# 1

# Urban Air Pollution

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## 1. Introduction

Over the last 60 years, the urban population has increased at an incredible pace. According to the statistical documents of the United Nations Environment Program (UNEP, 2006), in 1900 the world only had 15 cities having a population of 1 million, whereas in 1950 the world had 83 cities having a population with more than 1 million and today there are more than 350 cities having a population more than 1 million. The population living in urban areas is about 50% of the world's population and the population living in urban areas will continue to increase rapidly in the future. In 2005, Asia had 50% of the most populous cities in the world. The urbanization process is a consequence of the explosion of the industrialization and automation process world-wide. People are attracted by high rates of economic growth in urban areas because there is more employment, educational opportunities and a better quality of life.

However, the urbanization process creates high density of street network, building, population and other activities (industry, etc.). These activities are relation with the high consumption of fossil fuel, such as people in urban areas uses more energy for cooking, air-conditioning, transportation, etc., and industry uses energy for production (Zarate, 2007). Consequently, these activities of high energy consumption emit a large amount of pollutants into the atmosphere which brings many environmental problems, for example, air, water and noise pollution as well as waste management. Among them, air pollution is one of the most serious environmental problems in urban areas. The World Health Organization (WHO) (WHO, 2005) has estimated that urban air pollution causes the death of more than 2 million people per year in developing countries, and millions of people are found to be suffering from various respiratory illnesses related to air pollution in large cities.

Therefore, the urban air quality management should be urgently considered in order to protect human health. Up to now, developed countries have made extensive efforts to improve the air quality through reducing emissions, such as: using cleaner energy, applying new air quality regulations, moving the industrial activities to the developing countries, etc. These efficient strategies at global scale are to move to developing countries. Air quality in developing countries has deteriorated considerably, thus exposing millions of people to harmful concentrations of pollutants because in developing countries the urban air quality management has not been adopted for a variety of difficulties.

## 2. Status of the air quality in large cities

A vast majority of the urban and suburban areas in the world is exposed to conditions which exceed air quality standards set by WHO. Especially, the large cities in developing countries have the highest air pollution levels. Some researches show that the emissions from Asian cities will rise and this will continue to have an impact on hemispheric background ozone level as well as global climate (Gurjar et al., 2005). In general the cities in developed countries have the concentrations of air pollutants lower than the cities in developing countries. A lot of measurements of air pollutants (such as $O_3$, $SO_2$, $NO_2$, TSP and PM10) in the world have been done; some of them are shown in the table 1.

Data in Table 1 has been extracted for the period 1999 – 2000 (only the data of Bogotá and HCMC were for the year 2005). Data were not complete for all cities because often measurements are not available for the same year.

Data has been used from urban stations to represent the overall pollution levels of the city. In the case of $NO_2$ concentrations (standard limit =40 $\mu$ g.m-3, WHO), the high concentrations for both the developed and developing cities occurred where the main source of emission is road traffic. However the road traffic emissions in developed countries are less dangerous than developing countries because they use modern vehicular combustion and emission control technology, clean fuel and more public transport. While in developing countries the out-dated vehicle technologies are used and few public transports are used. As results most cities in developing countries such as: Shanghai, Delhi, Jakarta, Beijing, HCMC, etc contain a relatively high level of air pollution. Especially, the maximum $NO_2$ concentrations in several cities of China are approximately three times higher than the WHO guideline value.

In the case of total suspended particles concentrations (standard limit =90 $\mu$ g.m-3, WHO), particle are normally related to $SO_2$ concentrations because TSP and $SO_2$ are emitted from burning coal for industrial activities. In general, the highest concentrations of TSP and $SO_2$ are found in developing cities, exceeding 300 $\mu$ g.m-3 where industrialization rate is rapid.

Particle matters (PM10) with diameters less than 10 $\mu$ m are very dangerous for respiratory human system. PM10 is originated from industrial and traffic sources, the values of PM10 are normally highest in developing cities where they use much old vehicle and diesel fuel.

The guideline value for the average annual value of $O_3$ does not exist. In some countries they apply the guideline for the maximum daily hourly $O_3$ at ground-level (standard limit = 180 $\mu$ g.m-3, TCVN) to manage air quality. So, Table 1 shows the maximum daily hourly $O_3$ concentrations. The highest $O_3$ concentrations are found in Mexico City (546 $\mu$ g.m-3), followed by Sao Paulo (403 - 546 $\mu$ g.m-3). The lowest maximum hourly concentrations of $O_3$ are found for the European cities where the lowest photochemical reaction occurs.

The tendency concentration of pollutants in the worldwide is to reduce because the local government and international organizations impose strong restriction laws and have the air quality management program. However, in developing countries the concentration of pollutants is tendency to increase because they develop too fast and release more pollutants and because they lack air quality management tools.

| City | Population[a] | $O_3$ | TSP[b] | PM10 | $SO_2$ | $NO_2$ |
|---|---|---|---|---|---|---|
| Tokyo, JP | 33.4 | | 49 | | 18 | 68 |
| Seoul, KR | 23.1 | | 84 | | 44 | 60 |
| Mexico, MX | 22.0 | 546 | 201 | 52 | 46 | 55 |
| New York, US | 21.8 | 272 | | 24 | 26 | 70 |
| Bombay, IN | 21.1 | | 240 | | 33 | 39 |
| Delhi, IN | 20.8 | | 415 | | 24 | 41 |
| Sao Paulo, BR | 20.3 | 403 | 53 | | 18 | 47 |
| Shanghai, CN | 18.6 | | 246 | | 53 | 73 |
| Los Angeles, US | 17.9 | 225 | | 39 | 9 | 66 |
| Jakarta, ID | 16.9 | | 271 | | | |
| Osaka, JP | 16.6 | | 43 | | 19 | 63 |
| Cairo, EG | 15.8 | | | | 69 | |
| Calcutta, IN | 15.4 | | 375 | | 49 | 34 |
| Manila, PH | 15.2 | | | | 32 | |
| Karachi, PK | 14.6 | | | | | |
| Dacca, BD | 13.6 | | | | | |
| Buenos Aires, AR | 13.5 | | 185 | | | 20 |
| Moscow, RU | 13.4 | | 100 | | | 80 |
| Beijing, CN | 12.4 | | 377 | | 90 | 122 |
| Rio de Janeiro, BR | 12.2 | | 60 | | 50 | 40 |
| Bogota, CO | 8.4 | 348 | | 58 | 40 | 39 |
| HCMC, VN | 6.3 | 247 | 260 | 79.6 | 44 | 34 |
| WHO standard[c] | | 160[d] | 90 | 20 | 50 | 40 |

Source: Baldasano et al. (2003); Erika (2007); ADB (2006) and HEPA (2006).
[a] Population expressed in millions, 2005.
[b] TSP = Total suspended particles.
[c] WHO standard for PM10 was manly issued in 2005, the rest in 2000. Source: WHO (2000) and WHO (2005).
[d] WHO standard for $O_3$ (maximum 1-h concentration). Source: Molina and Molina, 2001

Table 1. Air quality in large cities of the world. Almost data reported correspond to the mean annual concentration in $\mu$ g.m$^{-3}$ (only $O_3$ is reported in maximum 1-h concentration).

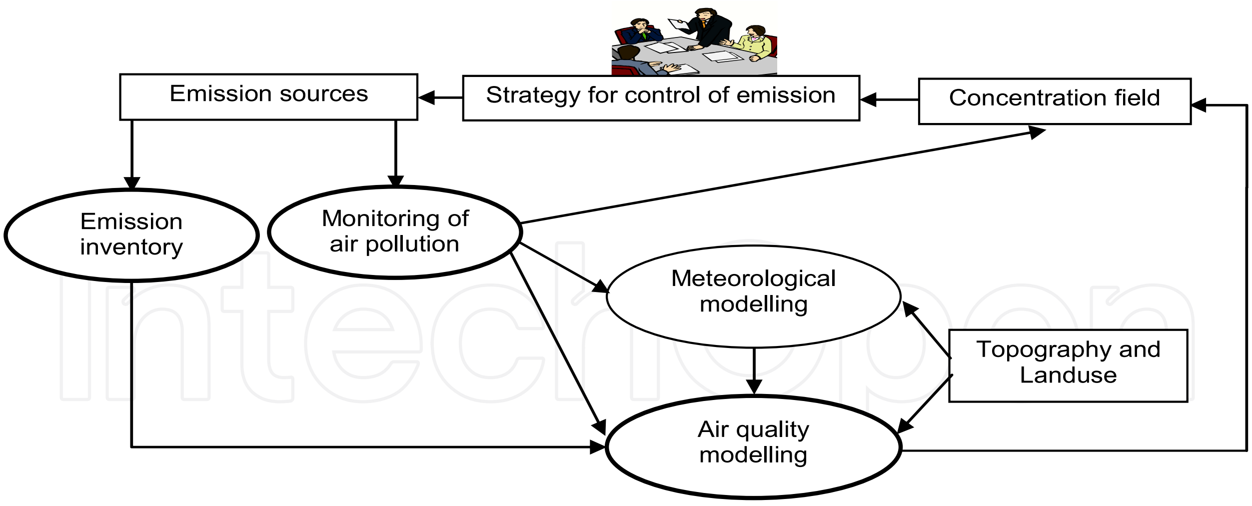


Fig. 1. Air quality management system for urban areas.

## 3. Air quality management

Air pollutions in cities are very complex because of several factors contributing to deterioration of the air quality in cities. These factors include: (1) a large amount of emission sources (traffic, industrial, residential, natural, etc.); (2) meteorological processes (wind components, temperature, moisture content, solar radiation, etc.); (3) chemical transformations (chemical reactions, dry depositions, etc.).

The design of effective abatement strategies for reduction emission becomes very difficult if we take into account the socio-economical problems. The population growth leads to increase economical as well as industrial activities which can not inhibited due to the development needs. These difficulties could be solved using an improved technology to reduce the pollution. However, the implementation of an improved technology is very costly. As an example it is quoted that it costs 7 billions US$ to install the catalytic converters in all new vehicles which are bought each year in United States (US) (Clappier., 2001).

The design of effective abatement strategies for reducing emission requires a good understanding of all factors related to air pollutions. Over past 20 years, a multitude of different urban AQM systems have been developed by scientists and environmental authorities (Moussiopoulos, 2004). These tools have been used very well to study air pollution and to propose efficient abatement strategies.

Many tools are integrated together in AQM system. These main tools which are presented in Figure 1 include: monitoring of air pollution, emission inventory (EI), air quality modelling and meteorological modelling. The current state of the art of these tools is presented in the next sections.

### 3.1 Monitoring of air pollution

Monitoring of air pollution is one of the most important tools in AQM. It helps us to understand the status of air pollution levels and to understand the evolution of air pollution. Monitoring gives us the information on emissions sources, because monitoring could be done on roadside for evaluating the traffic emissions and in industrial park for evaluating the industrial emission sources. Nowadays, almost all large cities in the world have installed the monitoring system in order to inform the level of pollution exposure to the population. Another important role of monitoring of air pollution is to validate the model which is used to simulate air quality.

There are different methods in use to monitor the air pollution including: automatic, semi-automatic and manual methods. Automatic methods use the equipments which can measure directly the pollution and can be moved anywhere for monitoring of air pollution. Example, the equipments manufactured by Environmental S.A, France, just to mention some, monitors automatically CO, $NO_2$, NO, $O_3$, PM10, etc. On the other hand, semi-automatic methods involve collecting air quality samples at the selected sites by placing the equipments there, samples are collected and then these samples are transported to laboratory for analysis. Such methods are used, for example, for collecting BTEX (Benzene, Toluene and Xylene) sample by collecting samples for a continuous duration of 6h and then transporting the samples to laboratory for analysis by Gas Chromatography (GC). The third category of methods called manual methods involves collecting the samples manually as is done for the case of CO monitoring.

