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Numerical Simulation of Air Pollution in Ulaanbaatar City, Mongolia

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Abstract: Air pollution has a major health impact on people living in UB (Ulaanbaatar) city. The excessive high particulate matter concentrations, especially in winter and in the ger areas, lead to serious illnesses and deaths. In order to get information to improve air quality in UB city, we investigate the current situation of location of ger areas and emission data of ger stoves and three thermal power plants. We reported the burning experimental result of the ger stoves and the present situation of the health hazard in a previous report. Now, in this report, we calculate the several diffusion simulations of air pollution in 2010. Our study has been carried out in collaboration with our Mongolian partner's TCDC (Tolgoit community development center, Songinokhairkhan district), and we want to make a contribution towards a cleaner and greener UB city.

Key words: Air pollution, diffusion simulation, particulate matter, health hazard.

1. Introduction

In the last ten years, in Mongolian metropolitan Ulaanbaatar city, the inflow of people from nomadic areas has increased remarkably, the population of UB city has rapidly doubled to 1.2 million people since the mid-1990s and the ger colony is expanding into the hills of the neighborhood of UB city north and west sides. UB city is located in a valley with mountains to the north and south. In winter, hot-water heating is supplied through plumbing to each house from the coal-fired thermal power plants and the heat-only boilers at the general collective housings such as those in the central part of the city [1, 2].

However, the black smoke becomes the main cause of the air pollution in the city's north and west sides, because of coal combustion in the ger area. The city's over 180,000 gers each burn an average of 5 t of coal and 3 m^3 of wood per year (Guttikunda) [3]. The extensive air pollution emission and temperature inversion in winter combine to cause excessive high pollution concentrations of PM (Particulate matter), sulfur dioxide and nitrogen dioxide.

The spatial PM concentration distribution across the city and ger areas is very high in Ulaanbaatar and about 430 $\mu g/m^3$ for PM 10 and 260 $\mu g/m^3$ for PM 2.5 as an annual average for the year of June 2008-May 2009 . This average exposure is about 10 times higher than the Mongolian air quality standards, and 6-7 times higher than the WHO (World health organization) target values (World Bank) [4] .

2. Air Pollution and Heating Stoves in Gers

From consecutive observation equipment of six stations (1, 2, 4, 5, and 7) of the CLEM (Central laboratory of environmental monitoring) in Ulaanbaatar, the data with machine parts made in France were collected from 2010 in Fig. 1.

Maeda of Suurikeikaku Co., Ltd. in Tokyo summarizes these data of CLEM for an observation example [5]. The yearly averaged values from Oct. 2010 to Sep. 2011 exceeded an environmental standard

