LAPORAN PENELITIAN

"Emission Inventories for Air Pollutants and Greenhouse Gases with Emphasis on Data Management in the Cloud"

Didin Agustian P. Ph.D

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Emission Inventories for Air Pollutants and Greenhouse Gases with Emphasis on Data Management in the Cloud

Development of an emission inventory (EI) is building up a complex and comprehensive dataset to provide useful information for air quality management (AQM) and assessment of greenhouse gas mitigation options. Accurate EI database is required to prioritize the emission reduction measures. This chapter highlights necessary steps of EI process and emphasizes the QA/QC required to minimize the uncertainty of EI estimates. A grid network for spatial allocations and temporal variations is required for identifying the hotspots and trends of the emissions in the domain. High resolution of gridded EI datasets would provide more detailed information of air pollution of a region during a specific time thus providing large datasets. When EI results are used to prepare the input data for 3D air quality modeling, hourly emissions of each species on every grid are required for the modeling period (a few months to several years) which can lead to a big challenge when tackling the overflow of data. Data computing and management through cloud system could potentially help to facilitate the storage and flows of an intensive amount of EI information. This chapter also illustrates with examples of EI databases developed by the authors for various domains, ranging from the whole Southeast Asia region to national and urban scales.

Chapter written by Thi Kim Oanh NGUYEN, Nguyen Huy LAI, Didin Agustian PERMADI, Nhat Ha Chi NGUYEN, Kok SOTHEA, Sukhuma CHITAPORPAN, Thongchai KANABKAEW, Jantira RATTANARAT and Surasak SICHUM.

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3.1. Introduction

Emission inventory (EI) is a comprehensive list of emissions from various sources of air pollutants and/or greenhouse gases (GHGs) in a defined area during a specific time (USEPA 2007). The emission sources covered in an EI include both artificial (e.g. fuel combustion, industrial manufacturing and biomass open burning among others; Shrestha *et al*. 2013) and natural (e.g. biogenic and geogenic emissions) sources. For an EI of GHGs, the emissions related to land-use and land-cover changes are also included (IPCC 2006). EI can be developed for a specific pollutant such as sulfur dioxide (SO_2) or black carbon (BC), a group of atmospheric substances or multi-pollutants depending on the intended uses of the dataset. Some of the key air pollutants that are important in air quality management (AQM) include particulate matter (PM), carbon monoxide (CO), SO_2, oxides of nitrogen (NO_x) and non-methane volatile organic compounds (NMVOCs). The key species of GHGs covered in an EI include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and F-gases. Recently, a group of pollutants known as the short-lived climate pollutants (SLCPs) is of interest from the toxic effects and climate forcing points of view.

The EI is an important activity in AQM. Based on EI results, key pollutants of concern and their key sources could be identified; thereby, the source emission control efforts can be prioritized to reduce air pollution in the domain. An accurate EI database, thus, is a prerequisite for effective AQM. For public information, the EI results presented in a simplified graphic format showing the pollution loads from different sources can be publicized to raise awareness of people, hence enhancing the participatory approach to the emission reduction. For air quality modeling, the emission input data generated by an accurate EI is a foremost requirement.

To ensure a high quality of an EI database, appropriate quality assurance and quality control procedure (QA/QC) should be applied which is viewed as an integral part in the EI process. The core elements of data quality objectives are to ensure transparency, consistency, comparability, completeness and accuracy (IPCC 2006). Estimation of emission amounts is commonly done by multiplying emission factors (EFs) and activity data (AD) of each considered source. Obtaining the representative EF for a specific emission source in a given geographical area would primarily require experimental studies involving the direct measurements which, in turn, would require large resources. In the lack of measurement data for a source, the EFs are normally obtained from the literature, thus entailing large uncertainty. Other source of uncertainty is the one inherited from the AD which rapidly changes in the developing countries. EI development therefore needs tremendous and continuous efforts to improve, and it is done periodically to ensure the representative EI database (USEPA 2007).

In principle, the EI database should be easily assessed and understood by many kinds of audiences and readers. The data providers could provide simplified graphics or maps for the public to track the trend of air pollution emissions in their locations. Because there are numerous sources present in a geographical EI domain which ranges from the urban to continental/global scale, the detailed EI datasets for a given time period would be huge. Therefore, the EI databases should be handled properly, and this data management can be supported by cloud computing (CC). Particularly, CC can be used to store and publicize the data, and manage the intensive data flow. This chapter therefore also highlights the potentiality of CC in EI data management.

3.2. Methodology for development of EI database

3.2.1. *Framework of EI development*

The overall framework of EI is presented in Figure 3.1. The EI Design phase is the first important task in preparing an EI, and it includes the following steps:

– identification of EI manager and EI compiler;

– identification of the key issues;

– selection of air pollutants and then further selection of sources along with respective data sources needed;

– selection of airshed (inventory domain), for example, based on administrative boundaries;

– selection of temporal resolution, for example hourly, daily or annual, which depends on the purpose of EI;

– design reporting document of EI.

Two main inputs for the EI calculation are EF and AD, and they have to be compiled in the next steps for the target sources. The AD includes, for example, the fuel consumption rate per year in industry and power plant (for point source category), number of vehicles and the average traveling distance per year (for on-road mobile source category), or fuel consumption rate for domestic cooking or amount of biomass subjected to open burning (for area source category). Relevant EFs, emission amount per unit of AD, for each source type within a category should be compiled from existing EI manuals or other published sources if locally developed EFs are not available. Emission calculation is done with QA/QC procedures employed to ensure the accuracy of the EI database (detailed in Shrestha *et al*. 2013).

The EI results can be verified by comparison with emission estimates prepared by other bodies and by comparison with estimates derived from fully independent assessments, for example atmospheric concentration measurements. There are several tools for verification of the EI results, including among others: (1) back-estimates to cross check the results with the previous EIs, (2) inverse modeling, opposite to dispersion modeling, to calculate back the EI that fits with the observation data and (3) satellite data may be used for the species that have relatively short life time in the atmosphere so that the observed levels can reflect the sources of emissions. The emission results of each species are normally presented with the uncertainty level or in the form of the best estimate along with a high and a low estimate.

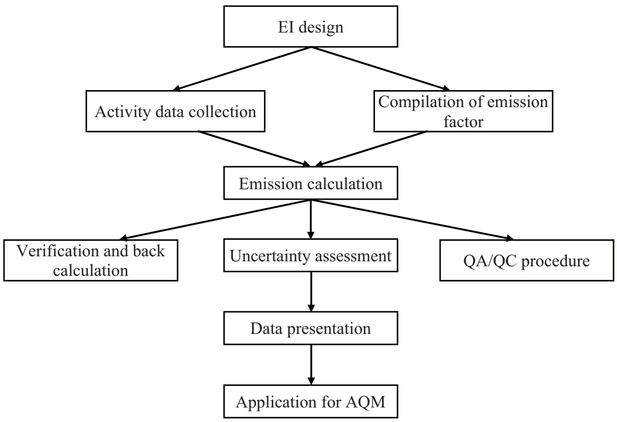

Figure 3.1. *Framework of emission inventory (source: adapted from MoE NZ 2001 and UNEP-APCAP 2018)*

The EI results are then presented to relevant stakeholders and used for AQM, for example for the formation of regulations and mitigation measures by policy makers, to general public to raise awareness, and as the input to dispersion modeling.

