 12 hours.



(a) Scenario 1

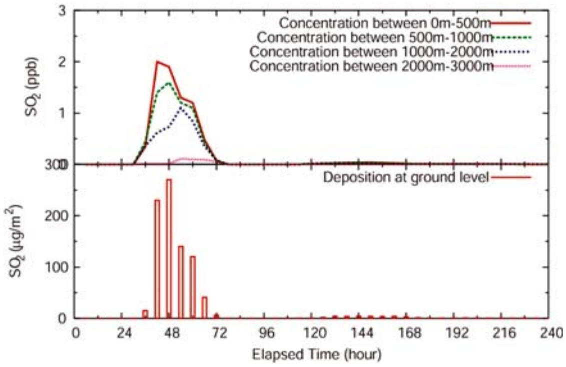


(b) Scenario 2

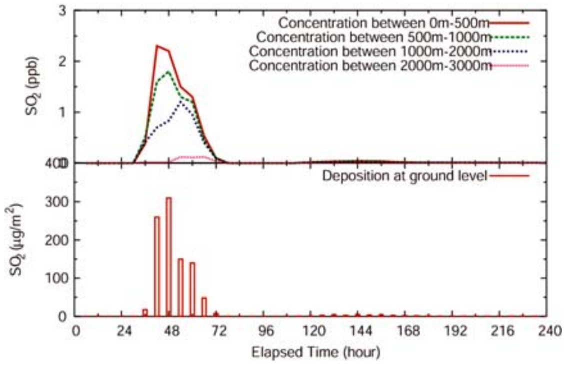


(c) Scenario 3

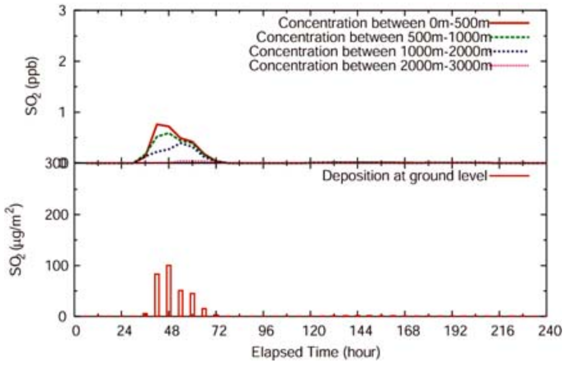
Figure 4. Time series variation of the air concentration (upper diagrams) and deposition amount (lower diagrams) of sulfur dioxide in the Niigata city of Japan.



(a) Scenario 1



(b) Scenario 2



(c) Scenario 3

Figure 5. Time series variation of the air concentration (upper diagrams) and deposition amount (lower diagrams) of sulfur dioxide in the Tsukuba city of Japan.

3.2. Advection and dispersion process of sulfur dioxide in the winter season

Firstly, simulation results in Scenario 1, 2 and 3 are shown in Figure 1, 2 and 3. These figures show the air concentration of sulfur dioxide 6, 36, and 96 hours after its release in the layer of 0-500m. In either scenario, the advection and dispersion process of air mass discharged from the two ministries Liaoning and Heilungjiang, located in the northern part of the country, differs from those of air mass from other three ministries. In the following descriptions, the former is denoted by air mass A and the latter air mass B.

Air mass A is transported to the southeast direction with a high concentration of sulfur dioxide being less dispersed and, about 24 hours later, it arrives at the western part of Japan. Then, it moves to the Pacific Ocean through the Japanese Archipelago in 96 hours. On the other hand, air mass B is slowly dispersed in the shape of a circle. Then, it arrives at the western part of Japan several hours later than air mass A.

Base on the simulation results in each scenario, the deposition amount of the sulfur dioxide after its 12-hour release was examined at some places of the Kanto region in Japan. Time series variations of the air concentration and deposition amount of sulfur dioxide in the Niigata city, located on the Japan Sea coast, and the Tsukuba city, located on the coast of the Pacific Ocean, under each scenario are shown in Figure 4 and Figure 5.

These figures show that the contribution of air mass A to the deposition amount of sulfur dioxide in Japan is relatively high since it arrives at the Japanese Archipelago in around 24 hours after its release with a high concentration. On the other hand, the contribution of air mass B is lower than air mass A since air mass B arrives at Japan after its sufficient dispersion.

Table 3. Rate of change in the deposition amount of sulfur dioxide in the Niigata and Tsukuba city among the three scenarios.

	Scenario		
	1	2	3
Niigata	1.0	1.156	0.372
Tsukuba	1.0	1.134	0.344

Table 4. Contribution ratio of the sulfur dioxide transported from the whole land of China to the Niigata and Tsukuba city under the three scenarios.

	Scenario		
	1	2	3
Niigata	61.1%	69.3%	15.4%
Tsukuba	20.6%	23.1%	5.2%

In comparison among the three scenarios, the deposition amount in the Tsukuba city, for example, was 21.37 μg/m^2 in Scenario 1 and 24.23 μg/m^2 in Scenario 2, on the average in 10 days after the release. Thus, the ratio of the deposition amount in Scenario 2 to that in Scenario 1 was 1.134 (=24.23/21.37). Likewise, the ratio of the deposition amount in Scenario 3 to Scenario 1 was estimated to be 0.344. Table 3 shows the rate of change in the deposition amount of sulfur dioxide in the Niigata and Tsukuba city among the three scenarios. According to the results at some places, if environmental measures will not sufficiently progress by 2010 in China, the deposition amount of the sulfur dioxide transported to Japan will increase to 1.1-1.2 times as much compared to the same environmental condition as the current situation. To the contrary, the deposition amount will decrease to 0.3-0.4 times as much when environmental measures will progress as they do in Japan.