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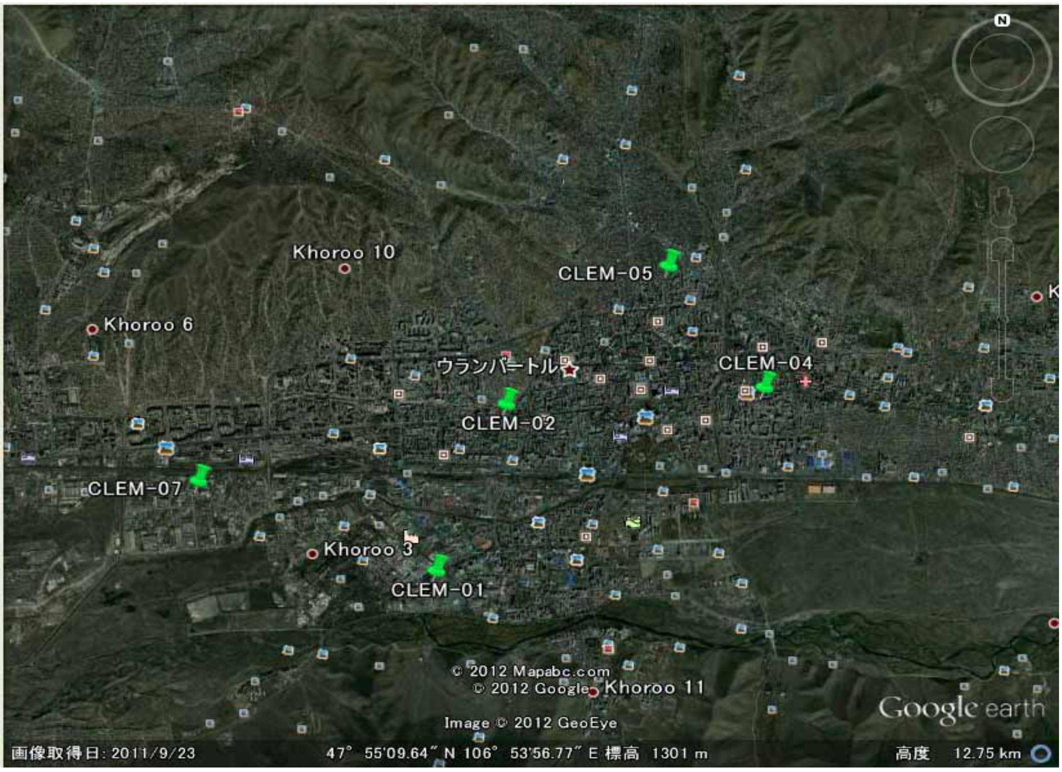


Fig. 1 Location of five monitoring stations (CLEM-1, 2, 4, 5, 7) in central Ulaanbaatar city.

Table 1 Yearly averaged values from Oct. 2010 to Sep. 2011 of each pollutant (presented by Maeda).

Annual average	Envioronmental standard (day)	CLEM observation ID					
		01	02	04	05	07	08
SO_2 (μg/m^3)	10	(26)	31	(12)	53	20	18
NO_2 (μg/m^3)	30	(40)	93	(49)	42	37	31
PM 10 (μg/m^3)	50	(152)	189	(120)	355	209	86
PM 2.5 (μg/m^3)	25	-	154	(49)	-	-	-

with SO_2, NO_2 and PM at all the eight stations of CLEM.

Because there are deficit values of measurements, bracket values are in the reference.

The yearly averaged maximum value of NO_2 is 93 μg/m^3 (0.046 ppm) in CLEM-2 in Table 1, and this spot is along the main street Enkhtaivan Ave. (Peace Ave.) extending to the east and west of the inner-city. As for NO_2 concentration, the effluent gas of the car is the main pollution source. On the other hand, the pollution of NO_2 is not so bad at 42 μg/m^3 (0.021 ppm) yearly averaged value in CLEM-5 which is near to ger areas.

The influence of exhaust smoke in winter season from the ger areas, which is 53 μg/m^3 (0.02 ppm), is seen in the yearly averaged maximum value of the SO_2 in CLEM-5. The coal of Mongolia, sulfur content is around 0.3% with good-quality. On the other hand, there is 3% to 4% sulfur content in Chinese coal.

The maximum value of PM 10 in CLEM-5 is 3.5 times higher than the yearly average standard 100 μg/m^3 of Mongolia. Due to the dominance of ger stoves as emission sources, PM concentrations in Ulaanbaatar show a strong seasonal variation with the winter being much worse than the summer due to the ger stove heating. The maximum value of PM 10 is monthly averaged concentration 660 μg/m^3 of Dec. 2011 and 700 μg/m^3 of Jan. 2012 in Fig. 2, and these values expressed the average of all observation stations of CLEM in the city. And so, in Jan. 2012, it was considerably

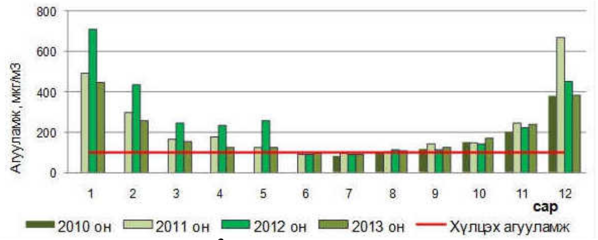


Fig. 2 PM 10 (μg/m^3) for monthly averaged values of all CLEM observation sites in UB city.