3.2.2. *Calculation of EI*

The common formula for emission calculation is by multiplying AD and EF, and for the sources that have control devices, the emission control efficiency (η) is also included as shown in equation [3.1]. The AD types required are varied by source; for example, fuel consumption rate is required for the EI of thermal power plants, manufacturing industry, residential and commercial combustion, while the amount of biomass subjected to burning is used in the EI of biomass open burning, the vehicle kilometer traveled (VKT) and the number of engine start-ups required for EI of traffic, etc. The collection of the actual emission control efficiencies (η) is also one of the challenges, as the values are varied according to the device's configuration, operation and maintenance:

$$Em_{i,j} = AD_{i,j} \times EF_{i,j} \times \frac{(100-\eta_{i,j})}{100} \qquad [3.1]$$

where $Em_{i,j}$ is the emission load of pollutant *i* of source *j* (mass unit/year); $AD_{i,j}$ is the activity data of pollutant *i* from source *j*; $EF_{i,j}$ is the emission factor of pollutant *i* from source *j*; and $\eta_{i,j}$ is the emission control efficiency (in percent) of pollutant *i* from source *j*.

3.2.3. *Sources of data*

3.2.3.1. *Emission factors*

In order to have a good emission estimate, the EFs should be measured for each key local source to generate EFs, taking into account the different fuel usage, operation of control devices, etc. This is a resource consuming task; hence, it is normally conducted comprehensively only in some countries such as United States of America (USA) (i.e. AP-42). For other places where no locally measured EFs are available, the compiled values by different published sources may be used (Table 3.1). However, most of the EFs from these databases are based on the measurements made in developed countries; hence, uncertainties may arise when applied for emission estimates in low- and middle-income countries.

No.	Source of information	References
1	Atmospheric Brown Cloud: Emission Inventory Manual (ABCEIM)	Shrestha *et al*. (2013)
2	EMEP/EEA Emission Inventory Guidebook 2016	EMEP/EEA (2016)
3	USEPA Emission Factor & AP-42	USEPA (2005)
4	IPCC Guidebook	IPCC (2006)
5	GAP: Global Air Pollution Forum Emission Manual	SEI (2004)

Table 3.1. *Summary of several EF compilations*

3.2.3.2. *Activity data*

AD should be collected at local sources by survey or from the national statistical books for the emission calculation. In many cases, these data are not available for many sources in the EI domain of interest. Several organizations have collected, synthesized and publicized the AD at the country level on the websites (Table 3.2) that can be extracted for use.

No.	Activity data	Source of information	Website
1	Fuel consumption data	International Energy Agency	http://www.iea.org/statistics/
2	International biomass fuel consumption data	United Nations Energy Statistics Yearbooks	https://unstats.un.org/Unsd/energy/yearbook/default.htm
3	Large point source (in Asia)	Regional Air Pollution Information and Simulation Model (RAINS-ASIA)	http://www.iiasa.ac.at/~heyes/docs/rains.asia.html/
4	Vehicle statistics	International Road Federation (IRF) World Road Statistics	http://www.irfnet.org
5	Ship movements	Lloyd's Maritime Information Service	http://www.Ir.org
6	Data on manufacturing and process industries	United States Geological Survey	https://www.usgs.gov/
		Mineral Yearbooks	http://minerals.usgs.gov/minerals/pubs/country/asia.html/
		Steel Statistical Yearbook	http://www.worldsteel.org/pictures/publicationfiles/
		United Nations Industrial Commodity Statistics Yearbooks	
		Food and Agriculture Organization (FAO)	http://faostat.fao.org/faostat/

7	Country-specific yield per hectare	Food and Agriculture Organization (FAO)	http://faostat.fao.org/site/567/DesktopDefault.aspx
8	Forest fire area	World Fire Web	http://ptah.gvm.sai.jrc.it/wfw/
		Along Track Scanning Radiometer (ATSR)	http://dup.esrin.esa.int/ionia/wfa/index.asp
		Moderate Resolution Imaging Spectroradiometer (MODIS)	http://modis-fire.umd.edu/MCD45A1.asp & http://www.geoinfo.ait.ac.th/mod14/
9	Solid waste generation per capita	United Nations Human Settlements Program	http://www.unhabitat.org

Table 3.2. *Available sources of activity data for emission inventory*

3.2.3.3. *QA/QC measures*

Quality assurance/quality control (QA/QC) procedure is an important part of EI to minimize the errors of EF and AD, estimation methods and finally in EI databases. Several QA/QC procedures are presented in IPCC (2006) and USEPA (2007) that provide various QA/QC elements to be applied, such as reality checks, peer review, sample calculations, computerized checks, sensitivity analysis, statistical checks, independent audit and emission estimation validation.

3.2.3.4. *Structure of EI database*

Depending on the purposes of the EI, the key sources and key pollutants may vary. Major anthropogenic sources include transportation, thermal power plants, manufacturing and processing industries, residential combustion, biomass open burning, etc. Major natural sources include biogenic emissions, forest fires, volcano eruptions, oceanic sources and so on.

The EI species can include the criteria gaseous pollutants (CO, SO_2, NO_x and NMVOC), specific VOCs (benzene, toluene, etc.) and other gases such as ammonia (NH_3) and hydrogen sulfide (H_2S), aerosol species: PM with the aerodynamic diameter less than 10 μm (PM_{10}) and 2.5 μm ($PM_{2.5}$), BC and organic carbon (OC), and GHGs. Temporally, the EI is normally developed for a period of one year (annual), but when the EI results are used for air pollution dispersion modeling purpose, an hourly emission database is required. Spatially, the EI can be conducted based on administrative boundaries (country, city/province, ward, etc.) for AQM purpose and by grid for dispersion modeling purposes.

3.2.3.5. *Existing global and regional EI databases*

Global and regional EI databases have been developed by international research projects and organizations, in order to get the input emission data for modeling applications. The regional and global EI databases have been normally developed using the top-down approach, using available AD from international and national statistical books. The EI databases are first developed based on historical data or projected estimation and, subsequently, are tested by simulating global or regional models to verify the developed EI databases and analyze the uncertainties before publishing. Table 3.3 presents the available global and regional EI databases (with online sources) conducted by organizations worldwide. Basically, these existing EI databases overlap each other by one or more emission sources, or by assessing and using previous EI to project or re-grid to form new datasets (i.e. emissions related to agricultural activities for Asian Russia and Central Asia of REAS2.1 were based on EDGAR 4.2). The common emission sources covered in these databases are usually key anthropogenic sources and biogenic sources, or individual sources such as biomass open burning or oceanic sources.