Among these, automatic method is the best one, because this method allows monitoring real time air pollution. A lot of measurements are made which can be later used these data to study the evolution of pollution in different periods and throughout the year. However, this method is very costly because the equipments are expensive, additionally, there is a need to maintain it regularly and we have trained technicians to operate the devices (Molina and Molina, 2004).

Nowadays, automatic and manual air pollution measurement networks have been installed in the world. In Europe some 1450 measurement stations covering 350 cities all over Europe have been installed, in US over 1000 stations are operated throughout the country by the US Environmental Protection Agency (US-EPA) (Baldasano et al., 2003), in Latin America there are more than 4000 urban monitoring stations (Belalcazar, 2009), in Asia countries with installed networks include China, Japan, Korea, India, Indonesia, Thailand, Vietnam, etc. In addition to these, WHO installed the monitoring networks in over 100 cities around the world since 1990s.

In Vietnam, the information from air pollution measurement networks is used to improve air quality. The air the cities of Vietnam before 1995 was polluted by lead due to traffic activities (several times higher than Vietnam air quality standard). The import of leaded gasoline was banned by Vietnam government, thereafter; the concentrations of lead in atmosphere are reduced and lower than the local air quality standard.

### 3.2 Emission inventory

Development of EI database is very important to describe the emissions and to manage air quality (Moussiopoulos, 2004; Ranjeet et al., 2008). The information from EIs helps us to understand the emission sources and also the emission fluxes in the study domain. The atmospheric pollutants needed for assessment and management of air quality are $SO_2$, NOx, CO, VOCs and particle maters (PM). The emission sources are grouped in different categories: mobile source (such as road traffic), area sources (such as agriculture, natural) and point sources (such as industry). Resolution in space of EI depends on the scale of study domain and the availability of information for generating emission inventories (EIs). In general the smaller the region of interest, the finer is the required spatial resolution of the EIs. Resolution in time of EIs must follow the activity pattern of emission sources.

The principal equation for calculation of emissions is combined by two variables:

$$E = e \times A \tag{1}$$

Where, $E$ is the total emission

e is the emission factor (EF)

A is the activity data of emitters

There are two main methods currently used for generating emission inventories: top-down and bottom-up

**Top-down approach**

A top-down approach starts to estimate the total emissions and uses several assumptions to distribute these emissions in space and time (Friedrich and Reis, 2004).

Strengths: this method is easy to apply because it needs less input information and the time to generate EIs is rapid. This method is particularly appropriate to estimate the inventories at large scale.

Weaknesses: one of the main limitations of this method is that the results of EIs are normally highly uncertain.

Examples of using top-down approach for generating EIs from the literature are:

- Bond and Streets calculated emissions of Carbonaceous aerosols, black carbon and organic carbon for the entire world by using total fuel consumption of the year and emission factors (g/kg of fuel burned) (Streets et al., 2004).
- Streets calculated emission of gaseous and primary aerosol in Asia by using parameters such as: energy use, human activities and biomass burning (Streets et al., 2003).
- Generoso combined the results of a global chemistry and transport model and satellite data to evaluate the emission produced by the Russian fires in 2003. In this research, they used top-down approach to estimate the emissions (Generoso and Bey, 2007).

**Bottom-up approach**

The bottom-up methodology is based on a source oriented inquiry of all activity and emission data needed for describing the behavior of a single source. It starts to evaluate the spatial and temporal repartition of the parameters used to calculate the emissions (Friedrich and Reis, 2004).

Strengths: this approach is more accurate than the top-down approach to evaluate the spatial and temporal repartition and is more appropriate for the small scale (city scale and lower).

Weaknesses: The main limitation of this method is that it needs a large amount of input data for generating EIs. Sometime, the information can even not be collected in the cities of developing countries. The time of generating EIs of this approach is longer than top-down approach

Examples of using bottom - up approach for generating EIs from the literature are:

- Erika combined the traffic fluxes obtained from a traffic model and emission factors per vehicles to calculate the traffic emissions in Bogota, Colombia (Erika, 2007).
- Molina measured emissions of industry and used GPS to locate the position of factory on the map to calculate the industrial emissions for Mexico City (Molina et al.2001).
- Brulfert calculated the EIs for Maurienne and Chamonix valley, France (G.Brulfert et al. 2004).
- Mattai calculated the EIs for London, England (J. Mattai et al. 2002)

The bottom-up approach is in general impossible due to lack of available information, while top-down approach might lead to poor accuracy level for urban EIs. So several researchers used top-down approach to generate EIs for point sources and area sources because data for these sources are not easy to access, while they used bottom-up approach to generate EIs for road traffic sources. An example from the literature is:

Sturnm generated EIs for urbanized triangle Antwerp-Brussels-Ghent which is located in Northwest Europe. He used the top-down approach for generating EIs for point sources (based on statistic data and emission factors from literatures) and area sources (based on collective data per km2). However for road traffic emissions he used bottom-up approach using road traffic emission measurements and an urban traffic flow model (Moussiopoulos et al., 2004).

**Combination of top-down and bottom-up approaches**

In the cities of developing countries, the data for generating EIs for traffic sources are generally not available, so it is difficult or even impossible to use bottom-up approach for generating EIs. In this chapter, we present a new road traffic emission model which combines top-down and bottom-up approaches (Bang et al., 2011).

The strengths and weaknesses of the combination of the two approaches are as follows:

Strengths: By using this method (1) the computation time is rapid; (2) less input data is needed to generate EIs; (3) we have control on the uncertainty in EIs due to input data; (4) we can generate EIs both for developed cities and developing cities and (5) the accuracy in the results of EIs is improved.

Weaknesses: the limitation of this method is that (1) we have to follow many steps to generate EIs and (2) we have to study the input parameters which generate most uncertainty in EIs.

### 3.3 Modeling of air pollution

The European Directive on evaluation ambient air quality (EU-N°96/62/CE 1996) requires the use of modeling tools to define high pollutant concentration zones. Modeling tools use mathematical formula to simulate all the atmospheric processes over various time and space scales. These processes are complex and nonlinear so that modeling is the only tool which takes into account all the processes.

Concerning the space scales of modeling, there are many scales such as global scale, regional or continental scale, mesoscale (city or country) and microscale (street canyons). There are many mesoscale models that are used to simulate urban air quality, such as METPOMOD, TVM-Chem, CIT, CHIMERE, CMAQ, TAPOM, etc. Input parameters of these air quality models are meteorological conditions, EIs, landuse, topography, boundary and initial conditions.

In recent decades, computer technology has rapidly developed; so many new mesoscale models are developed. With the increased power of computer technology, the time scale of modeling more refined. The new models can now simulate air quality for long periods and on temporal resolution from few hours to few months.

One of the most important functions of air quality modelling is to evaluate the effective of abatement strategies to reduce air pollution in cities. Modeling tools are also used to study the impact of different activities on urban air quality and to evaluate the methodology for generating EIs, such as Erika used TAPOM model to evaluate the accuracy of different methodology for generating EIs for Bogota city, Colombia (Erika et al., 2007).

### 3.4 Analysis of uncertainties

**Uncertainty in emission inventory**

One of the most important strengths of the emission inventory is generate the uncertainties of EIs due to the input parameters. There are many methods used to calculate uncertainty. One of these methods called analytical method is as follows:

Emissions are calculated as the combination of different parameters:

$$E = H_1 \times H_2$$

Where, E is the emission

H1 is the parameter to quantify the activities

H2 is an emission factor per unit of activities

H1 and H2 can depend on many other factors like the number of vehicles, road parameters, etc.

When H1 and H2 are simple enough it is possible to compute directly the uncertainties. For example when H1 and H2 are constants:

$$E = (\overline{H}_1 + \Delta H_1) \times (\overline{H}_2 + \Delta H_2)$$

Where, $\overline{H}_1$ , $\overline{H}_2$ is the average of H1, H2 respectively

$\Delta H_1$ , $\Delta H_2$ is the uncertainty of H1, H2 respectively.

$$E = (\overline{H}_1 \times \overline{H_2}) + (\overline{H}_1 \times \Delta H_2) + (\overline{H}_2 \times \Delta H_1) + (\Delta H_1 \times \Delta H_2) \text{ and also: } E = \overline{E} + \Delta E$$

In this example the uncertainty on E is equal to:

$$\Delta E = (\overline{H}_1 \times \Delta H_2) + (\overline{H}_2 \times \Delta H_1) + (\Delta H_1 \times \Delta H_2)$$

As we can see in this example the calculation of the emissions is non-linear and generates several uncertainty terms. All these terms rapidly become impossible to calculate analytically when the parameters used in the emission calculation are more complex. In such situation, the most oftenly used approach is the Monte-Carlo method (Hanna et al. 1998). The detailed of Monte-Carlo method is explained as follows:

The Monte Carlo methodology has been used to evaluate the uncertainties in previous air quality studies (Hanna et al., 1998; Sathya., 2000; Hanna et al., 2001; Abdel-Aziz and Christopher Frey., 2004). In the emission inventory model, the EIs are generated as the combination of different input parameters:

$$E = f(H_1, \ldots H_n) \tag{2}$$

where $H_i$ are the input parameters (i=1, n). $H_i$ can change due to the uncertainties. Each parameter $H_i$ is distributed around an average $\overline{H}_i$ and a standard deviation $\sigma_i$.

The Monte Carlo method (Ermakov, 1977) generates for each input parameters a pseudorandom normally distributed numbers $\eta^H$ ($\sigma = 1$ and mean= 0) which can be used to compute several values of $H_i$:

$$H_i^k = \overline{H}_i + \eta^H \sigma_i \tag{3}$$

The percentage of standard deviation $\sigma_i$ could be calculated as: $\tilde{\sigma}_{Hi} = \dfrac{\sigma_i \times 100}{\overline{H}_i}$

The equation (3) becomes: $H_i^k = \overline{H}_i \left( 1 + \dfrac{\tilde{\sigma}_{Hi} \eta^H}{100} \right)$

These parameters $H_i^k$ are used to calculate several values of $E^k$: $E^k = f(H_1^k, \ldots H_n^k)$. The average value $\overline{E}$ and the standard deviation $\sigma_E$ are deduced from the distribution of $E^k$.

The percentage of standard deviation $\sigma_E$ could be calculated as: $\tilde{\sigma}_E = \dfrac{\sigma_E \times 100}{\overline{E}}$

The classification of standard deviation $\tilde{\sigma}_E$ is based on the standard deviation of the input parameters $\tilde{\sigma}_{Hi}$:

If $\tilde{\sigma}_{Hi}$ is the standard deviation of input parameters due to spatial and temporal repartition, the values $\tilde{\sigma}_E(x, y, t)$ are the standard deviation of emission for all input parameters but in space and time.

If $\tilde{\sigma}_{Hi}$ (the standard deviation of each input parameters) is constant in the entire domain, then the values of $\tilde{\sigma}_{E_{Hi}}$ are the standard deviations of emission for all the domain but for each input parameter.

Examples from the literature for uncertainties in emission inventory and Monte-Carlo application to air quality model are:

- Kuhlwein calculated uncertainties of input parameters in modeling emissions from road transport. The emission inventory was calculated by the working group "urban emission inventories" of GEMEMIS and the working group "Val.3 of Saturn" (Kuhlwein J et al. 2000)
- Hanna evaluated the effect of uncertainties in UAM-V input parameters (emissions, initial and boundary conditions, meteorological variables and chemical reactions) on the uncertainties in UAM-V ozone predictions by using Monte-Carlo uncertainty method in framework of research: "Uncertainties in predicted ozone concentrations due to input uncertainties for UAM-V photochemical grid model applied to July 1995 OTAG domain" (Hanna et al, 2001).