Fig. 3 Exhaust gas investigation coming out of a ger stove.

cold. On the contrary, the value of PM 10 in Dec. 2010 is around 370 μg/m^3 and it was not so cold.

3. Measurement of Particulate Matter (PM) of Ger Stoves

Heating stoves have always been used in Mongolia to survive the cold and harsh winter season. The effluent gas investigation of the ger stove was carried out in Mar. 2013 with a ger home of a student of the 117th school in Chingeltei district in Fig. 3. The results of the ingredient analysis of the Baganuur coal and the Nalaikh coal which are usually used in ger areas in Mongolia are as follows:

Sulfur contents: 0.2% ~ 0.4 % (normal Japanese and Chinese coal: 0.5% ~ 4%);

Ashes: 5% ~ 8% (normal coal: 10% ~ 15%).

From these values, coal in Mongolia is high quality smokeless coal.

Exhaust gas survey shows the density of soot particle and TSP (Total suspended particulate) exhausting smoke from a chimney by coal combustion. The results of these experiments are as follows:

(1) Traditional stove: 3.2 g soot particles occurs when coal combustion of 1 kg. TSP concentrations are about 20-40 mg/m^3 when calculating atmospheric CO_2 density at 1%;

(2) Improved stove: 0.6 g or more soot particles occurs when coal combustion of 1 kg. TSP concentrations are about 5-10 mg/m^3 when calculating atmospheric CO_2 density at 1%.

Stoves are the primary heating devices for all households in the ger areas. Improved stoves not only can be lower fuel consumption for fuel efficiency, but also can provide better combustion efficiency. So that a lower level of pollutants fell to about 1/2 (50% reduction) is estimated.

The improved stoves, as a tool to reduce air pollution, are subsidized by both the Government of Mongolia and the Millennium Challenge Account-Mongolia (MCA-M), sell for only a fraction of their actual cost. These stoves are five to eight times cheaper than traditional ger stoves. There is no apparent negative opinions toward improved ger stoves.

There are 184,200 households in the ger areas of Ulaanbaatar in 2012 in Fig. 4, the spread of improved ger stoves is terminated in Nov. 2012, and MCA-M program ended in 2013:

About 70,000 improved stoves provided in 2011, and 29,000 improved stoves provided in 2012;

75% households possess improved stoves in Chingeltei district;

80% households possess improved stoves in Sukhbaatar district;

Khan uul district is continuing the spread of improved stoves activity;

An improved stove made in Canada possesses only the function of hot-water heating apparatus;

Eight types of improved stoves were introduced until 2013 for more ger districts.