Dataset	Scale	Year	Major parameters	References
EDGAR v4.3.2 (Anthropogenic)[a]	Global (0.1° × 0.1°)	1970–2012	SO_2, NO_x, CO, NMVOC, PM_{10}, $PM_{2.5\_bio}$; $PM_{2.5\_fossil}$, BC, OC and NH_3	Crippa *et al.* (2018)
EDGAR v4.3.2 (Anthropogenic)[b]	Global (0.1° × 0.1°)	1970–2012	GHGs (CH_4, CO_2, N_2O)	Janssens-Maenhout *et al.* (2017a)
EDGAR v4.3.2_FT2016 (Anthropogenic)[c]	Country level	1990–2016	Fossil CO_2 and GHGs (CH_4, CO_2, N_2O)	Janssens-Maenhout *et al.* (2017a,b); Olivier *et al.* (2017)
EDGAR v4.tox2 (Anthropogenic)[d]	Global (0.1° × 0.1°)	1970–2012	Mercury	Muntean *et al.* (2018)
CGRER (Anthropogenic)[e]	Asia (0.5° × 0.5°)	2000–2006	SO_2, NO_x, CO, VOC, PM_{10}, $PM_{2.5}$, BC and OC	Street *et al.* (2000); Zhang *et al.* (2009)

Dataset	Scale	Year	Major parameters	References
REAS (Anthropogenic)[f]	Asia (0.5° × 0.5°)	2000–2008	SO_2, NO_x, CO, NMVOC, PM_{10}, $PM_{2.5}$, BC, OC, NH_3, CH_4, N_2O and CO_2	Ohara *et al*. (2007); Kurokawa *et al*. (2013)
	Northeast Asia (0.5° × 0.5°)	2005	Polycyclic aromatic hydrocarbons (USEPA priority PAH species, from fluoranthene to benzo[g,h,i]perylene	Inomata *et al*. (2012)
MACCity-anthro[g] (Anthropogenic)	Global (0.5° × 0.5°)	1960–2020	CO, NH_3, NO_x, SO_2, BC and OC	Granier *et al*. (2011)
MACCity-bb[g] (Biomass burning)	Global (0.5° × 0.5°)	1960–2020	CH_4, NMVOC, CO_2, CO, NH_3, NO_x, SO_2, BC and OC	Granier *et al*. (2011)
CAMS-REG-GHG (Anthropogenic)	Europe (0.0625° × 0.0625°)	2003–2009	CH_4, CO, NH_3, NMVOC, NO_x, PM_{10}, $PM_{2.5}$ and SO_2	Kuenen *et al*. (2014)
CAMS-GLOB-ANT (Anthropogenic)	Global (0.5° × 0.5°)	2018	CH_4, NMVOC, CO, NH_3, NO_x, SO_2, BC and OC	Elguindi *et al*. (n.y)
CAMS-GLOB-BIO (Biogenic)	Global (0.5° × 0.5°)	2016–2017	BVOC (isoprene, monoterpenes, methanol, acetone, sesquiterpenes)	Sindelarova *et al*. (2014)
CAMS-GLOB-SHIP (Shipping)	Global (0.25° × 0.5°)	2016–2018	CO_2, NO_x, SO_x, CO and $PM_{2.5}$	Jalkanen *et al*. (2016)
ECLIPSE-GAINS-V5a (Anthropogenic)[h]	Global (0.5° × 0.5°)	1990–2050	CO, NO_x, SO_2, NMVOC, NH_3, CH_4, BC, OC, $PM_{2.5}$, PM_{10} and OM	Kilmont *et al*. (2013)
RETRO (Anthropogenic, biogenic, oceanic, and biomass burning)[i]	Global (0.5° × 0.5°)	1960–2000	CO, NO_x, CH_2O, CH_4, BC, OC and SO_2	Schultz *et al*. (2007a, 2007b); Schultz *et al*. (2008)
Junker-Liousse (Anthropogenic)[j]	Global (1° × 1°)	1860–2003	BC, POC	Junker and Liousse (2008)

Dataset	Scale	Year	Major parameters	References
Andres-CO2-v2016 (Anthropogenic)[k]	Global (1° × 1°)	1950–2011	CO_2	Andres *et al*. (1996)
GFASv1.3 (Biomass burning)[l]	Global (0.1° × 0.1°)	2003–2016	CO_2, CO, VOC, NO_x, N_2O, $PM_{2.5}$-, TPM, TC, OC, BC, SO_2, NH_3, H_2	Kaiser *et al*. (2012)
GFED4 (Biomass burning)[m]	Global (0.25° × 0.25°)	1997–2015	C, CO_2, CO, CH_4, NMVOC, H_2, NO_x, N_2O, $PM_{2.5}$, TPM, TC, OC, BC, SO_2	Giglio *et al*. (2013); van der Werf *et al*. (2010)
IS4FIRES (Biomass burning)[n]	Global (0.5° × 0.5°)	2000–2011	$PM_{2.5}$, PM_{10}	Sofiev *et al*. (2009)
DECSO-NOx (Anthropogenic)[o]	East Asia, Middle East, South Africa and India (0.25° × 0.25°)	2007–2014	NO_x	Mijing *et al*. (2013)
PKU (Anthropogenic)[p]	Global (0.1° × 0.1°)	2002–2013	OC	Huang *et al*. (2015)
GICC (Biomass burning)[q]	Global (1° × 1°)	1900–2005	CO, NO_x, BC, OC	Mieville *et al*. (2010)
GUESS-ES (Biomass burning and biogenic)[r]	Global (1° × 1°)	1970–2009	CO_2, CO, CH_4, NMVOC, TPM, $PM_{2.5}$, NO_x, N_2O, NH_3, SO_2, BC, OC	Knorr *et al*. (2012)
AMMABB (Biomass burning)[q]	Africa (0.5° × 0.5°)	2001–2006	CO_2, CO, NO_x, SO_2, BC, OC	Liousse *et al*. (2010)
MEGAN-MACC (Biogenic)[s]	Global (0.5° × 0.5°)	1980–2010	BVOC	Sindelarova *et al*. (2014)
APIFLAME (Biomass burning)[t]	Euro-Mediterranean (0.001° × 0.001°)	2012–2014	CO, CO_2, VOC, NH_3, SO_2, NOx, BC, $PM_{2.5}$-, TPM	Turquety *et al*. (2014)
EMEP (Anthropogenic)[u]	Europe (0.5° × 0.5°)	1980–2020	SO_{-2}, NO_x, VOC, PM, GHG	Vestreng *et al*. (2007)

Dataset	Scale	Year	Major parameters	References
IASB-TD-OMI (Biomass burning and biogenic)[v]	Global (0.5° × 0.5°)	2005–2014	HCHO	Stavrakou *et al*. (2015)
L14-Africa (Anthropogenic)[w]	Africa (0.25° × 0.25°)	2005–2030	CO, NO_x, SO_2, NMVOC, BC, OC	Liousse *et al*. (2014)

[a]http://edgar.jrc.ec.europa.eu/.

[b]http://edgar.jrc.ec.europa.eu/overview.php?v=432&SECURE=123.

[c]http://edgar.jrc.ec.europa.eu/overview.php?v=432_AP.

[d]http://edgar.jrc.ec.europa.eu/overview.php?v=4tox2.

[e]https://cgrer.uiowa.edu/projects/emmison-data.

[f]https://www.nies.go.jp/REAS/.

[g]http://www.pole-ether.fr/eccad.

[h]http://www.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5.html.

[i]http://accent.aero.jussieu.fr/RETRO_metadata.php.