**Uncertainty in air quality simulation**

Results of numerical simulations are more reliable if the estimation of uncertainties in model prediction is generated. The uncertainties of the air quality model due to input parameters could be generated by using the standard deviation (square root of variance) around the mean of the modeled outputs (Hwang et al., 1998). Up to now, the Monte-Carlo (MC) technique is a brute-force method for uncertainty analysis (Hanna et al., 2000). A simple program was developed (named EMIGEN) by our research team using the MC technique for generating different emission files. The MC technique used in EMIGEN includes different steps: (1) we generate a series of random numbers which follow a normal distribution; (2) the EI results of emission inventory model are used as the input parameters for EMIGEN. The uncertainties of the input parameters for other sources (industrial, residential and biogenic sources), can be calculated by using the available data which is estimated the emissions in developing cities; (3) Running EMIGEN to get one hundred EI files. These hundred EI files are used as input for the air quality model. The uncertainty and the median of pollutants are calculated from 100 MC air quality simulations. The results of pollutants and their uncertainties from the output of the air quality modeling are divided into two pollutant types, primary and secondary pollutants. Their results from 100 MC in using air quality model are used to calculate the uncertainties in process to simulate air pollution.

## 4. Air quality study over developing countries: A case study of HCMC

### 4.1 Air quality in HCMC, Vietnam

HCMC is the largest city in Vietnam and is the most important economic center in Vietnam. HCMC became one of 100 rapid economic growth cities in the world (Gale, 2007). The population of city is 6.105 million (8% population of Vietnam), however the city accounts for 20.2 % GDP, 28 % industrial output of Vietnam. HCMC had 28500 factories and 2,895,381 motorcycles. They are the most important sources which contribute to air pollution in HCMC.

The HCMC's government has been set-up a number of air quality monitoring stations around the city for monitoring air pollution due to road traffic and industrial activities. The results are shown in Table 2.

The measurements results show that air quality in HCMC are polluted by TSP, PM and especially $O_3$. The highest TSP concentrations are found in 2001 about 900 $\mu$ g.m-3 (10 times higher than WHO standard). TSP concentrations reduce to the value of 260 $\mu$ g.m$^{-3}$ in 2005 (Table 2). The high TSP concentrations in HCMC are related to the construction and traffic activities (Belalcazar., 2009). The mean annual concentration of $NO_2$ and $SO_2$ are lower than WHO standard, but their average daily/hourly values regularly exceed the WHO standards. PM10 and $O_3$ are the most critical pollutants in HCMC, because their concentrations are very high and almost exceeded the WHO standard during the period 2001- 2006. They have high toxic health effects. The measurements show that $O_3$ concentrations are highest during the midday where the highest photochemical processes are happened. The high $O_3$ concentrations are related to high VOCs concentrations in HCMC. However, there is very few information on VOCs concentrations which are monitored in the Asian countries due to their complex in measurement. Up to 2007, the first long-term study on the VOCs levels in HCMC was carried out by Belalcazar (Belalcazar., 2009). He measured continuously roadside levels of 17 VOCs species in range C2 - C6 during the dry season (from January to March) of 2007 in HCMC. Table 3 firstly shows VOCs concentrations in HCMC, then compare with available roadside VOCs concentrations of other Asian cities.

| Pollutants | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | WHO standard |
|---|---|---|---|---|---|---|---|
| TSP | 900.0 | 475.0 | 486.7 | 496.7 | 260.0 | - | 90 |
| PM10 | - | 122.5 | 83.5 | 61.5 | 79.6 | 77.4 | 20 |
| $NO_2$ | - | - | - | - | 34.0 | 32.1 | 40 |
| $SO_2$ | - | - | - | - | 44.2 | 28.5 | 50 |
| $O_3$ | - | - | 238 | 266 | 247 | - | 160[a] |

Source: HEPA (2004); HEPA (2005) and HEPA (2006).
[a] WHO standard for $O_3$ (maximum 1-h concentration). Source: Molina and Molina (2001).

Table 2. Air quality in HCMC from 2001 to 2006. Almost data reported correspond to the mean annual concentration in $\mu$ g.m-3 (only $O_3$ is reported in maximum 1-h concentration).

Unfortunately, the air quality standard for all VOCs compounds does not exist. Only some individual VOCs standard limits are defined by WHO based on health effects. Among those, benzene is one of the very toxic VOCs. The measurements of benzene in HCMC show a very high concentration of 14.2 ppbv (annual mean WHO standard - 6ppbv). The VOCs concentrations in HCMC are generally higher than other Asian cities. The benzene concentrations in Hanoi are higher than in HCMC, because benzene in Hanoi is measured at peak hours (short time) when the highest benzene concentration happed during the year.

Up to now, very few researches attempts have been made for improving air quality in developing cities, especially in HCMC. These researches attempts are on air pollution status and effective abatement strategies. The researches on status of air pollution analyzed the data from the monitoring networks to evaluate air pollution status of the city. These results help the government in proposing solutions to reduce air pollution level today and in the future (Hang et al., 1996; DOSTE., 2000).

| VOCs | HCMC (Mean) | Changchun (Mean) | Karachi (Mean) | HongKong (Mean) | Hanoi (Mean) |
|---|---|---|---|---|---|
| n-Propane | 3.7 | | | | |
| Propene | 19.5 | | | | |
| n-Butane | 22.6 | | | | |
| Trans-2-Butene | 5.2 | | | | |
| 1-Butene | 4 | | | | |
| Cis-2-butene | 5.2 | | | | |
| i-Pentane | 80.3 | 14.7 | 74 | | |
| n-Pentane | 21.8 | | | | |
| Trans-2-Pentene | 16.4 | | | | |
| 1-Pentene | 4.6 | | | | |
| 2-methyl-2-butene | 3.8 | | | | |
| Cis-2-Pentene | 4.2 | | | | |
| 2,3-Dimethylbutane | 8.6 | | | | |
| 2-Methylpentane | 7.7 | 6.1 | 39 | | |
| 3-Methylpentane | 43.5 | | | | |
| n-Hexane | 91 | 1.7 | 71 | 4.4 | |
| Benzene | 14.2 | 11.9 | 19.7 | 8.2 | 40 |
| total | 356.3 | | | | |

Sources: Belalcazar (2009).

Table 3. VOCs levels in BTH street (HCMC) and comparison with the VOCs levels in other Asian cities (concentrations are in ppbv).

The researches on effective abatement strategies propose solutions to reduce air pollution. It consists mainly of master thesis which is carried out at IER (Institute for Environment and Resources in HCMC). These researches are focused only on some typical aspects of abatement strategies at small scale, due to the lack of the information for research, methodology, etc. Nguyen (2000) proposed some methods to reduce air pollution by traffic in HCMC as well as for developing public transportation system and using unleaded gasoline. Another study proposed technical solutions for reducing air pollution level by traffic activities (Duong, 2004).

In conclusion, both the developed and developing cities have air pollution problem, especially in the developing countries where it is related to high level of air pollution. It's urgent to adapt an air quality management (AQM) system for improving the air quality in these cities. In the next section, the research for improving air quality in HCMC is carried out by using numerical tools.

### 4.2 Emission inventory of air pollution over HCMC

#### 4.2.1 Traffic source

**Methodology**

The following Fig. 2 shows an outline of the process of generating an EI for HCMC where the input data is limited and using the EMISENS model (Bang, 2011).

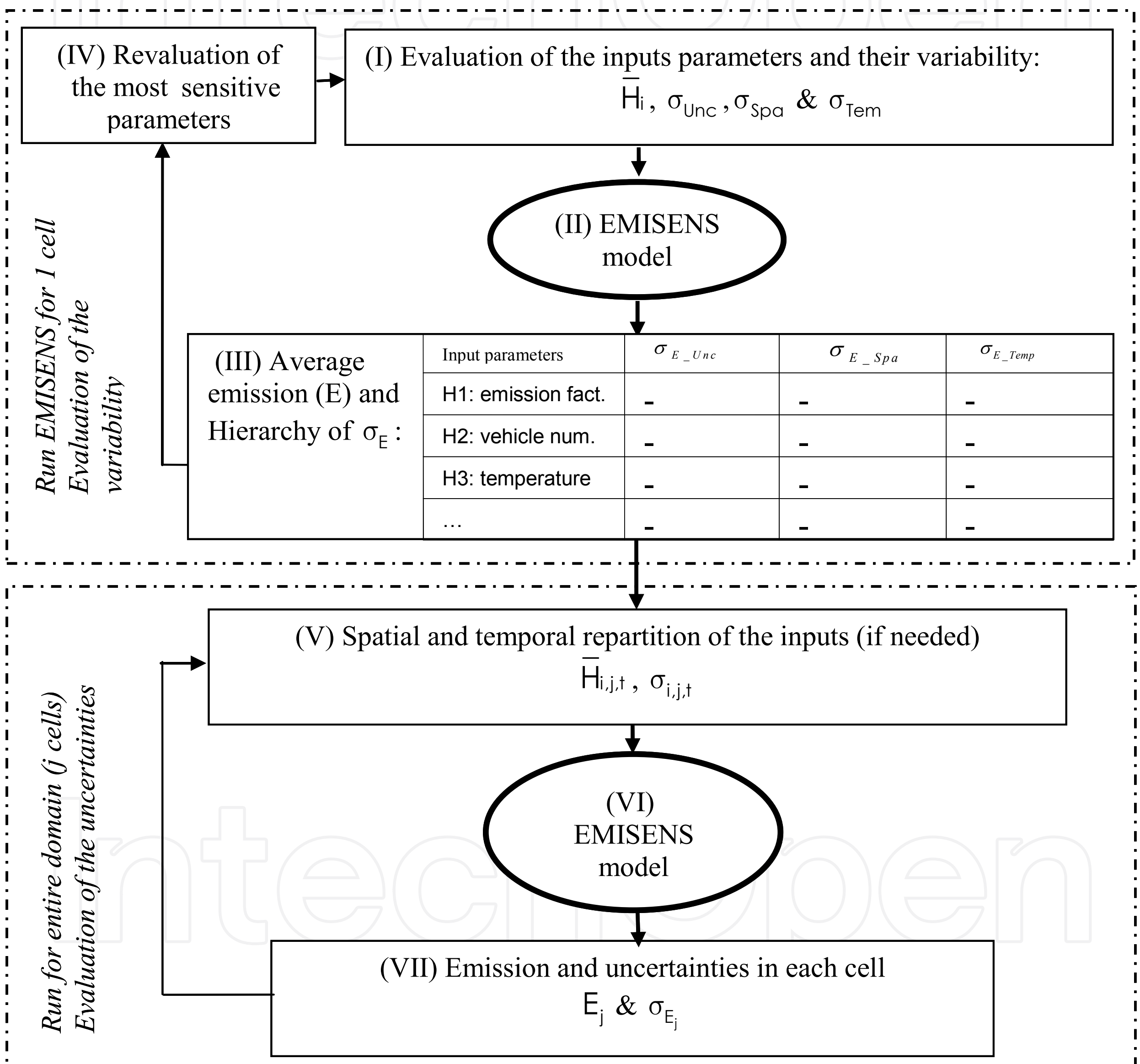


Fig. 2. Research process outline ($\overline{H_i}$ is the average value of input parameters. $\sigma_{Unc}$ , $\sigma_{Spa}$ and $\sigma_{Tem}$ are the standard deviation of the input parameters due to the uncertainties, the spatial and temporal variability, respectively. The $\sigma_{E\_Unc}$ , $\sigma_{E\_Spa}$ and $\sigma_{E\_Tem}$ are the standard deviation of the emissions due to variability of the input parameters. The $E_j$ & $\sigma_{E_j}$ are the emission and their standard deviation for each cell.

This process can also be applied for other cities than HCMC.

i. We collected the necessary data: minimum information to compute emission, estimation of the variability of the parameters (use the literature, other EI, existing data from HCMC, etc.).
ii. We run the EMISENS model with variable parameters in one cell.
iii. Results of model are a list hierarchy of standard deviation ($\sigma_{E_j}$) due to input uncertainties.Then, we analyze the results to identify the parameters which generate the maximum of variability in the EI.
iv. After the determination of the most sensitive parameters, we try to find more information of these parameters and will conduct additional campaigns to reduce the level of uncertainties of these parameters. We rerun the EMISENS model to revaluate the standard deviation of the emissions.
v. Identification of the parameters that generate significant standard deviation in space and in time and generate a spatial and temporal distribution of these parameters.
vi. We run the EMISENS model for each cell (run the model with parameters variable in all cells of the grid).
vii. Results of model are the emissions of each pollutant for each cell including its uncertainties ($E_j$ and $\sigma_{E_j}$).

