EVALUATION OF MODEL ESTIMATED ANTHROPOGENIC PM2.5 EMISSIONS OVER ASIA

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KEY WORDS: Exhaust emission, biomass burning, black carbon and emission inventory.

ABSTRACT

This study aims to evaluate model estimated emissions over Asia. Firstly, two main anthropogenic emission sources of particulate matter whose aerodynamic diameter is less than 2.5 μm ($PM_{2.5}$), exhaust emission and biomass burning were estimated by bottom-up approach model developed with literature survey and satellite remote sensing over Asia from 2000 to 2009. Secondly, estimation error ofestimed exhaust emission and biomass burning $PM_{2.5}$ were evaluated with compared to reported anthropogenic traffic Black Carbon (BC) and forest fire BC inventories quantitatively over Asian mega cities. It was found that total black carbon $PM_{2.5}$ from exhaust emissions in 2000 is 740 Gg, that from biomass burning is 404 Gg in 2002 in Asian 22 countries easter than Pakistan. Relative errors compared with black carbon inventory are 72% overestimation from exhaust emission and 1% underestimation from biomass burning over Asia.

1 INTRODUCTION

1.1 Backgrounds and objective

Air pollution is a serious problem over urban and even rural areas of the world because of emissions from vehicles, factories, dusts, forest fires and poor legal regulations which are not prepared precisely or poor force (JICA, 2005). Particulate matter (PM) is a complex mixture of solid and liquid particles which remain suspended in the air. It is one of the major pollutants that affects air quality in urban and even rural areas of the world (Gupta, *et al.*, 2006). PM whose aerodynamic diameters is less than 2.5μm ($PM_{2.5}$) remains in the inner part of lung and results in asthma, bronchitis and even cancer.Exposure experiments concluded that long term exposure to combustion related fine particulate air pollution is an important environmental risk factor for cardiopulmonary and lung cancer mortality (Pope *et al.*, 2002). It is reported that $PM_{2.5}$ mainly produced by exhaust emissions are estimated about 40% of all $PM_{2.5}$ emissions in Tokyo[1], and forest fire events about 30% in USA[2], about 20 % in Canada[3]. However, they were estimated and measured by different methodologies and assumptions. The investigation in global scale especially for in Asia is not enough. Our previous studies reported spatiao-temporal patterns of exhaust emissions and biomass burning PM2.5 by integrating bottom-up approach model development and satellite remote sensing over Asian mega cities (Kishi *et al.*, 2008)(Kishi *et al.*, 2009). However, estimated results haven't evaluated by other previous research findings.

Based on these backgrounds, the objective of this study is to evaluate estimated emissions over Asia by compared with reported emission inventory datasets. Study area is focused on Asian 22 countries easter than Pakistan; Bangladesh, Bhutan, Brunei, Burma, Cambodia, China, India, Indonesia, Japan, Laos, Malaysia, Mongolia, Nepal, NorthKorea, Pakistan, Philippines, Singapore, SouthKorea, SriLanka, Taiwan, Thailand and Vietnam

2 METHODOLOGY

2.1 Framework and data used in this study

Figure 1 shows a framework of evaluation of bottom-up approach model estimated anthropogenic $PM_{2.5}$ emissions over Asia. Firstly, exhaust emissions and biomass burning $PM_{2.5}$ are estimated by developing bottom-up approach model with literature survey, statistical datasets and land cover properties observed from satellite. Secondly, estimation errors of estimated $PM_{2.5}$ are evaluated by comparing black carbon $PM_{2.5}$ obtained from reported BC inventory. Finally, time series of anthropogenic $PM_{2.5}$ emissions inventory is developed over Asian countries.