[j]http://accent.aero.jussieu.fr/Junker_metadata.php.

[k]http://cdiac.ess-dive.lbl.gov/trends/emis/overview_2010.html.

[l]ftp://ftp.mpic.de/GFAS/v1p3.

[m]https://daac.ornl.gov/VEGETATION/guides/fire_emissions_v4.html.

[n]http://www.geiacenter.org.

[o]http://www.globemission.eu.

[p]http://inventory.pku.edu.cn/.

[q]http://accent.aero.jussieu.fr/GICC_metadata.php.

[r]http://stormbringer.nateko.lu.se/public/guess030124/.

[q]http://accent.aero.jussieu.fr/AMMABB_metadata.php.

[s]http://gmes-atmosphere.eu/about/project_structure/input_data/d_emis/.

[t]http://www.pole-ether.fr/eccad.

[u]http://www.emep-emissions.at/emission-data-webdab.

[v]http://emissions.aeronomie.be/index.php/omi-based.

[w]http://www.aeris-data.fr/redirect/L14-Africa.

Table 3.3. *Existing global and regional emission inventory databases*

3.2.3.6. *State of the art of cloud computing for EI compilation*

EI compilation requires mathematical operation which involves large datasets. Comprehensive input databases are normally stored in a place and are further processed to get the output of calculated emissions. Further, the results need to be visualized and summarized, and whenever necessary, the EI compiler is often required to report to the authorized organization. The EI process should be updated regularly, and in this case, the size of the database is getting larger. Previously, EI compilers use dedicated EXCEL tools (IPCC, GAP, ABCEIM) or database program (dBASE) to compile EI and at the same time to process and visualize the outputs. Many EI compilers of the regional/global initiatives mentioned in Table 3.3 publicize the EI output in the relevant project websites, but process the EI development separately in the individual system. Recently, with the emerging CC technology and the advantages of automation and scalability (Bijwe *et al*. 2015), some EI compilers have started using the technology.

Multi-resolution Emission Inventory (MEIC) is a technology-based bottom-up air pollutant and GHG inventories for anthropogenic sources in China, which is developed and maintained on the basis of CC platform by Tsinghua University, and it allows users to conveniently access all customized emission products online (http://www.meicmodel.org/). A streamlined EI (SLEIS) data management application has been developed by a private company, Windsors, which is known as an interface program to compile EI in cloud system (http://www.windsorsolutions.com/products/SLEIS). The city of Alberquerque is reported to use a cloud-based version of SLEIS, and the system is hosted on an Amazon server. CC has been successfully employed to run USEPA Motor Vehicle Emission Simulator (MOVES) model that provides abundant computing resources on demand (Faler *et al*. 2012). A cloud-based Greenhouse Gas Air Pollution Interaction and Synergies (GAINS) model was developed to facilitate larger reusability and warehousing system of the global GAINS emission data (Nguyen *et al*. 2011). Further development of Database-as-a-service (DBaaS) in cloud would be potential and useful for EI compilation in the future.

3.3. Case studies

3.3.1. *Southeast Asia (SEA)*

The emission database for the SEA region was compiled from the EI developed for major anthropogenic sources in Indonesia, Thailand and Cambodia in 2007, and the online sources of CGRER and EDGAR v4.3.2 for other countries in the modeling domain (Permadi *et al*. 2018). The major anthropogenic sources covered by the EI for the three selected countries included power generation, manufacturing industry, on-road transport, aviation, residential and commercial cooking, fugitive emissions (from fuel), agro-residue open burning, forest fire, solid waste open burning, agriculture-related activities, and solvent and product use (Table 3.4). The EFs were compiled from the published sources, including those measured in SEA as detailed in Permadi *et al*. (2018).

Sectors	**Types of activity data**	**Activity data**		
		Indonesia	**Thailand**	**Cambodia**
Power generation	*Fuel consumptions (Mt/year)*			
	Coal	23.4	20.5	–
	Natural gas	3.2	29.8	–
	Fuel oil	9.4	0.75	0.62
	Biomass	6.3	–	–
Manufacturing industry	*Fuel consumptions (Mt/year)*			
	Coal	5.4	12.3	–
	Gasoline	0.34	0.013	–
	Fuel oil	18	2.4	0.52
	Biomass	–	20.7	–
On-road transport	Number of registered vehicle (million/year)	48	26	1.9
Aviation	Landing and take-offs (LTO) (×1000/year)	344	555	39
Residential and commercial cooking	*Fuel consumption (Mt/year)*			
	Coal	0.028	–	–
	Wood	100.5	7.6	0.4
	Kerosene	7.3	0.13	0.0003
	LPG	1	1.15	0.005
	Charcoal	20.4	3.9	0.042
	Other biomass	–	0.14	–
Fugitive emissions (from fuel)	Coke production (Kt/year)	182	–	–
	Gas production (Tg/year)	8,654	31.24	–
	Oil production (Tg/year)	29	6.2	–
	Gasoline distributed (Mt/year)	13.7	5.4	–
Agro-residue open burning	Total dry crop residue openly burned (Mt/year)	43.5	18.2	4.3
Forest fire	Total forest area burned, including peatland fire (ha/year)	545,881	1,851,850	98,761
Solid waste open burning	Total dry solid waste burned (Mt/year)	1.26	0.28	0.175
Agriculture-related activities	Total number of livestock population (head, $\times 10^6$)	1,359	328	22.3

	Fertilizer consumption (Mt/year)	6.8	3.6	–
Solvent and product use	Paint (Kt/year of paint)	606	–	–
	Degrease (t/year of solvent consumed)	103	–	–
	Chemicals (Kt/year of products)	1,269	–	–
	Other product use (i.e., ink, domestic solvent, glue and adhesives) (Kt of products)	161	–	–

Table 3.4. *Summary of activity data from the considered emission sources in three countries in 2007 (Permadi* et al*. 2018)*

The results of national emission estimated for Indonesia, Thailand and Cambodia for the base case of 2007 are presented in Table 5.5 for 12 species (SO_2, NO_x, CO, NMVOC, NH_3, CH_4, PM_{10}, $PM_{2.5}$, BC, OC, CO_2 and N_2O). Sector-wise, the emissions of PM and the carbonaceous species, i.e. PM_{10}, $PM_{2.5}$, BC and OC, were mainly contributed by the residential and commercial combustion in Indonesia (43–80%) and Cambodia (55–78%), while biomass open burning (including forest fire and crop residue) was the main sources for these pollutants in Thailand (31–74%). In Indonesia, the SO_2 emission was mainly from the transport sector (36%) and the power generation (33%). However, the manufacturing industry was the main contributor of SO_2 in Thailand and Cambodia, i.e. 66% and 33% respectively. NO_x emission was dominated by the oil and gas operation in Indonesia (44%), power generation in Thailand (34%) and forest fires in Cambodia (60%). NH_3, an important precursor for $PM_{2.5}$, was mostly contributed by manure management and fertilizer practices in all three countries, i.e. 63% for Indonesia, 75% for Thailand and 78% for Cambodia.