4. Diffusion Simulation Method of Particulate Matter

In the case of the flat topography that does not have

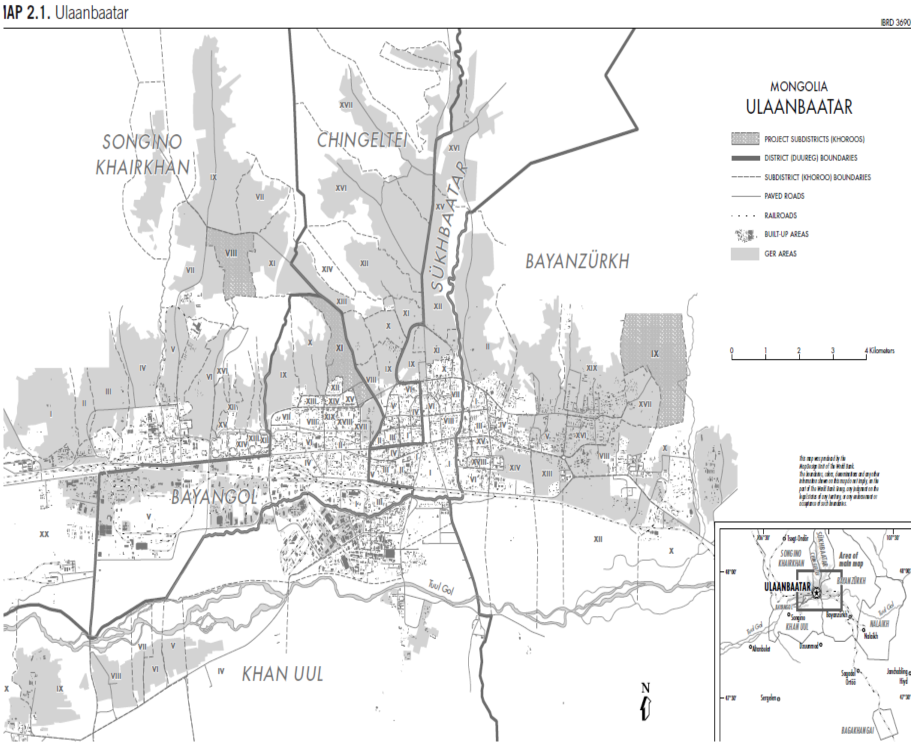


Fig. 4 Location map of the ger distributions in Ulaanbaatar city (gray parts are ger areas).

large hills and mountains, it will be enough in analysis which used an atmospheric computational model by using the three-dimensional Cartesian coordinates. This model is not such a complicated computer program to use. Therefore, we developed a simple computer program Quick Mac 3D Heat & Diff version that solves wind velocity calculation phase and diffusion process calculation phase alternately in time marching scheme [6]. Mac means the Marker and Cell method for incompressible flow solver.

Diffusion of coal combustion ejection gas from ger areas in the central five districts in UB city was assumed. And then, by the diffusion simulation, we estimated TSP concentrations on the ground.

4.1 Calculation Method for Three-Dimensional Wind Velocity Field

As the input data, it uses wind direction and wind speed value at 10 m height from the ground for the computation. By this procedure, thes wind velocities that exist from the ground to 1 km of the sky are estimated by 1/4 power law. In making these velocity values as an initial value, the whole wind field is calculated in Navier-Stokes equation of motion. The calculation is advanced in time in order to satisfy the incompressible condition in each computational mesh. In this N-S equation, we adopt the third-order accurate quick scheme for its convection terms [7, 8]. Simultaneously, the calculation of three-dimensional turbulent field is also solved alternately. Two turbulent equations are turbulent energy (k) transport equation and energy dissipation rate (ε) equation. Therefore, turbulent viscosity ν_t is calculated by turbulent energy (k) and energy dissipation rate (ε).

4.2 Calculation Method for Three-Dimensional Diffusion Field

The wind velocity field in each three-dimensional mesh point was calculated by N-S equation in the previous phase. The three-dimensional flow velocity is expressed by the three velocity components as U (u, v, w) in Fig. 5. The concentration of the pollution diffusive matter is shown in the computing cell center. Following partial differential equation of time

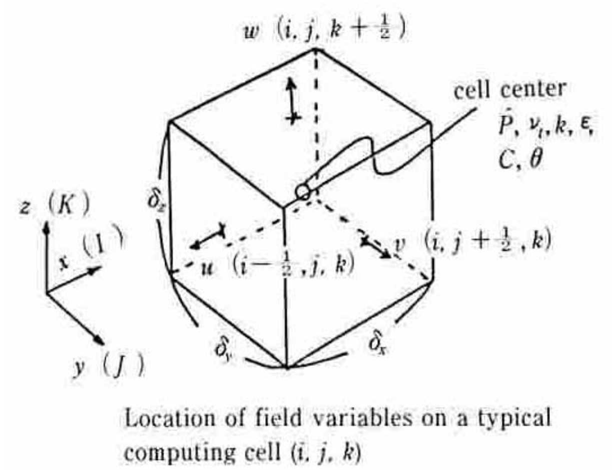


Fig. 5 Location of field variables within the computing Cell (velocities u, v, w are staggered layout, pressure P and concentration C are in the center).