**Input data**

The air quality of HCMC is controlled by HoChiMinh environmental protection agency (HEPA). However, the research on air quality for HCMC is mainly studied by Institute of Environment and Resources (IER), Vietnam national university in HCMC (VNU-HCM). The database for air quality studies in HCMC is still limited because there have not been a lot of research conducted for this city. The only available source of data or other information about this city are the reports on air quality from monitoring activities and some research conducted by master student of VNU-HCM.

Within the framework of this research, several campaigns were organized which focused mainly on the on-road traffic activities (vehicle fleet, traffic flow, etc.) using different methods.

Fig.3 shows the daily average variation of the fleet composition (in %) at 3 Thang 2 street (urban street category).

The fleet is almost dominated by light gasoline vehicles (motorcycles: 92%, cars: 3.46%, light trucks: 2.8% and buses 0.1%). Only 1.1% of the fleet is made of heavy truck diesel vehicles. The fleet distribution can be assumed the same for all streets in HCMC in the urban category. The fleet composition we have determined is also similar to the fleet of HOUTRANS project which was counted for the whole city of HCMC (HOUTRANS, 2004). We organized survey for the characterization of the vehicles (on road). The campaign was organized during the year of 2007 and 2008.

Some results of the campaign are shown in the Fig.4. This figure describes the distribution motorcycle age. We can conclude that motorcycles currently used in HCMC have been produced in recent years (more than 32% of motorcycles are produced less than 1 year and about 94% of motorcycle are produced less than 10 years) and more than 98% are the 4 strokes motorcycles. The main fuel used by motorcycles is gasoline. In spite of the fact, that most of motorcycles used in HCMC are not very old, they are a major producer of pollution. The reason is that they are manufactured by low standard technology (older than EURO II standard). The largest fraction of the motorcycles are imported from China and Taiwan which are very cheap in price and easily meet the requirement of the local people according to their purchasing power.

The survey further revealed that there are more than 25% cars which are less than 1 year old and more than 70% cars which are less than 4 years old. More than 98% cars use the gasoline for fuel and the rest of cars use the diesel oil.

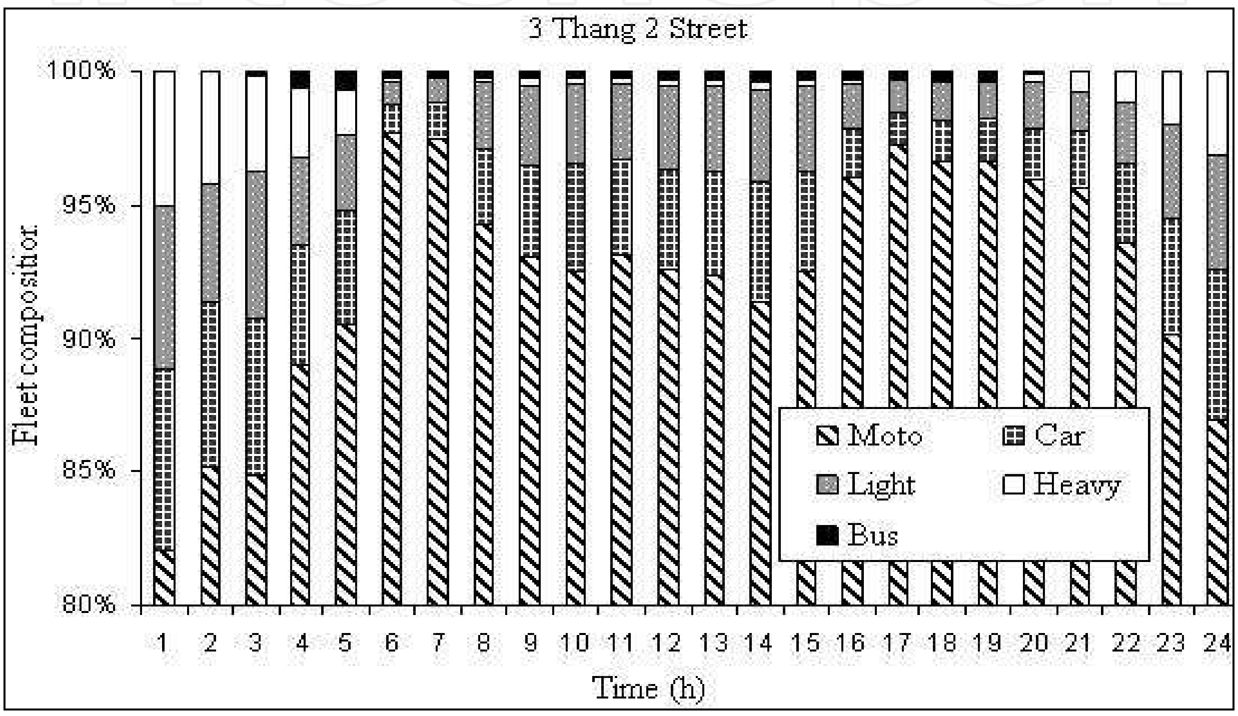


Fig. 3. Daily variations of the fleet composition at 3 Thang 2 street (urban street category).

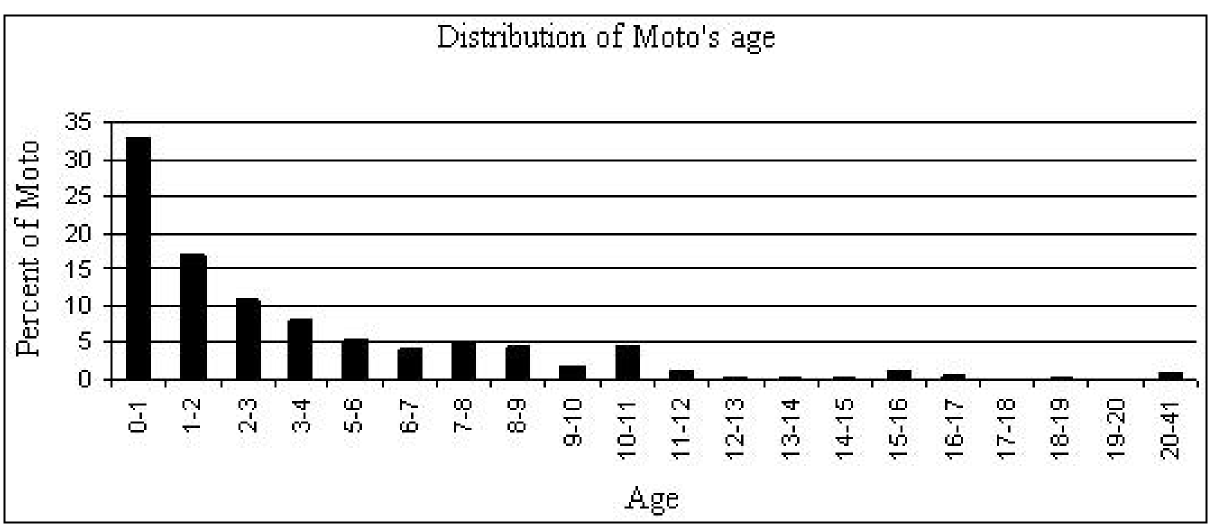


Fig. 4. Distribution of Moto’s age in HCMC.

**Emission factors (EFs)**

The EFs from the three different sources are shown in Table 4. The differences of emissions factors from three sources can partly be explained by the different quality of fuel and the maintenance of vehicles. The motorcycle's engines are not regularly maintained in Vietnam and more than 60% of the motorcycles in Hanoi and in HCMC exceeded the emissions standard (Trinh, 2007).

We evaluated the EFs from the 3 different sources. The main EFs which were used in this study are the EFs from HCMC (NOx, NMVOC and CO). However, there is no data available for the EFs of $SO_2$ and $CH_4$ for HCMC. So we used the emission factor of $SO_2$ from China because the characterizations of China's vehicles are similar to HCMC. For the emission factor of $CH_4$, we unfortunately had to use the emission factor of $CH_4$ from Copert IV. The EFs and their uncertainties which were used in this study are shown in Table 4.

| Vehicle | NOx[a] | CO[a] | $SO_2$[b] | NMVOC[a] | $CH_4$[c] |
|---|---|---|---|---|---|
| Motorcycle | 0.05±0.02 | 21.8±8.67 | 0.03±0.015 | 2.34±1.17 | 0.115±0.121 |
| Bus | 19.7±5.2 | 11.1±5.3 | 1.86±1.08 | 89.9±33.01 | 0.077±0.051 |
| Light | 1.9±0.9 | 34.8±15.5 | 0.05±0.029 | 15.02±7.36 | 0.017±0.018 |
| Heavy | 19.7±5.2 | 11.1±5.3 | 1.86±1.08 | 89.9±33.01 | 0.062±0.041 |
| Car | 1.9±0.9 | 34.8±15.5 | 0.18±0.105 | 15.02±7.36 | 0.0031±0.0032 |

Source:
[a]: the EFs were calculated for HCMC (Belalcazar et al., 2009; Ho et al., 2008)
[b]: the EFs of China (DOSTE, 2001)
[c]: the EFs were calculated from Copert IV.

Table 4. EFs (in g.km-1.vehicle-1) and their uncertainty.

- Result of total emissions:

The total result of traffic emission is presented in Table 5 as follows:

| Pollutants | Total emissions [ton h-1] | Total uncertainties (%) |
|---|---|---|
| NOx | 3.44 | 19.56 |
| CO | 331.4 | 33.77 |
| $SO_2$ | 0.733 | 27.09 |
| NMVOC | 46.24 | 27.55 |
| CH4 | 2.04 | 49.66 |

Table 5. The average of emission and their total uncertainties of all parameters over HCMC.

**Temporal and spatial distribution**

Temporal distribution: the vehicle flows from existing traffic counts were analyzed to derive the temporal distribution (Fig.5).

Spatial distribution: the spatial distributions are based on the length of each street category ($L_{Is}$) in each cell of study domain. The MapInfo software is used to distribute the parameters spatially. As expected, Fig. 6 shows that most of the urban streets are concentrated in the districts of central HCMC.

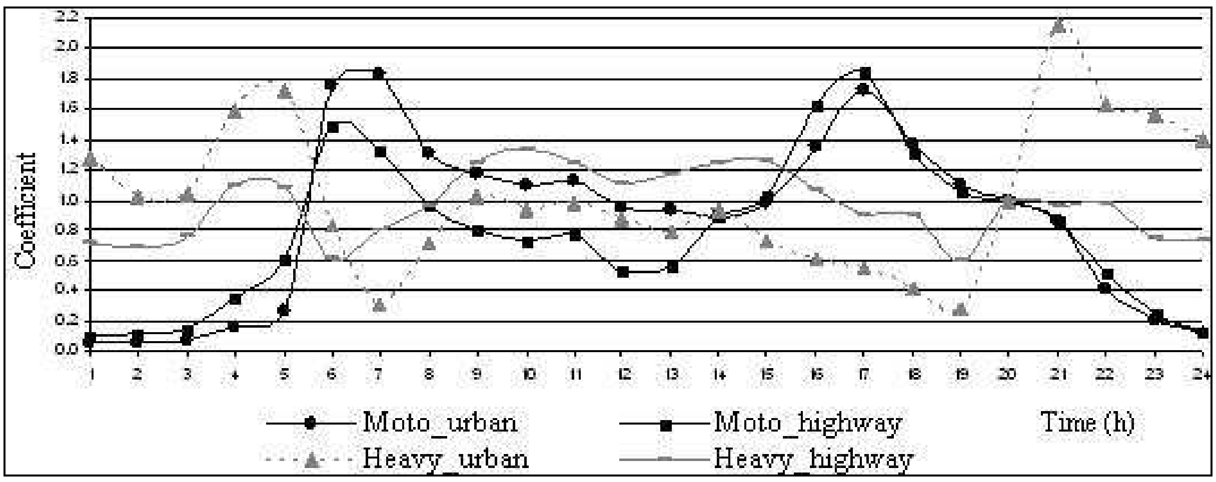


Fig. 5. Normalized hourly distribution of Motorcycles (Moto) and Heavy trucks, per urban and highway street category. A factor of 1.0 is attributed to the hour between 1900LT and 2000LT to both categories of streets, for a working day.