[1]Ministry of the environment (http://www.env.go.jp/)
[2]U.S. Environmental Protection Agency (http://www.epa.gov/)
[3]Environment Canada (http://www.ec.gc.ca/)

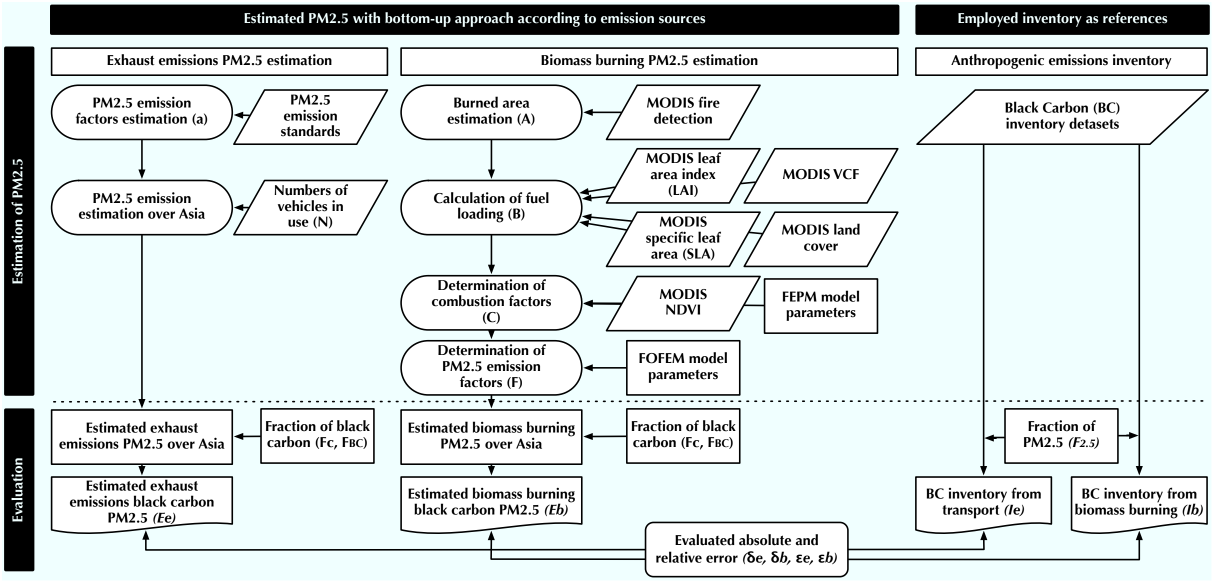

Figure 1. Flowchart of evaluation of bottom-up approach model estimated anthropogenic $PM_{2.5}$ emission over Asia.

2.2 Estimation of exhaust emissions $PM_{2.5}$ with bottom-up approach

Total exhaust emissions $PM_{2.5}$ from 2000 to 2007 in Asian countries are estimated by equation 1 (Kishi *et al.*, 2008);

$$E_e = \sum_{i=p,c} N_{ijk} a_{ijk} b_{ijk} \qquad s.t. \quad b^* = 1 \tag{1}$$

where E_e is estimated total amount of exhaust emissions $PM_{2.5}$ in each country (denoted as j) and year (k) . i stands for car types including passenger car (p), commercial car (c). N is the number of vehicles in use (JAMA, 2008). a is the emission factor which represents an exhaust regulation by law (ADB, 2006). b is defined as the ratio of diesel vehicles to that of gasoline. It is supposed that all vehicles are diesel one in this study because not all data is available among 22 countries

$PM_{2.5}$ emission factors are defined by government restrictions in each country. European emission standards, EURO 1 to 4[4] are referenced to consider the factor over Asian countries except for Japan and Taiwan. Japan have employed emission standards of Japan[5] and Taiwan have that of United States[6]. Countries those who have no emission standards are regarded as EURO 0 and it is estimated by exponential approximation (Kishi *et al.*, 2011).

2.3 Estimation of biomass burning $PM_{2.5}$ with bottom-up approach

Total biomass burning $PM_{2.5}$ emissions from 2002 to 2009 in Asian countries are estimated by equation 2. Proposed approach for monitoring of biomass burning particulate emissions across contiguous United States (Zhang *et al.*, 2008) is applied to Asia Easter than Pakistan with MODIS remote sensing data by following formula (Kishi *et al.*, 2009);

$$E_b = \sum_{k=1} \sum_{l=1} \sum_{j=1} \sum_{i=1} A_{ijk} B_{ijl} C_{ijkl} F_{ijkl} \tag{2}$$

where E_b is the biomass burning $PM_{2.5}$ emissiona in a certain time period and location (Mg), A is burned area (Km^2), B is the amount of fuel mass available for combustion (Mg/Km^2), C is the combustion factor, F is the emission factor for $PM_{2.5}$, k is the time period, l is the fuel type. i and j define the detected fire location in column and row. They are determined with literature survey and MODIS land cover products shown by Table 1.