Table 2 Typical vertical diffusion coefficient (m/s).

Stability	Eschenroeder	Case 1	Case 2
Strongly stable	0.5	-	-
Stable	1	0.5	1
Neutral	2	2	5
Unstable	10	5	20
Strongly unstable	50	-	-

development type may be solved using the finite-difference method. The time marching equation with convection and diffusion terms results in the following partial differential equation:

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}+w\frac{\partial c}{\partial z}= \frac{\partial}{\partial x}\left(K_H\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_H\frac{\partial c}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_V\frac{\partial c}{\partial z}\right)+Q \quad (1)$$

where, K_H is a horizontal diffusion coefficient, K_V is a vertical diffusion coefficient, Q is a generation rate of the pollutant (TSP) per unit time.

4.3 Setting of the Horizontal and Vertical Diffusion Coefficients

The estimation method of horizontal direction coefficient of diffusion K_H is described. In the horizontal diffusion, the spreading width is spatially various, and it is difficult to consider it a fixed constant. For the present simulation, the following values were used for K_H coefficient estimation: Value used in the diffusion model from conventional point source calculation and value referring to the calculation example of the one-dimensional plume model. It was assumed so as not for the diffusion width to spread too much over uniformly all time and space in Fig. 5. Consequently,

$$K_H = 10\ \mathrm{m^2/s} \quad (2)$$

Next, the estimation method of vertical diffusion coefficient K_V is described. Okamoto (Okamoto 1976) supposed that the distribution of vertical diffusion coefficient is the trapezoid distribution. Okamoto set the height, which K_V becomes the maximum value, to be 100 m. We estimate that the vertical coefficient K_V is the following value with the atmospheric stability by consulting a model of Eschenroeder.

Okamoto uses the value of the above Case 2 for its own finite difference model in Table 2.

Regarding vertical direction coefficient of diffusion in the strongly unstable mixing layer, Yokoyama (Yokoyama 1992) is illustrating to be a degree as a maximum of 50 m^2/s, showing a change as the actual measurement for 24 h in the day to brightened. In this present simulation, we suppose that vertical coefficient K_V is the following value for the neutral atmospheric condition:

$$K_V = 2\ \mathrm{m^2/s} \quad (3)$$

4.4 Simulation Method for the Diffusion Field of Pollutants

In the simulation of UB city, the center of the computational mesh was put at the near central UB city. It was divided by 20 × 11 × 32 equally-interval difference meshes in x, y, z direction respectively. The mesh spacing is 1,000 m in the horizontal direction, and 25 m in the vertical direction. Therefore, it becomes a calculation field the distance from east to west is 20 km, the distance from north to south is 11 km, and the height from the ground to sky is 750 m which covers 5 districts of UB city. TSP pollutant is continuously discharged from the ground of ger homes to the inside of the computation mesh in the every unit time (s).

5. Diffusion Simulation of Particulate Matter from Ger Areas

In the simulation of UB city, it was divided into 20 × 11 difference meshes in horizontal x, y direction respectively in Fig. 6a. Each household has two traditional ger stoves with our computer program. Emission of ger stoves with households in calm conditions of atmosphere is assumed, and TSP pollutant is continuously discharged from the ger areas to 1,000 × 1,000 m^2 mesh on the ground. Computing meshes are shown in the following figures. The average TSP values of winter season from Nov. to Feb. are calculated.

In calm conditions, the maximum value of TSP concentration of one hour simulation is 125 μg/m^3 in winter season. In the same simulation condition, The maximum TSP concentration of 6 h computation is also about 4,300 μg/m^3 in Fig. 6b. The site of maximum value is located in Zuun ail (100 ail), which has CLEM-5 observation station that is near to ger areas in the upper central region. If we estimate the PM 10 concentration from TSP values, PM 10 can be calculated with TSP × 0.65.