Table 3.7 also presents the emissions from other SEA countries and from the Southern part of China included in the modeling domain which, in fact, showed significant contributions to the emission in the domain. In the SEA region, it is seen that Indonesia and Thailand were collectively the largest contributors of all pollutants, covering 25–62% of 2007 in SEA domain and 15–41% of the modeling domain (including Southern China).

Species	Indonesia	Thailand	Cambodia	Other SEA countries	SEA countries	Southern part of China	Total modeling domain
SO_2	997	827	41	2,695	4,560	6,204	10,781
NO_x	3,282	701	97	2623	6703	4166	10,910
CO	24,169	9095	2877	19,054	55,195	33,377	89,252
NMVOC	3840	1120	331	5644	10,935	4441	15,613
NH_3	1258	469	110	1543	3380	2247	5613

CH_4	3950	1053	713	13,833	19,549	14,640	34,218
PM_{10}	2046	782	115	1763	4706	3644	8458
$PM_{2.5}$	1644	607	65	1466	3782	2653	6519
BC	226	47	7	159	439	362	821
OC	674	240	40	604	1558	643	2245
CO_2	508,022	260,988	28,296	856,225	1,653,531	1,406,860	3,092,654
N_2O	180	84	60	271	595	346	941

Table 3.5. *EI results for base year in the Southeast Asia and the modeling domain in 2007 (Permadi* et al. *2018)*

The emission data were prepared for each district in Indonesia, and each province in Thailand and Cambodia on annual average which were further derived to monthly and hourly data using relevant proxies used for modeling purpose. The extracted emission data for the rest of the modeling domain were also gridded and converted from annual basis to monthly and hourly emissions as detailed in Permadi *et al.* (2018). Overall, the emission database consisted of hourly emissions of 33 species for every grid (169 × 133) and 12 months of the year; hence, it is a large dataset to be further processed by the modeling system.

Spatially, it is clearly shown that pollutant emissions were densely concentrated in the city areas in all countries. Figure 3.2 shows the spatial distributions of the annual average emissions of BC and CO at 0.25° × 0.25° over the modeling domain.

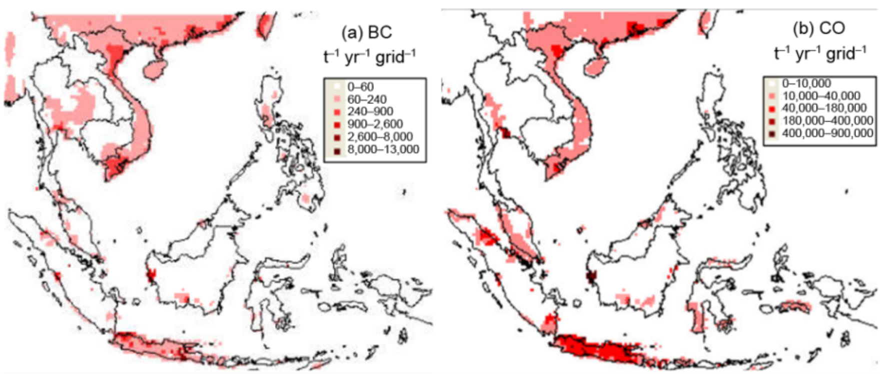

Figure 3.2. *Gridded (0.25°×0.25°) annual emissions for selected pollutants (BC and CO) over modeling domain (Permadi* et al. *2018). For a color version of this figure, see www.iste.co.uk/laffly/torus3.zip*

3.3.2. *Vietnam inland domain*

The EI for the entire Vietnam inland domain, covering 63 provinces/cities, was conducted for the base year of 2010 (Huy 2015; Huy and Kim Oanh 2017). The study domain of inland Vietnam has a total area of 331,210 km^2. Six major anthropogenic sources were covered, including the on-road vehicle, biomass open burning (forest fires and agricultural residues), residential combustion, gasoline filling stations, industrial activities and power generation sector, and the natural biogenic source.

The AD were collected by an actual survey conducted for the gasoline filling stations and also from various published reports for different emission sources as summarized in Table 3.6. The EFs for traffic fleets were compiled from previous vehicle emission modeling studies for Vietnam (Kim Oanh *et al*. 2012; Van 2014; Trang *et al*. 2015), while for other sources, the EFs were taken from the compilation in ABCEIM (Shrestha *et al*. 2013).

No.	Requested data/emission sources	Data collected and data sources
1	General information of Vietnam Demographic data	General Statistical Office (GSO)
2	*Emission inventory*	
	Transportation	Emission factors (EFs), Vehicle Kilometer Traveled (Kim Oanh *et al*. 2012; Van 2014; Trang *et al*. 2015), number of vehicles (Vietnam Register Report)
	Biomass open burning	EI prepared by Dong (2013)
	Residential cooking	EFs, activity data (Shrestha *et al*. 2013), fuel consumption per capita, fuel type) (JICA 2010; Phuc 2012; Nhung 2013)
	Gasoline station	Number of gasoline stations (surveyed using Google Earth) Available gasoline sale/consumption/demand data (surveyed and compiled from Internet sources)
	Industrial source	Fuel consumption of industrial sector (surveyed and compiled from Internet sources) National industrial productivity from Ministry of Industry and Trade (MOIT) Downscaled data from Emission Database for Global Atmospheric Research (EDGAR)
	Thermal power plants	Activity data (compiled by Internet sources and personal communication with Vietnam Electricity (EVN))
3	Biogenic source	Global Biosphere Emissions and Interactions System (GLOBEIS)

Table 3.6. *Major EI sources and data collection (Huy 2015)*

The total 2010 annual emissions of SO_2, NO_x, CO, NMVOC, CH_4, NH_3, PM_{10}, $PM_{2.5}$, BC and OC in Gg/year are presented in Table 3.7.

Source	SO_2	NO_x	CO	NMVOC	CH_4	NH_3	PM_{10}	$PM_{2.5}$	BC	OC
Anthropogenic sources (Gg/year)										
On-road mobile source	8.3	366	3542	767	15.8	16	62	46.3[a]	11	12
Biomass open burning	7	73	5350	223	134	118	285	259	17	97
Gasoline station	-	-	-	8.14	-	-	-	-	-	-
Industry	387	179	350	49.3	6.63	12.4	246	71	2.54	4.61
Thermal power plants	142	141	11.3	2.29	0.60	0.49	19.3	8.01	0.02	0.10
Residential cooking	71.4	68	5552	206	324	21.9	380	288	62	182
Total anthropogenic sources										
	616	827	14,805	1256	481	169	992	626	93	296
Biogenic source (Gg/month)										
August	-	6.6[b]	94[c]	364	-	-	-	-	-	-
December	-	4.82[b]	51[c]	198	-	-	-	-	-	-
Total biogenic source (Gg/year)										
	-	68.5	870	3372	-	-	-	-	-	-
Total emission (Gg/year)	**616**	**896**	**15,675**	**4628**	**481**	**169**	**992**	**626**	**93**	**296**

[a]Based on $PM_{2.5}/PM_{10}$ ratio of 0.70 (Kim Oanh *et al*. 2013);

[b]NO emission (GLOBEIS model);

[c]CO emission (GLOBEIS model)

Table 3.7. *Annual emissions from different sources in Vietnam (Gg/year), 2010 (Huy 2015)*

The emission shares of the sources are presented in Figure 3.3. It is clearly seen that CO emission was mainly contributed by three sources: on-road vehicle (22%), biomass open burning (33%) and residential cooking (35%). For NMVOC, the biogenic emission (73%) was nearly three times higher than the total from the major anthropogenic sources (27%). On-road mobile source was the main contributor to NO_x (40%), while the industrial sector was the largest contributor to SO_2 (61%). Two important sources of PM were residential cooking and biomass open burning: residential cooking shared 36% of PM_{10} and 41% of $PM_{2.5}$ emissions, whereas biomass open burning accounted for 27% of PM_{10} and 37% of $PM_{2.5}$.