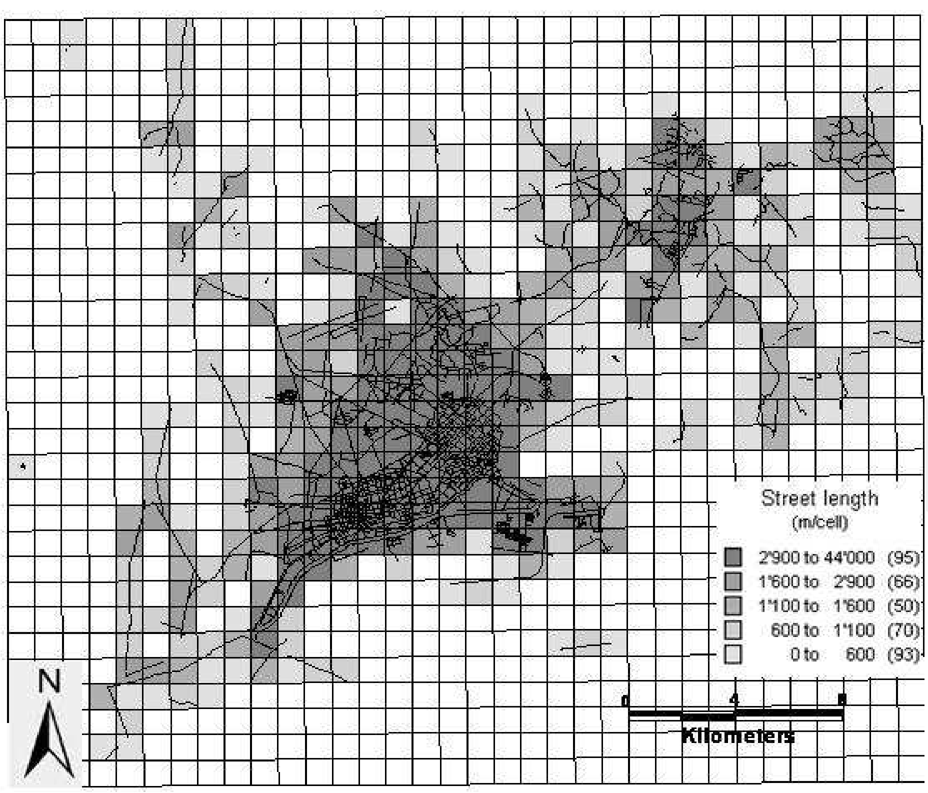


Fig. 6. The network of urban streets category in the study domain. The different colour is the number of kilometres of street length per cell. The numbers in parentheses is the number of cells.

**Result of emissions in spatial**

Finally, we run the EMISENS model for all cells of study domain. The outputs of the model are the emissions and their uncertainties in each cell (Fig.7 and Fig.8). For each pollutant, the emissions are calculated for each cell per hour. The results of CO in Fig.7 show that most of the emissions occur in the centre of the city where we can see the highest of street density of urban streets. In contrast, in the uncertainty map (Fig.8) the lowest uncertainties occur in urban streets in the city centre. Because we sub-divided the urban streets into three urban street categories, the uncertainty for urban streets is relative small.

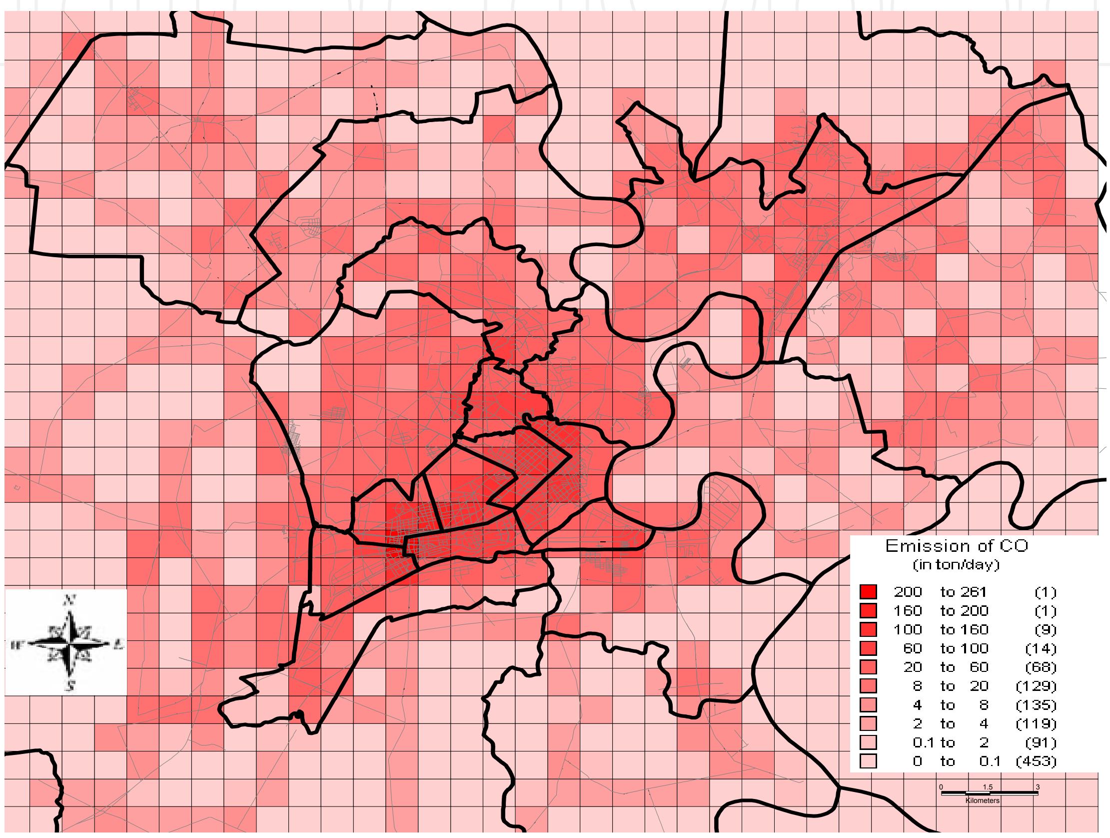


Fig. 7. The traffic emission map of CO. The contour of the districts (black colour) and the street network (grey colour). The numbers in parentheses are the number of cells.

### 4.2.2 Industriel sources

The industry is second most important source of atmospheric pollution in HCMC (Bang et al., 2006; Nguyen et al., 2002). The city spans only 0.6% of the whole country's area but more than 20% industrial producing capacity and 40% industrial output of whole country (Nguyen, 2002) is located in HCMC. The main industries in HCMC are thermo-electricity, cement production, steel lamination and refinement, weaving and dying, food processing and chemistry. The existing information for industries is very poor and an official detailed database does not exist. Most of the industries in HCMC have the following characteristics:

- The factories are old and their operation times are over 20 years.
- They have old technology which is imported from Soviet Union.
- The engines consume much energy and fuel due to old and poor quality engines. The fuel used is of a low quality.

The above list mentions the major characteristics of a majority of the industries in HCMC. In this study, the emissions from industrial sources are calculated by using a top-down approach. Starting from the total emissions in Vietnam (Table 6) and the percentage of distribution of pollutants in different sectors in Vietnam (Fig.9), we estimate the yearly industrial emissions for Vietnam. The industry of HCMC accounts for 20.2% of the total industrial emissions of Vietnam (HCMC statistics, 2003).

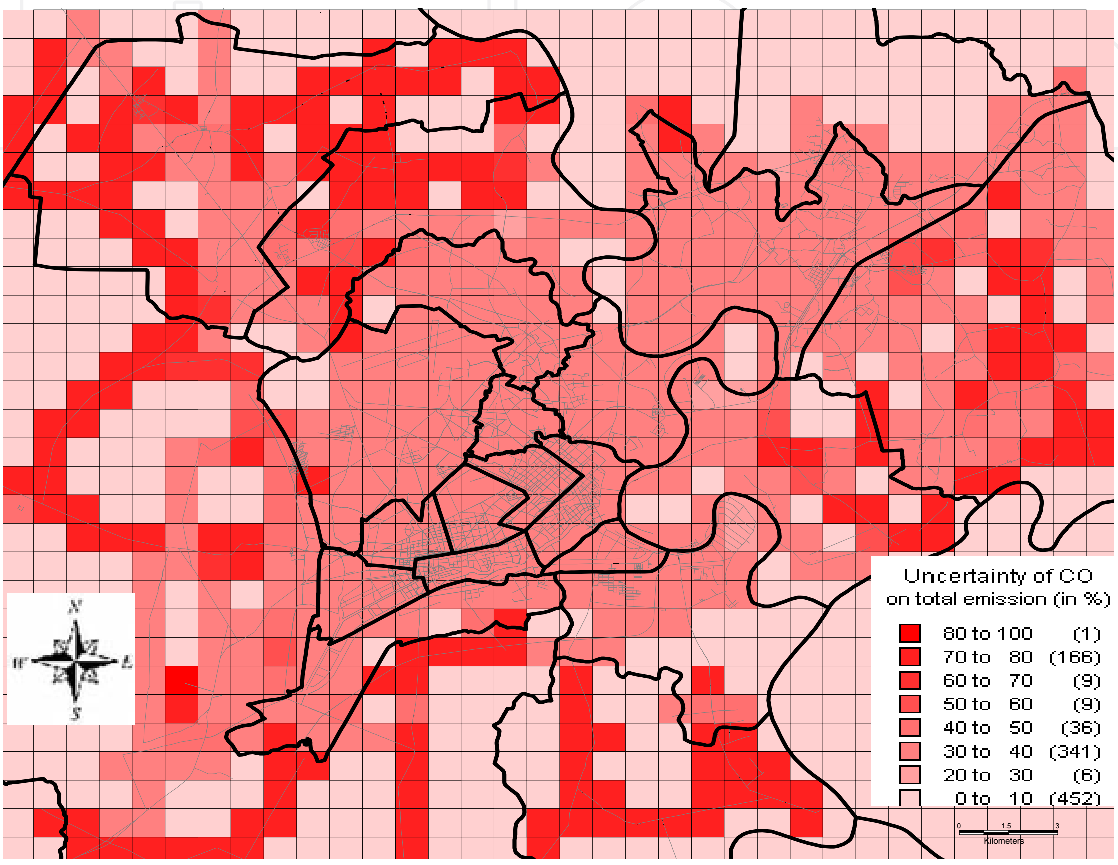


Fig. 8. The uncertainty map of CO. The contour of the districts (black colour) and the street network (grey colour). The numbers in parentheses are the number of cells.

| Pollutants | Total Emission (Tg/year) |
|---|---|
| $SO_2$ | 0.193 |
| NOx | 0.283 |
| $CO_2$ | 169.200 |
| CO | 9.248 |
| $CH_4$ | 2.907 |
| BIO NMVOC | 1.037 |
| ANT NMVOC | 1.168 |
| COVNM total | 2.205 |

Sources: Mics-Asia, 2000 (1 Tg = 106 ton).
Note: BIO NMVOC: NMVOC Biogenic; ANT NMVOC: NMVOC Anthropogenic

Table 6. Total emission in Vietnam.