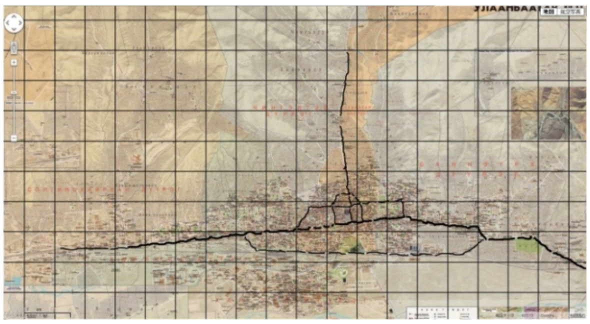
Emission of traditional ger stoves with more than 180,000 ger households were assumed, and raw coal is the most popular heating fuel among households, and total amount of coal used in ger areas is about 743,000 t (2011) or 880,000 t (unknown year from JICA [9]). Therefore, we can estimate that coal consumption per year of one household is 4.2 t per year. Many households will buy their coal at the end of Sep. or the beginning of Oct. when it starts to get colder.

The TSP emission rate in traditional stove is 3.2 kg soot particles of our experiment (JICA proposed 3.4-5.4 kg [9]) with coal combustion of raw coal 1 t. And it is assumed that total amount of coal will be used during four months of the winter (from Nov. to Feb.). The number of ger households within 1,000 × 1,000 m^2 mesh area is calculated all over UB city getting from the map in 2010, and each household has two traditional stoves, so we can estimate the smoke discharge of each 1km square mesh area. Another fuel source is wood, and TSP emission rate in traditional stove of wood will be 3.8 kg soot particles from wood 1 t (JICA data [9]). Wood consumption per year of all ger areas is about 540,000 t (unknown year from JICA).

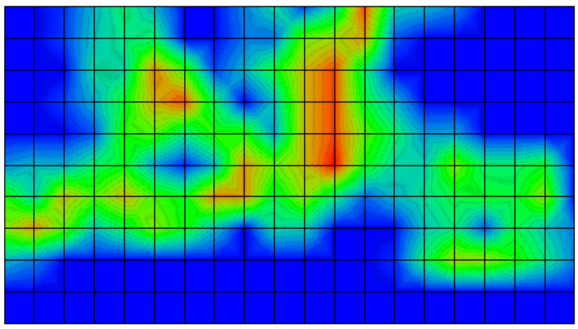
But we don't use this wood emission data in our present simulations. Alternatively, the dry feces of the domestic animal, old used tires and home garbage are burned in ger stoves.

6. Diffusion Simulation of Particulate Matter from Ger Areas When North Wind with 2 m/s Blows in Succession

The maximum value is located in Zuun ail (100 ail) by the simulation of north wind blowing. The maximum TSP concentration of 6 h full coal combustion computation is about 5,000 μg/m^3 in Fig. 7, and PM 10 can be calculated to 3,250 μg/m^3. If each household



(a)



(b)

Fig. 6 (a) Computing meshes of Ulaanbaatar city; (b) Computing result of diffusion by calm condition (grey regions show the high concentration of TSP in winter).

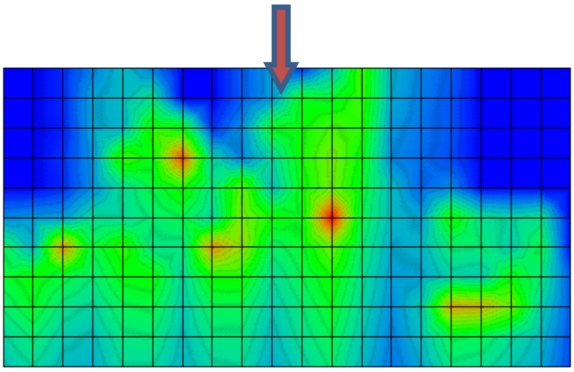


Fig. 7 Computational result of diffusion when north wind 2 m/s blows.

has only one traditional stove, we can estimate the PM 10 value is about 1,600 μg/m^3. If each household has one improved stove, we can estimate that the PM 10 value is about 800 μg/m^3. Early and late in the heating season, homes are heated partially in the day and night, and not continuously. During this time, wood is often used, because a wood fire is easier to start and gives more rapid heat than coal. During the middle of winter season, ger homes are heated 24 h per day. Coal is generally used, and peaks of full combustion are at the evening, midnight and early morning .