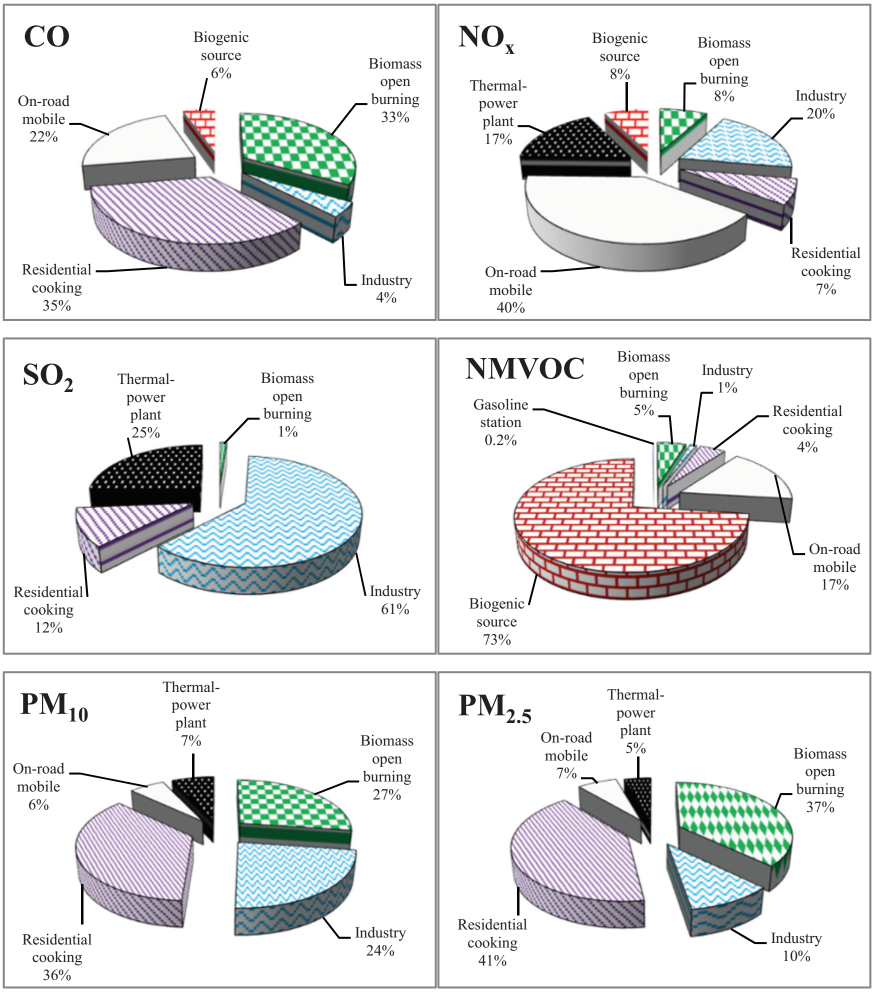

Figure 3.3. *Emission share of different sources in Vietnam inland domain in 2010 (Huy 2015). For a color version of this figure, see www.iste.co.uk/laffly/torus3.zip*

The emissions of the 10 species were prepared for each province of the inland Vietnam. Further, for the modeling purpose, the emissions were gridded (12 km), and gridded hourly emissions were calculated for considered species which resulted in a large dataset to handle. Examples of the spatial distributions of $PM_{2.5}$ and SO_2 emissions from industrial activities in inland Vietnam (Huy and Kim Oanh 2017) are presented in Figure 3.4.

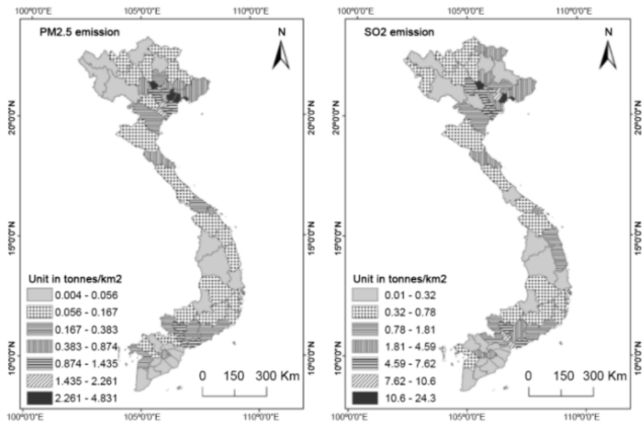

Figure 3.4. *Spatial distributions of $PM_{2.5}$ and SO_2 emissions (tonnes/km^2) from industrial activities in inland Vietnam, 2010 (Huy and Kim Oanh 2017)*

3.3.3. *Bangkok Metropolitan Region, Thailand*

The EI domain covered the Bangkok city and eight provinces, namely, Nonthaburi, Pathum Thani, Samut Prakan, Samut Sakhon, Nakhon Pathom, Chachoengsao, Nakhon Nayok and Chon Buri, with the total area of 70 × 100 km² (Figure 3.5) and hereby named as the Bangkok Metropolitan Region (BMR) domain for short. The EI results for the domain by several AIT studies from key sources were updated to 2016, and the results for key pollutants of NO_x, CO, NMVOC, SO_2, NH_3 and PM_{10} are presented in Table 3.8.

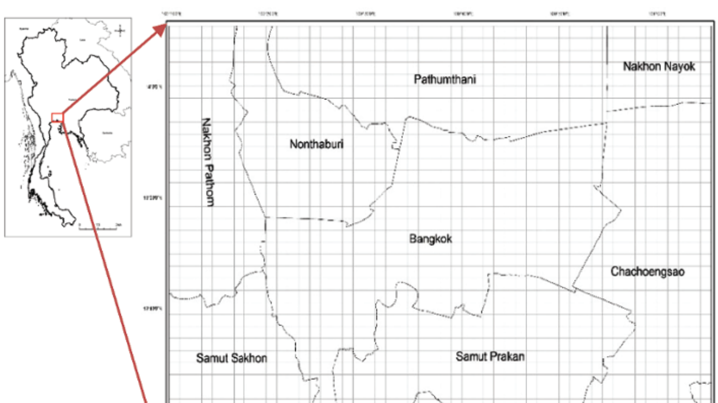

Figure 3.5. *Location and provincial boundaries of the BMR EI domain (Ha Chi 2018)*