2.4 Referenced black carbon emissions inventory datasets

Reported Black Carbon (BC) inventory datasets whose diameter are corresponding to PM_{10} are employed to evaluate model estimated exhaust emissions and biomass burning $PM_{2.5}$. Anthropogenic BC inventory datasets in 2000 are ob-

[4]European Union: Air pollution (http://europa.eu/legislation_summaries/environment/air_pollution/)
[5]Ministry of Environment, Japan: Emission standards for vehicles(http://www.env.go.jp/air/car/)
[6]U.S. Environmental Protection Agency: Emission standards reference guide (http://www.epa.gov/otaq/standards/)

Table 1. Satellite data used for estimating biomass burning $PM_{2.5}$ emissions

Corrected satellite data with MODIS	Temporal and spatial resolution	Data source	Purpose
Fire data	Monthly and 10 km	University of Tokyo	Estimation of burned area
Land cover type	Static and 10 km	Boston university	Development of fuel loading
Leaf area index	Monthly and 4 km	Boston university	Development of fuel loading
Specific leaf area	Static and 60 km	University of Tokyo	Development of fuel loading
Vegetation continuous field	Static and 1 km	Global land cover facility	Development of fuel loading
NDVI	8days and 10 km	Lille University	Determination of moisture condition

tained from Center for Global and Regional Environmental Research (CGRER), University Iowa[7]. BC inventory is estimated by wide variety of source types, species and regions including transportation and biomass burned roughly described by equation 3 (Streets *et al.*, 2003). ;

$$I_{j,k} = \sum_{l}\sum_{m}\sum_{n} A_{j,k,l,m} ef_{j,k,l,m}(1-\eta_{j,k,l,m}\alpha_{j,k,l,m})X_{j,k,l,m} \quad (3)$$

where j, k, l, m, n represents species, region, sector, fuel and activity type, abatement technology. I is emissions in this inventory, A is activity rate, ef is unabated emission factor, η is removal efficiency of abatement technology, α is a maximum application rate of abatement technology (n), X is actual application rate of abatement technology (n) ; note that the set of abatement technologies includes a no-control case, such that $\sum_{n} X = 1$

2.5 Evaluation of anthropogenic $PM_{2.5}$ emissions estimation

Anthropogenic $PM_{2.5}$ emissions estimated by bottom-up approach and employed by referenced inventory are compared and evaluated as black carbon particulate matter less than 2.5μm by employing fraction parameters of carbonaceous PM out of PM_{10}, black carbon of carbonaceous PM and $PM_{2.5}$ of PM_{10} because $PM_{2.5}$ is defined only by aerodynamic diameter and BC is by the chemical component. Absolute and relative errors between estimated black carbon $PM_{2.5}$ and reported $PM_{2.5}$ are assessed by equation 4 and 5 shown by Table 2 (Streets *et al.*, 2001) (Bond, *et al.*, 2004);

$$\delta_i = E_i F_C F_{BC} - I_i F_{2.5} \quad (4)$$

$$\epsilon_i = \frac{\delta_i}{E_i F_C F_{BC}} \quad (5)$$

where, δ_i is calculated absolute error of black carbon $PM_{2.5}$ estimated in our study according to emission sources (i); estimated exhaust emission $PM_{2.5}$ (E_e), biomass burning $PM_{2.5}$ (E_b), reported inventory for exhaust emission (I_e) and biomass burning (I_b). ϵ_i is calculated relative error of that. F_C is the fraction of carbonaceous PM out of total PM_{10}, F_{BC} is the fraction of black carbon out of total carbonaceous PM and $F_{2.5}$ is the fraction of $PM_{2.5}$ out of PM_{10}. In this study, F_c of fire is regarded as 1 because biomass burning $PM_{2.5}$ is estimated from carbonaceous fuel loadings and fraction of $PM_{2.5}$ of fire is employed from fraction of PM_{fine} because no available factor of $PM_{2.5}$ was found.