PM concentrations are increasing in winter season from November to February mainly due to the residential (namely gers and houses) heating in ger areas and coal combustion in heat-only boilers.

HOBs (Heat-only boilers) are installed in schools and other institutions, factories, and so on. But we don't involve the HOB emission sites in those simulations because of the small part of smoke sources.

7. Diffusion Simulation of Particulate Matter from Three Thermal Power Plants

7.1 Various Kinds of Data for Power Plants (from JICA)

Data of each position coordinate of stacks, height of stack, inside diameter, effluent gas temperature and effluent gas velocity, monthly averaged operation pattern for three power plants is used to the simulation program.

The heights of stacks are as follows:

(1) Power plant 2: 100 m;
(2) Power plant 3-1: 100 m;
(3) Power plant 3-2: 150 m;
(4) Power plant 4: 250 m.

From monthly averaged operation pattern for three power plants, we estimate the exceeding rate from the average during the four months in middle of winter season. These values are as follows:

(1) Power plant 2: 1.24;
(2) Power plant 3-1: 1.55;
(3) Power plant 3-2: 1.45;
(4) Power plant 4: 1.14.

Coal consumptions of three power plants in 2010 are the following values:

(1) Power plant 2: 190,210 t/year;
(2) Power plant 3-1: 346,906 t/year;
(3) Power plant 3-2: 690,047 t/year;
(4) Power plant 4: 2,879,677 t/year.

TSP emission-factor of three power plants in 2010:

(1) Power plant 2: 15.2 kg/coal 1 ton;
(2) Power plant 3-1: 5.5 kg/coal 1 ton;
(3) Power plant 3-2: 1.9 kg/coal 1 ton;
(4) Power plant 4: 0.2 kg/coal 1 ton.

We can estimate the TSP emission values of No. 2 smoke stack from Table 2, then in winter four months, 2853 t × 4/12 × 1.24 (exceeding rate) is equal to 1179 t in power plant No. 2. This value becomes 113.7 g per second. TSP emission rate in power plant No. 3-1 becomes 94.8 g per second when computing in the same way. In No. 3-2 power plant, TSP is emitted by 61.2 g per second. In No. 4 power plant, it is emitted by 21.1 g per second in Fig. 8.

7.2 Computational Result from Smoke of Three Power Plants in Winter Season

The average TSP values of three power plants in winter season from Nov. to Feb. are calculated. Under stable atmospheric condition, the maximum value of TSP concentration of 6 h simulation when northwest

Table 2 Yearly total emission values in 2010 (t/year).

Power plant	TSP	PM 10	SOx	NOx	CO
No. 2	2,853	1,855	209	42	2,473
No. 3-1	1,902	1,237	692	221	31,477
No. 3-2	1,311	852	1,380	442	-
No. 4	576	374	6,335	8,351	-
Total	6,643	4,318	8,616	9,056	33,950

Fig. 8 Power plants No. 4 (left) and No. 2 (right).

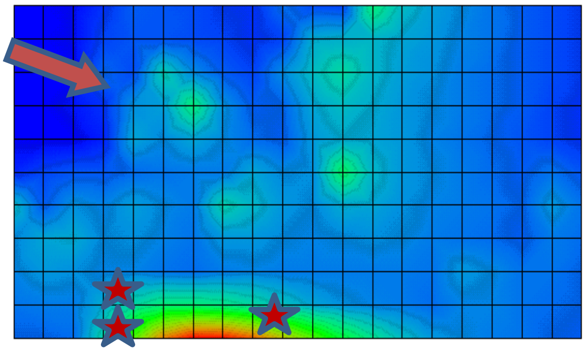


Fig. 9 Diffusion simulation from power plants No. 4 & 2 (left) and No. 3 (right) when northwest wind 2 m/s blows.