No.	Emission Source	NO_x	CO	NMVOC	SO_2	NH_3	PM_{10}
1	Aviation	17.6	17.6	8.85	1.19	–	0.18
2	Biogenic	0.34	0.83	116	–	–	–
3	Biomass open burning	3.74	227	8.93	0.75	5.40	13.1
4	Cremation	0.01	0.01	0.001	0.03	–	0.00 1
5	Farm machine	0.12	0.07	0.03	–	–	0.02
6	Gasoline station	–	–	6.88	–	–	–
7	Industry	53.3	134	14.7	90.7	–	12.4
8	Livestock	–	–	–	–	10.9	–
9	Oil tank	–	–	0.98	–	–	–
10	On-road mobile sources	256	377	44.4	0.74	1.21	27.3
11	Power plant	26.3	23.4	3.38	2.53	1.02	0.87
12	Residential	5.12	1.22	0.20	0.43	2.94	0.29
13	Soil	1.22	–	–	–	0.24	–
Total Emission		**364**	**782**	**204**	**96**	**22**	**54**

Table 3.8. *EI updated to 2016 for the BMR domain, Gg/year (Ha Chi 2018)*

In the domain, the on-road mobile source was the main contributor of PM_{10} (50% of the total), NO_x (70%) and CO (48%), while the natural biogenic emission had the highest share for NMVOC (with 57%). About 94% of the total SO_2 emission was from industry, while 50% of NH_3 was from livestock activities. Note that some important sources of coarse particles – for example soil, road and construction dust – were not included in this EI; hence, it may underestimate the PM_{10} emissions. The PM emitted from vehicle exhausts and biomass open burning, on other side, would predominantly be in the fine particle size range ($PM_{2.5}$).

The emissions of the considered species of biogenic emission were directly calculated for every cell (2 × 2 km) of the 50 x 35 grid net in the EI domain. The emissions of the anthropogenic sources were first prepared for each province in the domain and then further segregated into 2 × 2 km. The gridded hourly emissions were then calculated to be used in the air quality modeling; hence, it resulted in a large dataset to manage.

3.3.4. *Forest fire emissions from Nakhon Si Thammarat, Thailand*

Emissions from forest fires cause a serious air pollution problem in many tropical countries. The forest fires frequently cause air pollution episodes in nearby local communities that particularly cause adverse health impacts, especially for children and the elderly people (WHO 2016).

Nakhon Si Thammarat (NST), located in the Southern Thailand, is rich in swamp forest (Figure 3.6) which occupies a total area of 560 km^2. The swamp forest in the province has been declared as the National Preservation Forest (The Project of Preservation and Development for Kuan Kreng Peat Swamp Forest); hence, the area is named as the "Kuan Kreng Swamp Forest". Almost every year around May to August, the swamp forest experiences drought conditions and, subsequently, forest fires occur intensively during this period. Photos in Figure 3.6 show the typical vegetation cover of the swamp forest.

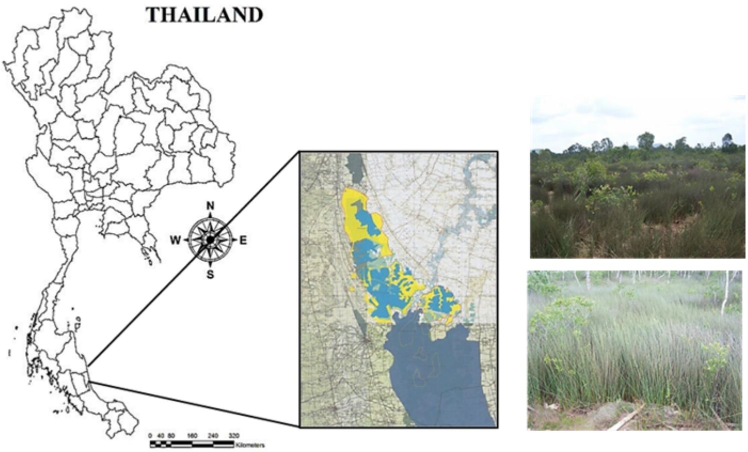

Figure 3.6. *Study area and typical vegetation cover of swamp forest. For a color version of this figure, see www.iste.co.uk/laffly/torus3.zip*

The EI was conducted for nine (9) species: CO, NO_2, SO_2, CO_2, NH_3, CH_4, NMVOC, BC and OC for a 10-year period from 2003 to 2012. Satellite hotspot data were collected to represent biomass burning in the area. Hotspots were overlaid with the land-use map of NST, and the only hotspots appeared in the forest area were attributed to forest fires. Figure 3.7 shows the number of hotspots overlaid on the forest area in 2012 in comparison with the forest fires obtained from the ground observation made by the Office of National Preservation Forest. Satellite and ground data indicated a good agreement for the fire observations in the area.

The activity data are the amount of burned biomass calculated from satellite hotspot detection (number of hotspots × effective burned area per fire pixel × burning efficiency × dry matter density). The values used for the listed parameters were taken from ABC EIM (Shrestha *et al*. 2013), except for the dry matter density that was taken from locally measured data for the Kuan Kreng Swamp Forest by Chaiyarak and Wanthongchai (2014). The EFs of each pollutant species were also taken from the compiled data in the ABC EIM (Shrestha *et al*. 2013).

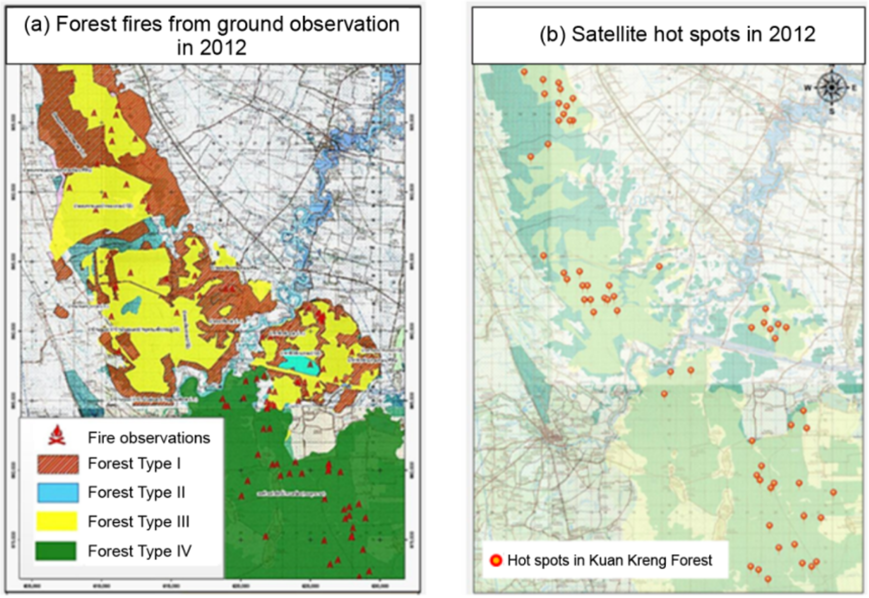

Figure 3.7. *Satellite hot spots (a) and ground observation of forest fires (b). For a color version of this figure, see www.iste.co.uk/laffly/torus3.zip*

The 10-year EI results show higher emissions in 2005, 2010 and 2012 (Table 3.9). These years also had high numbers of hotspots of 59, 82 and 68 respectively. Kirtphaiboon *et al*. (2014) found that rainfall variability in Thailand is related to ENSO. For example, years 2009 and 2010 were classified as strong and weak El Niño respectively with low intensity of rainfall (Kirtphaiboon *et al*. 2014). The strong El Niño and droughts in 2009 could induce fires in the swamp forest also in the subsequent year of 2010. During the intensive burning periods in the mentioned years, smoggy blanket was observed to cover the nearby area and communities for a few days to weeks. A sharp increase of air pollution levels in the rural areas during fire episodes could be easily felt and seen by naked eyes which would cause substantial adverse health effects, yet to be quantified. The year 2011 had no forest fire hotspots detected by satellite that may be due to short fire periods that could not be detected by MODIS (TERRA and AQUA) which overpasses the area twice a day (10:30 and 13:30 respectively).