Table 2. Employed fractions of carbonaceous PM, black carbon and $PM_{2.5}$ according to emission sources.

	Carbonaceous PM (F_c)	Black carbon (F_{BC})	$PM_{2.5}$ $(F_{2.5})$
Traffic	0.93	0.81	0.95
Fire	1.00	0.25	0.90

3 RESULTS AND DISCUSSIONS

3.1 Evaluation of anthropogenic black carbon $PM_{2.5}$ estimations over Asia in 2000

Estimated black carbon particulate matter less than 2.5 μm from exhaust emission in 2000 and biomass burning in 2002 with bottom-up approach is compared with referenced black carbon $PM_{2.5}$ inventory for traffic and biomass burning emissions in 2000 in 22 Asian countries. Estimated black carbon $PM_{2.5}$ amount and corresponding estimation error values are shown by Table 3. These three points can be indicated;

- Total exhaust emissions black carbon $PM_{2.5}$ are estimated by developed model about 740 Gg/yr in Asian 22 countries. Japan and China have extremely large exhaust emissions about 63% of all Asian countries. Indonesia, Thailand,

[7] Center for Global and Regional Environmental Research (http://www.cgrer.uiowa.edu/EMISSION_DATA/)

Philippines, South Korea and india are following to Japan and China. Their emissions are totally 20% emissions of all exhaust emissions. On the other hand, for the referenced inventory data, India has the largest emissions about 34% of all Asia. Following to India, China has about 28% and Japan has about 10%.

- Total biomass burning black carbon $PM_{2.5}$ is estimated by developed model about 404 Gg/yr in Asia. The largest biomass burning black carbon $PM_{2.5}$ is estimated in India about 33% of all Asian emissions. China, Burma, Thailand, Laos and Vietnam are following to India and about 53% of all biomass burning emissions are from these 5 countries. On the other hand, in the referenced inventory data, China has the largest biomass burning emissions about 25% of all Asia. India, Indonesia are following to China about 18% and 13%.
- Focused on the relative errors, total emissions in Asian 22 countries is 72% overestimation for the traffic sector and only 1% underestimation for the biomass burning sector comparing to referenced inventory datasets. For the traffic sector, Burma has smallest relative error about 13%, but India has largest error for -224%. For the biomass burning sector, Philippines has the smallest errors about 3%, on the other hand, Mongolia has the largest error about -1,629% excluding zero value estimations .

3.2 Estimation of time series of anthropogenic $PM_{2.5}$ estimations over Asia

Figure 2 and 3 show annual time series of estimated anthropogenic $PM_{2.5}$ emissions over Asian 22 countries. Figure 2 shows total exhaust emissions are decreasing from 2000 to 2007 in large emission countries. Japan, China have extremely large exhaust emissions compared to other Asian countries in 2000, but their emissions are decreased drastically. Japan has reduced the exhaust emissions about 84% in 7 years. China also reduced the emissions about 47% from 2000 to 2003, but emissions are increasing after that. On the other hand, other countries' emissions which have small amount of $PM_{2.5}$ are keep increasing. Figure 3 shows total amount of biomass burning $PM_{2.5}$ seems to be increasing in Asia but there are strong annual variation. India has about 13 times larger $PM_{2.5}$ emissions in 2007 comparing to 2006. Especially extremely large amount of biomass burning $PM_{2.5}$ is estimated in 2007 in many Asian countries.

3.3 Discussions

The number of vehicles in use is slightly increasing in every Asian countries but emission standards are becoming strict clearly shown by Japan and China. Emission regulation factors defined by governmental emission standards have large impact for exhaust emissions estimation shown by Figure 2 and Equation 1. In this bottom-up approach model, every vehicle is regarded as diesel one and assumed to move for $100km$ per day for $PM_{2.5}$ stock estimation. This assumption feels unrealistic because these factors must be different in each country. In addition to that, enforcement of law should be considered as a removal efficiency parameter.