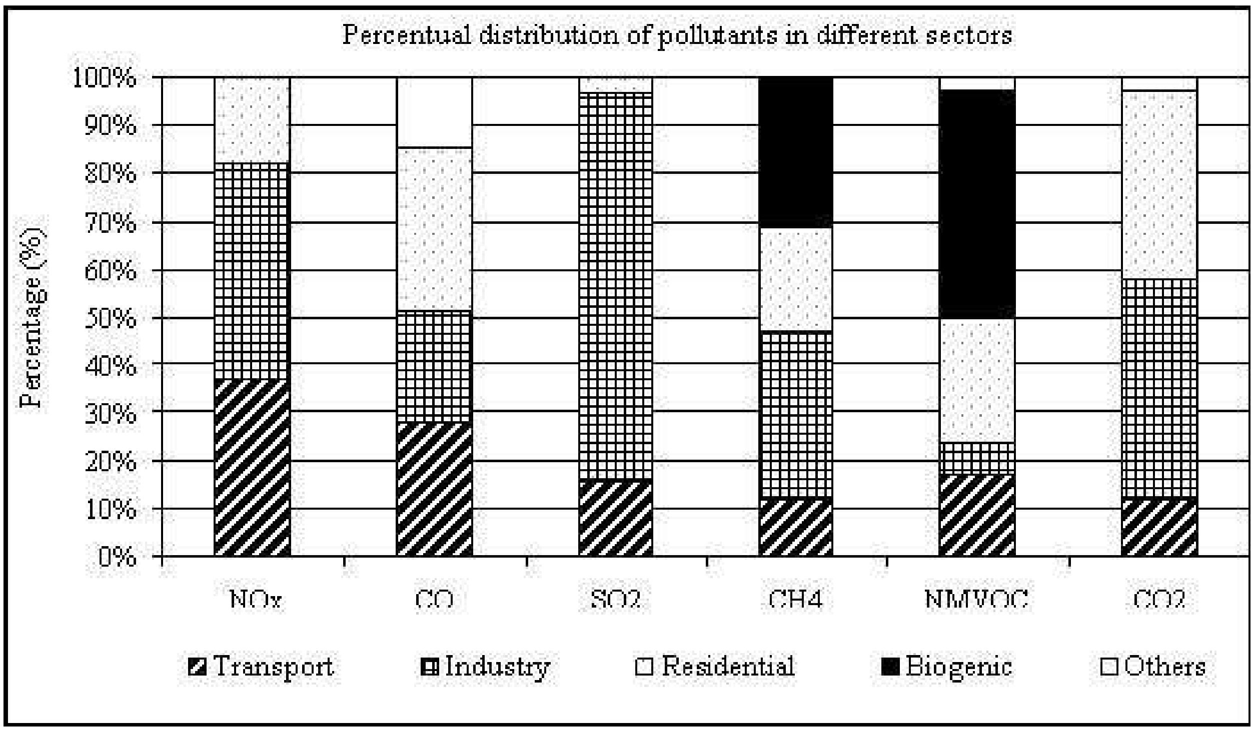


Fig. 9. Percentage of distributions of pollutants in different sectors in Vietnam.

The total emissions of Vietnam are shown in Table 6. These values were estimated by Mic-Asia project from all sources of emission in Vietnam. The project also estimated the contribution of different emission sources (Fig.9)

Fig.9 shows that the main emission sources in Vietnam are transport and industries depending on the pollutant type.

**Temporal distribution**

The results of the air quality monitoring program in south of Vietnam conducted by the Institute of Environment and Resources (IER, 2006) were used to estimate the monthly, daily and hourly coefficient distribution of industrial emissions in HCMC. The results show that November is the most polluted month because it is the post-rainy season in HCMC. During this time period, all the companies want to complete their already planned targets of products for the specific year. So the companies utilize the maximum of the available resources and run their industries at full capacity to meet their targets. On a weekly basis, Friday is the day of the week with largest emissions as it suffers maxima of pollution at 0900LT in morning and 1400LT in afternoon.

**Spatial distribution**

The spatial distribution of industrial emission sources is estimated by using the population density in each cell. We also used the GIS software for distributing the emissions spatially.

### 4.2.3 Residential sources

The main emission sources of residential areas are anthropogenic, which are mainly caused from the gastronomic activity at the residences and restaurants in HCMC. Natural gas is the major source of domestic fuel and is mainly used for cooking purposes. However, there are many small restaurants in HCMC which still use the fossil coal. The pollutants such as $SO_2$ and CO are mainly produced by the burning of this fossil fuel (Dinh, 2003).

**Temporal distribution**

We estimated the monthly, daily and hourly coefficients for the temporal distribution of residential emissions in HCMC by using the data of the air quality monitoring program in south of Vietnam conducted by the IER (IER, 2006). The monitored results show that December is the most polluted month of the year. This is because December is the start of hot season in HCMC. Saturday is the most polluted day of the week because of the weekend. Normally people cook more dishes on weekend than normal days of the week. The maximum pollution is measured at 1100LT on Saturday which is corresponds to lunch time in HCMC.

**Spatial distribution**

The spatial distribution of residential emission sources on each cell of study domain is also estimated using the population density in each cell.

### 4.2.4 Biogenic sources

Only volatile organic compounds (VOCs) are calculated for biogenic emission sources. The biogenic EI are very important for air quality modelling, because biogenic VOCs contribute significantly to the formation of ozone (Varinou et al., 1999; Rappenglück et al., 2000, Moussiopoulos, 2003). The largest contribution through biogenic emissions is caused by trees, which emit 10 times more biogenic VOCs as compared to smaller plants. The biogenic VOCs are mainly divided in 3 major pollutants: Isoprenoids, Terpenes and other VOCs (EEA, 1999).

**Temporal distribution**

The emissions of biogenic VOCs depend on the air temperature and the intensity of solar radiation (EEA, 1999; Rappenglück et al., 2000; Moussiopoulos, 2003). So, the estimation of monthly, daily and hourly coefficient for biogenic source in HCMC is based on the results of solar-radiation measurements (from the urban air quality monitoring of HEPA (HEPA, 2006)). The monitored results show that the highest intensity of solar radiation is in the month of April, because the April is in the middle of the hot season in HCMC. Midday is the time when the maximum of radiation intensity is observed.

**Spatial distribution**

In this research, we estimate the emission for the districts in centre of HCMC. We assume that the percentage of green space is similar every where in the domain. The spatial distribution of biogenic emission sources to each cell of study domain is estimated by using the area of each cell.

### 4.2.5 Results

Table 7 presents the results of total EI for all emissions sources in HCMC and the percentage of contribution of each emission source towards the total emissions in HCMC. The column "total emissions" represents the total emissions (in ton per day). The last four columns correspond to the percentage of contribution of each emission source on total EI.

| Pollutant | Total emissions | Industry (%) | Residential + other (%) | Biogenic (%) | Traffic (%) |
|---|---|---|---|---|---|
| NOx | 106.27 | 15.79 | 6.46 | - | 77.75 |
| CO | 8860.25 | 5.45 | 4.78 | - | 89.77 |
| $SO_2$ | 1603.37 | 80.42 | 18.49 | - | 1.10 |
| NMVOC | 1241.45 | 1.90 | 8.33 | 0.38 | 89.39 |
| $CH_4$ | 214.81 | 27.02 | 33.19 | 16.98 | 22.80 |

Table 7. Total emissions in HCMC [ton day-1] and the contribution of each emission source on the total emissions in HCMC (in %).

Table 7 shows that the emissions of $SO_2$ (80.42%) from industrial sources are very important. Because the industry in HCMC uses a lot of diesel oil, mazut oil and fossil coal which contain high percentage of sulphur as fuel (Dinh, 2003).

The traffic sources contribute with a high percentage of total emissions (NOx 77.75%; CO 89.77%; and NMVOC 89.39%).

### 4.3 Modeling of air pollution over HCMC

#### 4.3.1 Models description and set-up

**Meteorological**

The Finite Volume Model (FVM) model used in this research is a three dimensional Eulerian meteorological model for simulating the meteorology. The model uses a terrain following grid with finite volume discretization (Clappier et al. 1996). This mesoscale model is non-hydrostatic and anelastic. It solves the momentum equation for the wind component, the energy equation for the potential temperature, the air humidity equation for mean absolute humidity and the Poisson equation for the pressure. The turbulence is parameterized using turbulent coefficients. In the transition layer these coefficients are derived from turbulent kinetic energy (TKE, computed prognostically), and a length scale, following the formulation of Bougeault and Lacarrere (Bougeault et al. 1989). In the surface layer (corresponding to the lowest numerical level), in rural areas, the formulation of Louis (Louis et al. 1979) is used. The ground temperature and moisture, in rural areas, are estimated with the soil module of Tremback and Kessler (Tremback et al. 1985). An urban turbulence module in the model simulates the effect of urban areas on the meteorology (Matilli et al. 2002 b). A second module, the Building Energy Model (BEM, Krpo 2009), takes into account the diffusion of heat through walls, roofs, and floors, the natural ventilation, the generation of heat from occupants and equipments, and the consumption of energy through air conditioning systems. The FVM model was developed at the Air and Soil Pollution Laboratory (LPAS) of the Swiss Federal Institute of Technology in Lausanne (EPFL).

For choosing the domain used in the meteorological simulations, we have to take account of their size and especial resolution due to the capacity of computer. The four selected domains (Fig. 10) are domain 1 (resolution of 75 km x 75 km cells 16 x 16 grid points), domain 2 (resolution of 16 km x 16 km cells 33 x 33 grid points), domain 3 (resolution of 5 km x 5 km cells 40 x 40 grid points) and domain 4 (resolution of 1 km x 1km cells 34 x 30 grid points). The domain 4 includes main part of HCMC. The results from nesting procedure for initial and boundary conditions are used over this domain. For the largest domain (domain 1), the initial and the boundary conditions are interpolated from 6-hourly data from National Centers for Environmental Prediction (NCEP). In vertical position the grids extend up to 10,000 m, with 30 levels. The vertical resolution is 10 m for the first level, and then it is stretched up to the top of the domain at 1000 m [(grid stretching ratio equal to 1.2) (Martilli et al. 2002)]. Land use data obtained from the U.S. Geological Survey (USGS) is used as input for the simulations. For obtaining more realistic initial conditions, a pre-run of one day is computed for the meteorological simulations.

**Air quality model**

The air quality model used for this research is the Transport and Photochemistry Mesoscale Model (TAPOM) (Martilli et al . 2003; Junier et al . 2004) implemented at EPFL and at the Joint Research Centre of Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA). It is a transport and photochemistry three-dimensional Eulerian model. It is based on the resolution of the mass balance equation for the atmospheric substances. This equation includes the advection by the mean wind, the vertical diffusion by the turbulence, the chemical transformation by reactions, the dry deposition and the emissions. The chemical transformations are simulated by using the RACM (Stockwell et al. 1997), the Gong and Cho (Gong et al. 1993) chemical solver for the gaseous phase and the ISORROPIA module for inorganic aerosols (Nenes et al. 1998). The transport is solved using the algorithms developed by Collella and Woodward (Collella et al. 1984). Then this algorithm has recently developed by Clappier (Clappier et al. 1998). Now there are a lot of atmospheric models uses this algorithm. The photolysis rate constants used for chemical reactions are calculated using the radiation module TUV which is developed by Madronich (Madronich et al. 1998). In vertical position, the grids extend up to 7300 m with 12 levels. The vertical resolution is 15 m for the first level, and then it is stretched up to the top of the domain at 2000 m (grid stretching factor of 1.2 for lower and 1.6 for upper layers of the grid).