The EI results can be used further for modeling study to capture how the pollutant plume is dispersed and spreads the pollution to the surrounding areas. The EI data should then be segregated into a grid net and with refined temporal distributions (hourly) and hence could result in a large dataset to be potentially managed by CC.

Year	Emission estimates (Mg/year)								
	CO	SO_2	NO_2	CO_2	NH_3	CH_4	NMVOC	BC	OC
2003	256.2	0.9	2.8	2077.6	3.1	25.4	8.5	0.7	5.2
2004	530.7	1.8	5.7	4303.7	6.4	52.6	17.7	1.4	10.9
2005	1079.7	3.7	11.6	8755.7	13.1	106.9	36.0	2.9	22.1
2006	109.8	0.4	1.2	890.4	1.3	10.9	3.7	0.3	2.2
2007	164.7	0.6	1.8	1335.6	2.0	16.3	5.5	0.4	3.4
2008	91.5	0.3	1.0	742.0	1.1	9.1	3.1	0.2	1.9
2009	54.9	0.2	0.6	445.5	0.7	5.4	1.8	0.1	1.1
2010	1500.6	5.1	16.2	12169.0	18.2	148.6	50.0	4.1	30.7
2011[a]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2012	1244.4	4.2	13.4	10091.4	15.1	123.3	41.5	3.4	25.5

[a]In 2011, EI data were not available since no satellite hotspot data were detected in this year.

Table 3.9. *Emission from the Kuan Kreng forest fires during 2003–2012*

3.3.5. *Phnom Penh (PNH), Cambodia*

An EI for the Phnom Penh (PNH) city of Cambodia was developed under the joint cooperation between the air quality research group of AIT, the Royal University of Phnom Penh (RUPP) and the Ministry of Environment of Cambodia (MOE) for the base year of 2013 with the financial support from the ASEAN-GTZ project on "Clean air for smaller cities". The study domain covers an area of 28 km^2 of the core city center (Chamkar Mon, Daun Penh, Prampir Markara and Toul Kork districts) (Figure 3.8). The EI covered key anthropogenic emission sources of on-road and non-road mobile sources, residential cooking, power plant, industrial diesel generator (industrial manufacturing process and boiler were not considered), commercial back-up generator and medical waste incinerator. Six emission species were included in the inventory, including PM_{10}, NO_x, SO_2, CO, NMVOCs and CO_2. The bottom-up approach using the actual survey was mainly used for the AD collection. The relevant EFs for the considered sources were extracted from the compiled EF in ABC EIM (Shrestha *et al*. 2013).

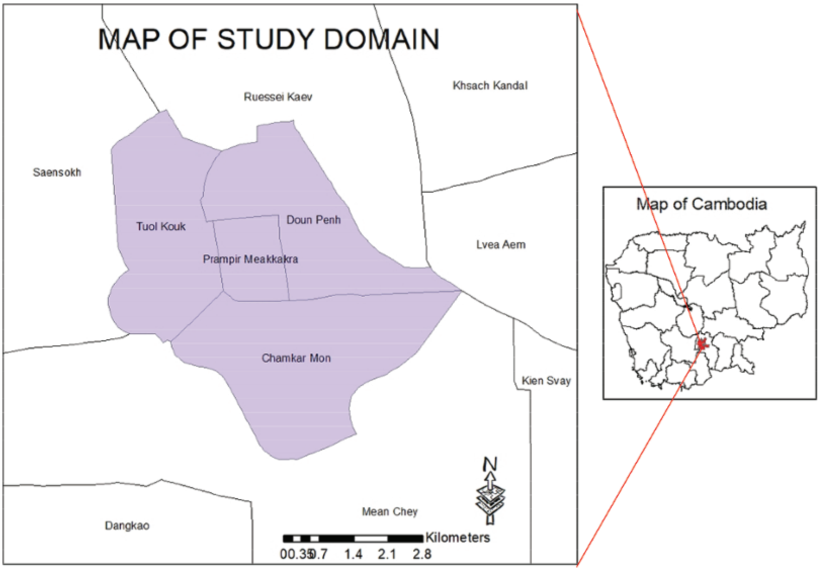

Figure 3.8. *Map of the EI domain of PNH*

The total annual emissions from the considered emission sources are presented in Table 3.10. The total emissions from the domain in 2013 (Kt/year) were 7.2 NO_x, 88 CO, 20 NMVOC, 0.6 PM_{10}, 2,613 CO_2 and 7 SO_2. Note that for all pollutants and CO_2, the emissions were mostly contributed by the on-road mobile source (55–98%), except for SO_2 that was dominated by the point source (99%). The EI results will be segregated into grids with fine resolution (about 2 km) and into hourly emissions for the dispersion modeling purpose which will be a large dataset to handle.

Source	NO_x	CO	NMVOC	PM_{10}	CO_2	SO_2
Power Plant	1,586	94	31	140	485,471	6,910
Industrial generator	80.0	17.3	6.5	5.7	2,977	5.3
Commercial sector generator	9.5	2.1	0.8	0.7	354.4	0.6
Residential cooking	14.6	3,054	175	109	57,762	6.4
On-road mobile source	5,087	84,078	19,612	310	1,938,699	11.2
Non-road mobile source (railway and airport)	420	379	37.9	4.0	127,445	26.6
Incinerator	1.2	0.1	0.4	8.7	506	0.3
Total	7198	87,625	19,864	578	2,613,214	6960

Table 3.10. *Emission inventory for PNH, 2013 (GIZ 2015)*

3.4. Summary and conclusion

Emission inventory is a comprehensive list of air pollutants emitted by different anthropogenic and natural sources from a geographical domain during a specific period of time. Development of good EI databases requires accurate AD and representative values of EFs for considered sources. A standard QA/QC procedure should be applied to minimize the uncertainty in EI results. An accurate EI database is a prerequisite for effective AQM, particularly to identify the major sources of key pollutants to prioritize the emission control efforts. EI results are further used to prepare the emission input data for 3D air pollution dispersion modeling which should be segregated into hourly values of the interested species and in every grid of the model domain. This would result in a large dataset to handle, and therefore there is a good potential to apply CC in this research area.

The case studies of EI development in various Southeast Asia domains, from the Southeast Asia region to city scale, or for specific source of forest fires illustrated the EI development process and the size of the EI databases, and highlighted the potentiality of CC applications.

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