According to Figure 3 and 3, total amount of biomass burning $PM_{2.5}$ emissions in Asia is close to that of inventory. However, they have large annual temporal variation. Hot spot detection counts may have strong impact for annual temporal variations in this bottom-up approach model shown by 2. Considering estimation errors, relative errors are large in many country, for example, Many countries including Indonesia, Mongolia and Nepal have large underestimation but India has very large overestimation. One of the main reasons for underestimation and overestimation can be considered for detection of hot spots from satellite because it only detects a fires which is burning when satellites are passing in that time, on the other hand, burning duration time is not consirdered.

In addition to model refinements, spatial and temporal resolution should be upgraded for monitoring of global atmospheric conditions. It is true that one year and country level estimation provided us informative findings but it is not sure it wold be related to actual human ambient conditions in urban area. Not only annual variations but also seasonal variations are confirmed especially for biomass burning (Kishi *et al.*, 2009). However, obtaining $PM_{2.5}$ measurement and inventory datasets in this fine temporal and frequent time resolution for model evaluation is difficult task. One proposing method is to employing satellite observation data to monitor human ambient $PM_{2.5}$ over global scale in fine resolution.

4 CONCLUSIONS AND FUTURE WORKS

This study evaluated model estimated emissions over Asia compared with reported emission inventory datasets. It is found that total black carbon $PM_{2.5}$ from exhaust emissions in 2000 is 740 Gg, that from biomass burning is 404 Gg in 2002 in Asian 22 countries easter than Pakistan. Relative errors compared with black carbon inventory are 72% overestimation from exhaust emission and 1% underestimation from biomass burning. In annual time series analysis, exhaust emissions are totally decreasing from 2000 to 2007 and biomass burning tends to increasing from 2002 to 2009 though annual variation is extremely large. For the future works, there are several points to be considered mentioned in discussion section. Firstly, Emissions estimation model with bottom-up approach should be refined continuously. Secondly, spatial and temporal resolution should be upgraded to analyze urban area conditions and expanding these model to global scale. We are planning to analyze urban area in 10 km gridded resolution over global mega cities by integrating modeling and satellite remote sensing.

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Table 3. Estimated and referenced black carbon $PM_{2.5}$, and corresponding estimation errors.

Country	Model estimation		Streets inventory		Absolute Error		Relative Error	
	Traffic Tg/yr	Fire Tg/yr	Traffic Tg/yr	Fire Tg/yr	Traffic Tg/yr	Fire Tg/yr	Traffic %	Fire %
Bangladesh	3,190	7,441	1,017	11,898	2,174	-4,457	68	-60
Bhutan	N/A	415	48	360	-48	55	N/A	13
Brunei	1,526	0	0	0	1,526	0	100	0
Burma	2,901	42,451	2,537	36,288	364	6,163	13	15
Cambodia	787	15,519	124	7,047	663	8,472	84	55
China	213,671	81,299	56,782	101,169	156,890	-19,870	73	-24
India	21,367	132,501	69,179	74,511	-47,812	57,990	-224	44
Indonesia	70,953	8,604	6,736	53,001	64,217	-44,397	91	-516
Japan	254,276	265	21,271	1,431	233,005	-1,166	92	-439
Laos	261	30,579	67	13,779	195	16,800	75	55
Malaysia	13,513	2,829	3,097	13,617	10,416	-10,788	77	-381
Mongolia	1,038	855	95	14,778	943	-13,923	91	-1,629
Nepal	N/A	398	627	3,735	-627	-3,337	N/A	-838
NorthKorea	N/A	0	1,036	1,026	-1,036	-1,026	N/A	N/A
Pakistan	14,993	5,184	8,636	8,073	6,357	-2,889	42	-56
Philippines	40,457	14,802	1,216	14,391	39,241	411	97	3
Singapore	3,050	0	333	0	2,718	0	89	0
SouthKorea	30,961	0	7,562	1,116	23,399	-1,116	76	N/A
SriLanka	6,248	0	1,321	2,457	4,928	-2,457	79	N/A
Taiwan	9,861	256	846	342	9,016	-86	91	-33
Thailand	48,211	34,125	13,329	31,320	34,883	2,805	72	8
Vietnam	2,826	26,140	7,828	17,982	-5,002	8,158	-177	31
Total	740,090	403,666	203,680	408,321	536,410	-4,655	72	-1