3.3. Estimation of the contribution ratio of sulfur dioxide transported from China

Next, the current study compared the simulation results of the air concentration of sulfur dioxide with its observation data. From Figure 4, the mean air concentration in the lowest layer in Scenario 1 was estimated to be about 0.217 ppb in the Niigata city. According to the report of the National Institute of Science and Technology Policy (Goto et al., 1993), the sulfur dioxide emitted from the five ministries of China in 2000 is estimated to be 3,923,000 ton, and that emitted from the whole land of China is 22,086,000 ton. Since the latter is about 5.63 (=2208.6/392.3) times as much as the former, the concentration of the sulfur dioxide transported from the whole land of China to the Niigata city can be approximated to be 1.222 ppb (=0.217x5.63), as a first approximation on the assumption that all emissions in China are transported to Japan with the same pattern.

On the other hand, according to the report “Environmental numerical value data base“ of the National Institute for Environmental Studies, the sulfur dioxide concentration observed in the Niigata city in the same period is about 2 ppb on average. Thus, the contribution ratio of the sulfur dioxide concentration transported from the whole land of China to the Niigata city is estimated to be 0.611 (=1.222/2.0), namely about 60%.

As for the Tsukuba city, the mean air concentration in the lowest layer in Scenario 1 was estimated to be about 0.219 ppb, and the concentration of the sulfur dioxide transported from the whole land of China to the city can be approximated to be 1.233 ppb (=0.219x5.63). Since the sulfur dioxide concentration observed in the Tsukuba city in the same period is about 6 ppb on average, the contribution ratio of the sulfur dioxide concentration transported from the whole land of China to the Tsukuba city is estimated to be 0.206 (=1.233/6.0), namely about 20%.

Since the study by Ichikawa and Fujita (1994) shows that the contribution ratio of the sulfur dioxide from China to the sulfur dioxide concentration in the Niigata city is about 60-65% in the winter season, the above value of about 60% in the Niigata city seems a valid estimate considering the difference in the estimation method.

Table 4 shows the contribution ratio of the sulfur dioxide transported from the whole land of China to the Niigata and Tsukuba city under the three scenarios. The contribution ratio in the Niigata city, located on the Japan Sea coast, is about three times as high as the value in the Tsukuba city, located on the coast of the Pacific Ocean. This means that the influence of the sulfur dioxide transported from China is significantly stronger on the side of the Japan Sea, and on the side of the Pacific Ocean, there seems to be significant influence of the sulfur dioxide transported from the southern Kanto region, which is one of the highly industrialized areas in Japan.

4. SUMMARY

The current study investigated a series of transport processes of sulfur dioxide, which is an acid material transported from the Chinese continent to Japan in the winter season, through material transport simulations using the advection and dispersion model HYSPLIT4 (Hybrid Single-Particle Lagrangian Integrated Trajectory version 4). Some experimental simulations based on three scenarios were performed to understand the influence of long-distance transport of the sulfur dioxide released from mainland China, and in addition, the influence of cross-border pollution by sulfur dioxide in the future is examined in the East Japan, based on the data of sulfur dioxide emissions in the future projected by the National Institute of Science and Technology Policy in Japan. The findings in the current study are summarized as follows.

- In comparison among the three scenarios in the Tsukuba city of Japan, the deposition amount was 21.37 $\mu g/m^2$ in Scenario 1 and 24.23 $\mu g/m^2$ in Scenario 2, on the average in 10 days after the release. Thus, the ratio of the deposition amount in Scenario 2 to that in Scenario 1 was 1.134 (=24.23/21.37). Likewise, the ratio of the deposition amount in Scenario 3 to Scenario 1 was estimated to be 0.344.
- The deposition amount of the sulfur dioxide transported from the Chinese continent to Japan will increase to 1.1-1.2 times as much compared to the same environmental condition as the current situation if environmental measures will not sufficiently progress by 2010 in China. To the contrary, the deposition amount will decrease to 0.3-0.4 times as much when environmental measures will progress as they do in Japan.
- Based on the comparison between the simulation results of the air concentration of sulfur dioxide and its observation data, the contribution ratio of the sulfur dioxide concentration transported from the whole land of China to the Niigata city of Japan is estimated to be about 60%, while the value in the Tsukuba city is estimated to be about 20%.
- The contribution ratio in the Niigata city, located on the Japan Sea coast, is about three times as high as the value in the Tsukuba city, located on the coast of the Pacific Ocean. This means that the influence of the sulfur dioxide transported from China is significantly stronger on the side of the Japan Sea, and on the side of the Pacific Ocean, there seems to be significant influence of the sulfur dioxide transported from the southern Kanto region, which is one of the highly industrialized areas in Japan.

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