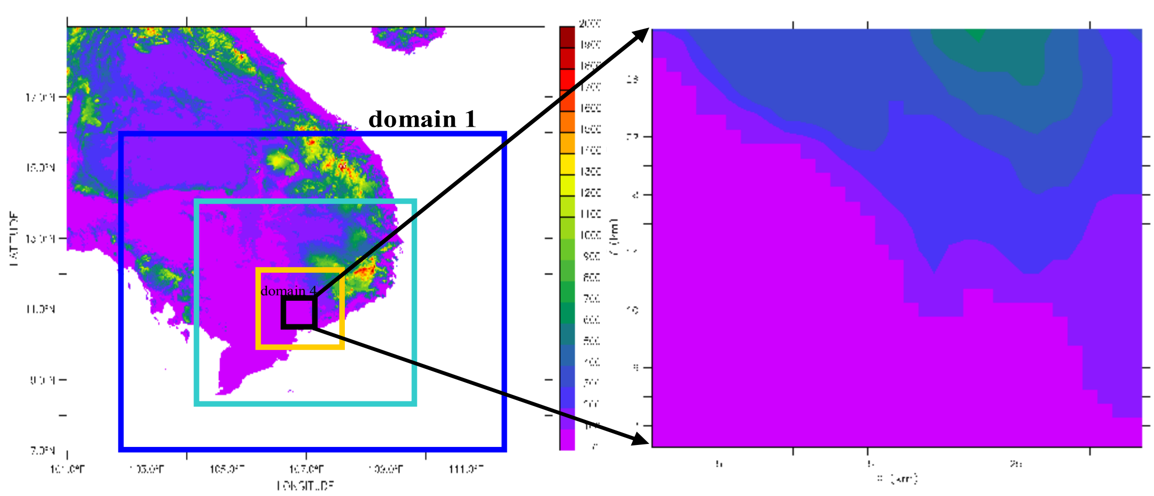


Fig. 10. Topography of South of Vietnam and description of simulated domains (left panel). The central black square (shown in left panel) used for the air quality simulation domain (right panel). (Source: http://edcdaac.usgs.gov/gtopo30/gtopo30.html (online & free downloading)).

Initial and boundary conditions for the photochemical simulations are based on measurements obtained by the Institute of Environment and Resources –VNU (IER-VNU) and the HEPA. Measurements taken from stations located in the surrounding of HCMC. They show 30 ppb of $O_3$ and very low values of NO and $NO_2$ (0.19 ppb).

A pre-run of one day with the same emissions (in emission inventory section) and wind fields (in meteorological modeling section) is performed. This calculation provides more realistic initial conditions for the air quality simulations. The air quality simulations are run for the episode of 3 day 6th - 8th February 2006.

### 4.3.2 Results

**Results of meteorological simulations over HCMC**

In the morning, the wind direction in HCMC is towards the north-west. At 0600LT (Fig. 11(a)), the wind is influenced by the Trade Winds. At this time, we do not observe the sea breeze phenomenon because it is too weak and the Trade Winds dominate the wind direction in the grid at this time. By 0900LT the wind is stronger and we observe the development of some small converge zones, produced due to the slope winds phenomenon developed in the city. Until 1300LT as shown in Fig. 11(b), the sun light has warmed up the ground rapidly. The slope winds are stronger at that time and air masses come up from the south plateau toward the highland area in the north. Some other air masses come from the east. Three main converge fronts can be perceived in the grid. The wind speed increases strongly and reaches its maximum at 1700LT as shown in Fig .11(c). At this time, the warming of the ground reaches its maximum and the sea breeze phenomenon develops strongly. From 2200LT until the next morning, wind fields are similar to 0600LT as it shown in Fig .11(d).

The measurements taken during the episode are used to validate these wind fields. The results of TSN station (Fig .13) show daily and nightly temperature values (Fig .12(a)). In general, FVM reproduces correctly the variation of the temperature. The results show that during all the day, measured and modeled temperatures are very similar. The model predicts well the time of the day when the sun rises (0700LT) and temperatures start increasing.

The maximum value of temperatures (between 1200LT and 1500LT) is 35.19°C. However it underestimates nightly temperatures, this can be explained by the NCEP nightly temperatures are also underestimated at ground level. These boundary conditions contribute to cool down the borders of the grid, and then the simulations are underestimated. The measurements of TSN station (Fig .12(b)) show very clearly the daily and nightly maximum and minimum wind speed values. Unfortunately, there are very few measurements for meteorology over HCMC area. The TSN station is located in west part of domain. We observed that minimum wind speed values are between 0500LT and 0700LT, when land and sea are coolest. The minimum wind speed was observed at the same time together with a change in the wind direction (Fig .12(c)). The maximum wind speed values observed during the day occur at the same time with the maximum of development of local phenomena. The change in wind direction due to the slope winds cannot be seen clearly, because TSN station is situated towards the west of city where the local phenomena are less notorious. The wind and temperature of simulation in vertical are agreement with the observations.

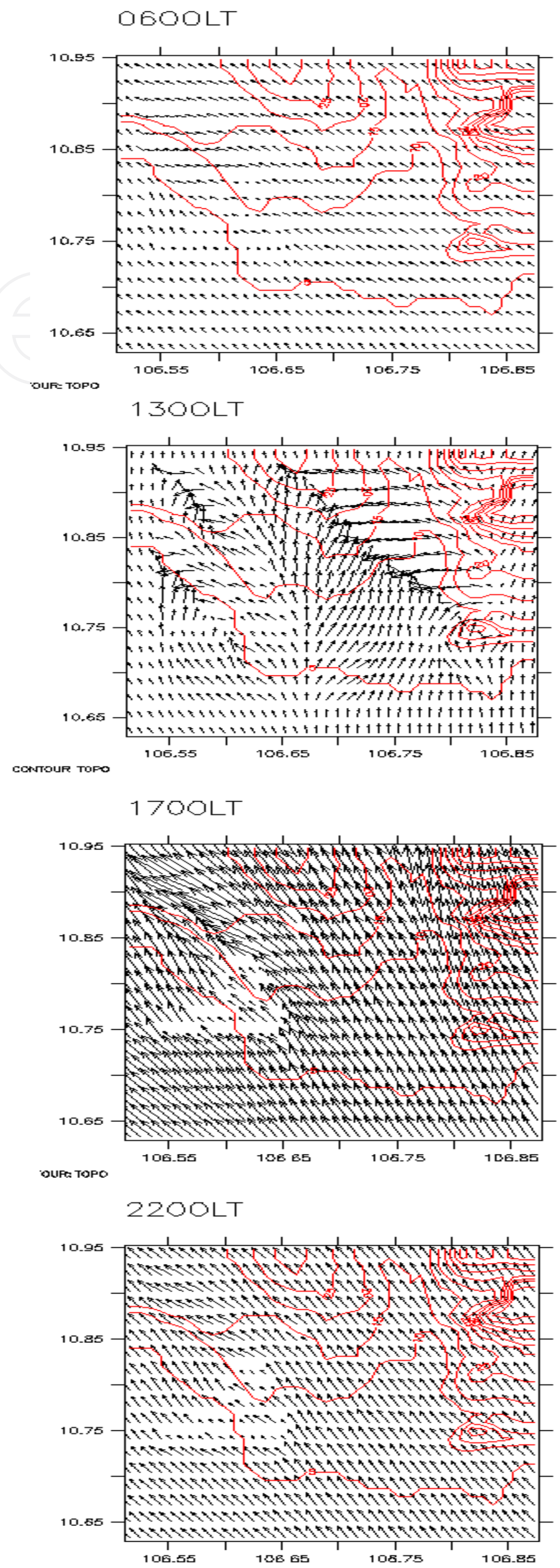


Fig. 11. Wind field results from simulations at ground level for the domain 34 km x 30 km, 7th February 2006. Geographical coordinates of the lower left corner: 10.64°N and 106.52°E. Maximum wind speed is 5.5 m s-1.

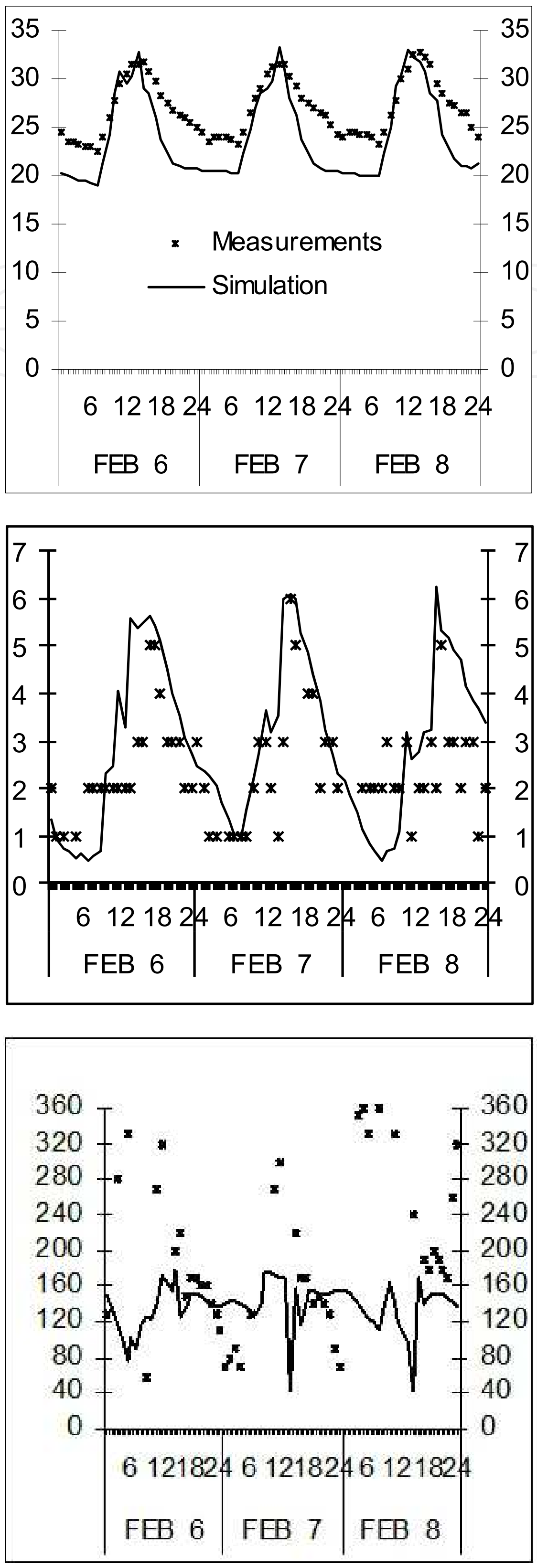


Fig. 12. Comparison between the results of simulated (solid line) and measured (starts). The temperature in °C (a), wind speed in m.s-1 (b), wind direction in degree (c) at ground level in TSN station, 6th – 8th February 2006.