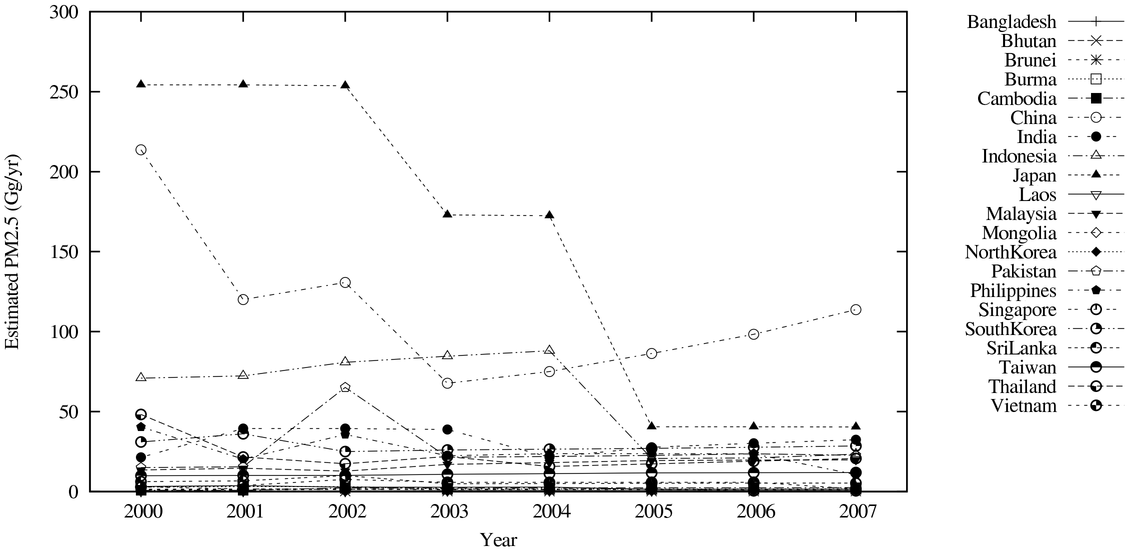

Figure 2. Estimated time series of exhaust emissions $PM_{2.5}$.

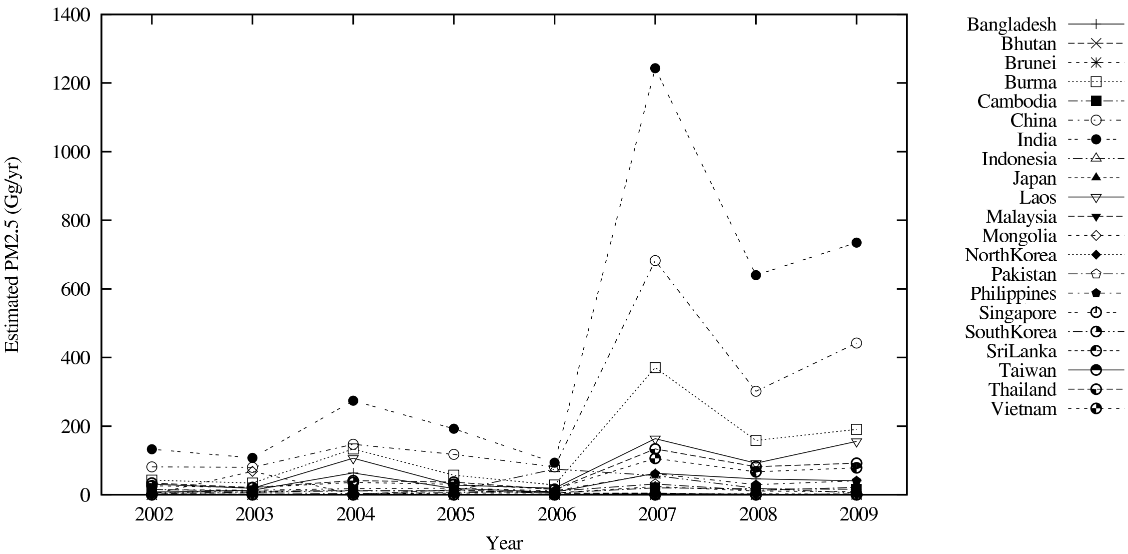

Figure 3. Estimated time series of biomass burning $PM_{2.5}$.