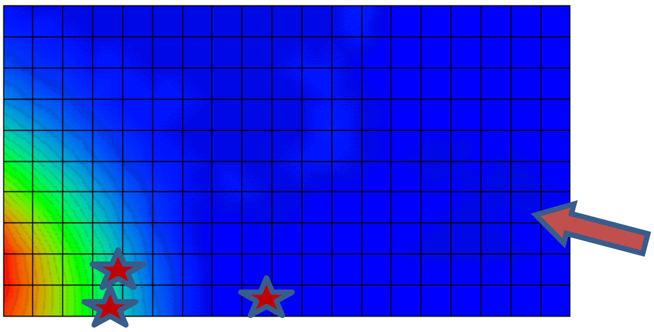


Fig. 10 Diffusion simulation from power plants No. 4 & 2 (left) and No. 3 (right) when southeast east wind 2 m/s blows.

wind 2 m/s blows is 13,500 μg/m^3 on the ground in Fig. 9. It is about 3 times higher than the ger district for pollution concentration from this calculation result. High pollution areas around power plants are the districts with less population.

When southeast east wind 2 m/s blows, the maximum value of TSP concentration of six hour simulation is 167,000 μg/m^3 on the ground in Fig. 10. The smoke from the second thermal power station and the third thermal power station attacks the residential area of Songinokhairkhan district that located in the western part of UB city. Sometimes in the morning of winter season, the smoke from the thermal power station flows transversely to horizontal direction and goes to the ground like Figs. 9 and 10. With most cases, smoke from the three thermal power plants goes above in the daytime.

8. Various Smoke Sources in UB City and Asthma Prevalence of Women

According to the air quality agency of UB city, the various sources of the air pollution seems to be the following:

(1) Emission of ger stoves with more than 180,000 households (50%);

(2) Exhaust emission from more than 300,000 vehicles (20%);

(3) Smoke from three thermal power stations (10%);

(4) Smoke from small & medium size boilers (6%);

(5) Smoke and soot from others (mine dust, gasoline stand, waste disposal treatment place, ger's dirt road) (14%).

From the foregoing percentage, an anti-smoke measure of the ger stoves in the ger districts of the winter season is very important for improvement of the air pollution [10].

We investigated the asthma prevalence [11] of about one hundred women that were over 20 years old in UB city in 2012 [12]. From the questionnaire result, an asthma incidence of 18 ~ 49 years old was 15.6%. The same investigation of 20 ~ 44 years old women in Japan indicates 5.4%. The asthma morbidity becomes about 30% respectively when the excrement of domestic animals, garbage of houses, and old used tires were burned for the fuel of ger stoves.

In addition, the asthmatic morbidities of our investigation according to residence types were as follows:

(1) Ger outside of the UB city (n = 13) (7.7%);

(2) Apartment in the UB city (n = 33) (15.2%);

(3) Ger inside of the UB city (n = 44) (18.2%).

9. Conclusions

The influence of the emission of ger stoves and three thermal power plants was investigated in this paper.

The several diffusion simulations of air pollution using the emission data of 2010 have been carried out by using our computer program. The excessive high pollution concentrations of particulate matter had been detected in ger areas of upper central areas from our simulation results.

The local inhabitants have stated that there were influences of the exhausting smoke from the three power stations. We have also simulated the diffusion process with two cases of the southeast east and the northwest wind. With the case of the southeast east wind, Songinokhairkhan district was polluted particularly by high concentrations.

We have also investigated the asthma prevalence of women in UB city in 2012, and persons living in ger districts of the city had high asthmatic prevalence.

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