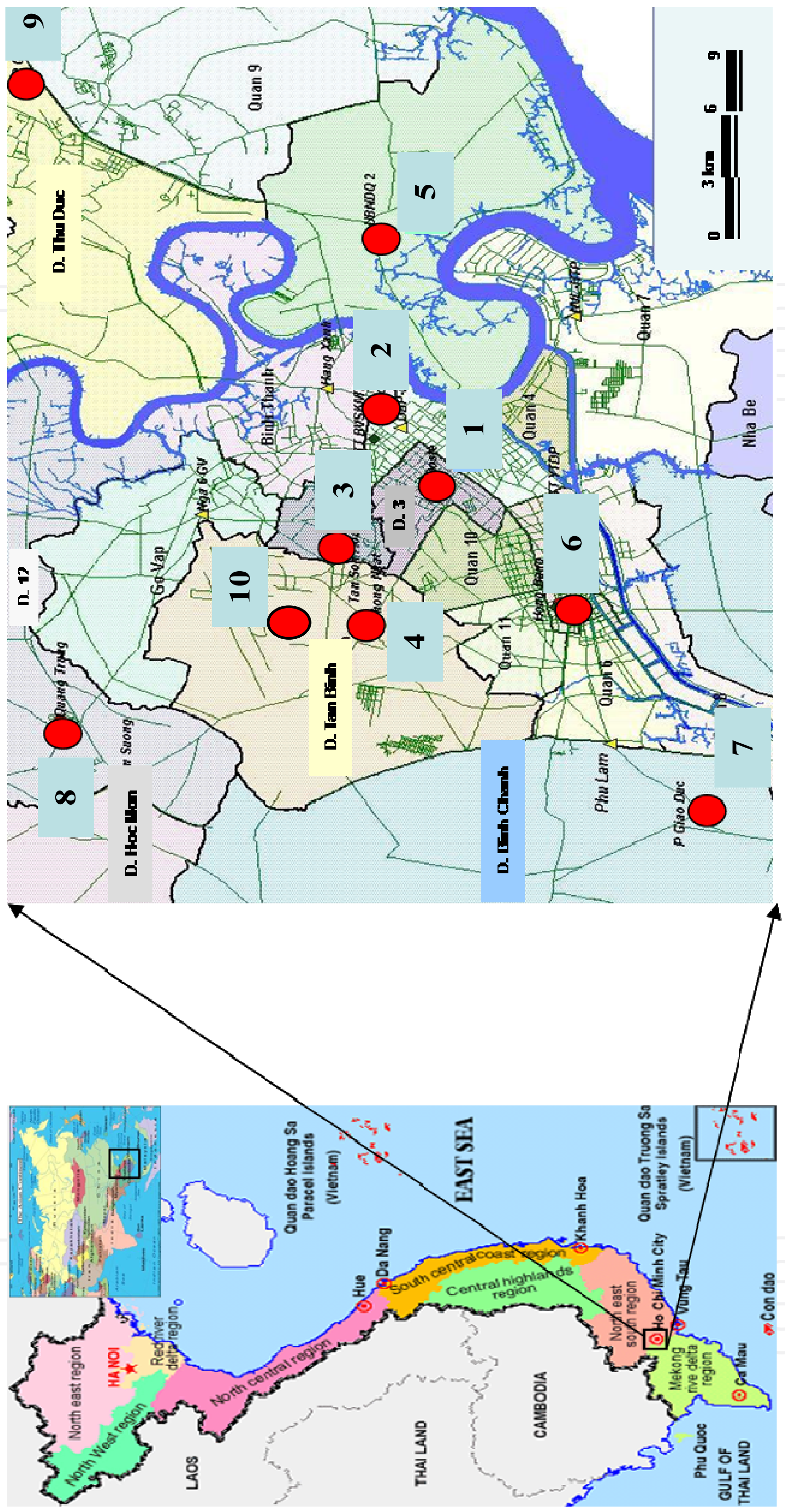


Fig. 13. The map on the left panel is the location of Vietnam. The map on right panel is presenting the location of monitoring stations in domain simulated. Five road-side stations (1. DO; 4. TN; 6. HB; 7. BC; 9. TD) and four urban background stations (2. ZO; 3. TS; 5. D2; 8. QT) for air quality monitoring are located on the map. The meteorological stations are located in TSN airport (station number 10) and Tan Son Hoa site (station number 3). (Source: Library of Institute of Environment and Resources (IER)-Vietnam).

**Results of air quality simulations over HCMC**

Evaluation of the uncertainty in air quality simulation: results of numerical simulations are more reliable if the estimation of uncertainties in model prediction is generated. The uncertainties of the air quality model due to input parameters could be generated by using the standard deviation (square root of variance) around the mean of the modeled outputs (Hwang et al. 1998). Up to now, the Monte-Carlo (MC) is a brute-force method for uncertainty analysis (Hanna et al. 2000). 100 MC air quality simulations are run for estimating uncertainty in the results of air quality and abatement strategies.

The uncertainty and the median of pollutants are calculated from 100 MC air quality simulations. The results of pollutants and their uncertainties from the output of the air quality modeling are divided into two pollutant types, primary (CO, NOx, etc.) and secondary pollutants ($O_3$).

Simulation of primary pollutants:_TN station is located in the centre of HCMC, and D2 station is located around the city, but both stations are representative for ambient air quality. They are not situated beside the road. Fig .14(a) shows that the concentration of CO (from measurements and simulations) has an important peak in the morning (between 0700LT and 1000LT). However, Fig .14(b) shows that the peak of NOx (from measurements and simulations) is presented later, between 0900LT and 1200LT. The peak is related to the highest emissions from traffic mainly due to the rush hour during this period in HCMC. The peak of NOx appears late than the peak of CO (around 2-3 hours), because the high emission of CO is related to the private vehicle (motorcycles and cars), while the high emission of NOx is related to the trucks (heavy and light trucks). In HCMC, trucks have limited circulation from the city centre during rush hours (600LT-830LT and 1600LT-2000LT). The peak is amplified to a very high concentration due to a low mixing height in the early morning. At this time the temperature of the air masses are still cold, the vertical diffusion of pollutants is very weakly so the pollutants are stored at ground level. The air-monitoring network in HCMC includes nine stations but due to the lack of calibration and maintenance of the equipments, measurements are available only for some day at some stations. The values of the peaks of both CO and NOx are in good agreement with observations. The second daily peak of CO and NOx is observed around 1700LT and 1800LT, because this is a second rush hour of the day. This peak is related to the traffic and it is sometimes underestimated by the model which may be attributed to an overestimation of the wind speed at this time.

The results from simulations which are shown in Fig .14 are the mean values of 100 MC simulations. Probabilistic estimate are shown by plotting concentration enveloped (mean $\pm 1\ \sigma$) with time. Fig .14(a) shows that the uncertainty for the CO simulated differ by a maximum of 1.8 ppm ($\approx$ 34.4% of mean value) at rush hour 0700 LT – 0800LT on 6th Feb 2006. The minimum uncertainty is 0.01 ppm ($\approx$ 0.5% of mean value) which is observed in the middle of all nights from 6th to 8th Feb 2006. Fig. 14(b) shows that the NOx uncertainty differs by a maximum of 11.28 ppb ($\approx$ 13% of mean value) at the same time of appearance NOx peak. The minimum uncertainty is 0.47 ppb ($\approx$ 5.9% of mean value) which is observed during the middle of night.

Simulation of secondary pollutants: HB station is located in the centre of HCMC (Fig .13). In general the concentration of $O_3$ in D2 station (Fig .14(c)) is higher than in HB station (Fig .14(d)), because D2 station is situated closer to the $O_3$ plumes than HB station.

The simulation shows high $O_3$ levels at the same stations as the measurements do on 7th Feb as shown on Fig .14(c), indicating a good reproduction of the plume position. We can see that the HB station is located closer to the south of the city than the D2 station (Fig .13). This confirms the fact that pollutants are being transported in the northern and north-western direction at 1300LT on 7th Feb. The uncertainty analysis for the air quality model is also studied by running 100 MC simulations. Fig .14(c) and Fig .14(d) show that the uncertainties of $O_3$ differ by a maximum of 5ppb ($\approx$ 8.6% of mean value) at 1100LT-1300LT on 6th - 8th Feb 2006 at both stations. The minimum uncertainty of $O_3$ is 1ppb ($\approx$ 15% of mean value) at 0700LT – 0900LT on 6th – 8th Feb 2006 at both stations.

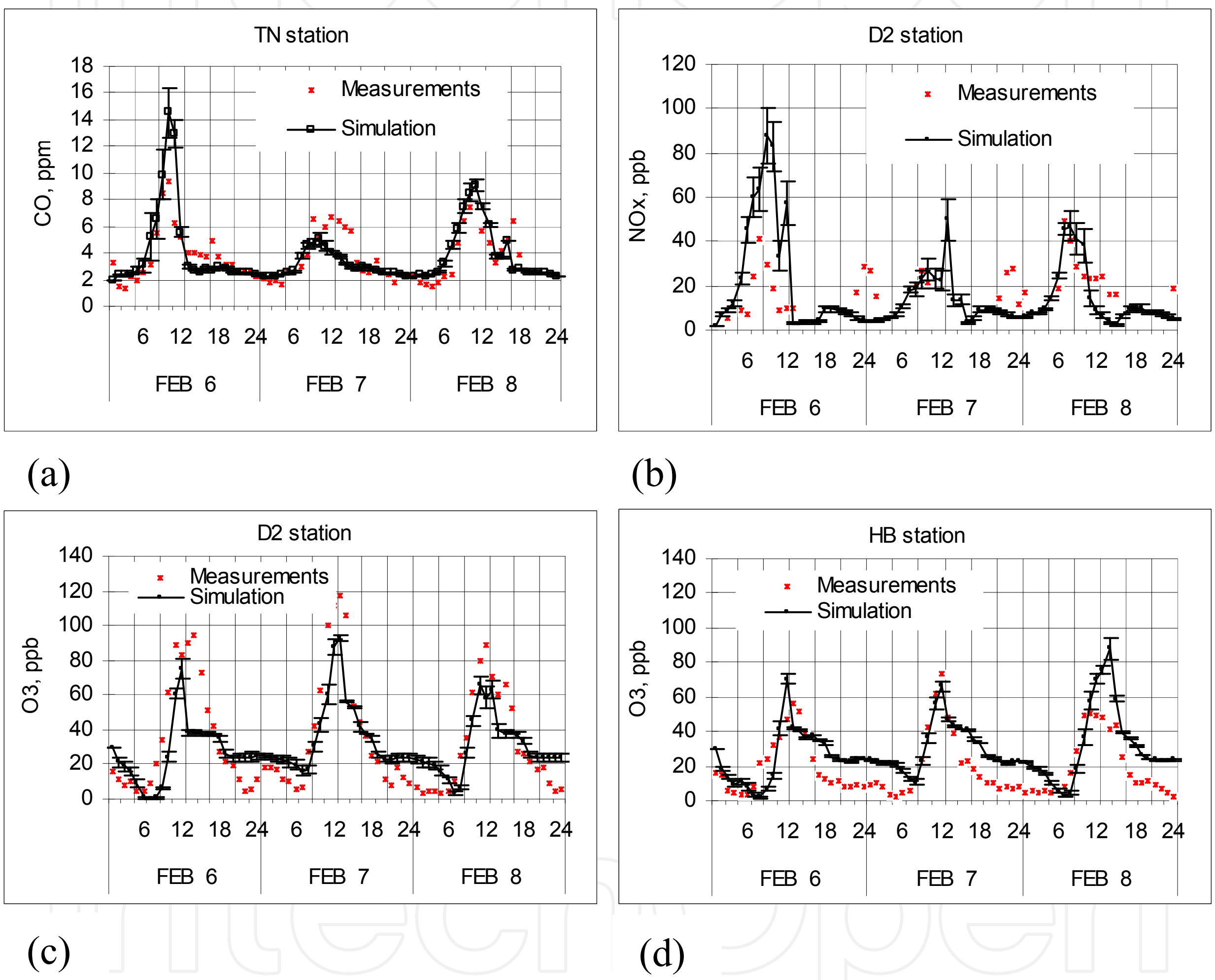


Fig. 14. Comparison between the results of measurements (stars) and simulation (solid line) during the selected episode (on 6th - 8th Feb 2006) for CO (ppm) at TN station, NOx (ppb) at D2 station and $O_3$ (ppb) at D2 and HB stations. The uncertainties of CO, NOx and $O_3$, from 100 MC simulations are presented by 1$\sigma$ (standard deviation). NOx refers to NO + $NO_2$.

**Spatial distribution of $O_3$**

Figure 15 shows the plume of $O_3$ developed during the 7th Feb 2006. In the early morning, there are very high concentrations of NOx stored in the centre of the city, which generates $O_3$ destruction at this location, while Fig .15(a) shows that at 1000LT $O_3$ is being formed in the neighboring city. At this time, pollutants are pushed to the north-west of city by the wind coming from the south-east. Figure 15(b) shows that until 1300LT, the time with the highest solar radiation, the maximum quantity of $O_3$ is formed. At this time, wind is divided in three main convergences which divide the plume of $O_3$ into two different small plumes. Two $O_3$ maxima are formed at this time on 7th Feb, 140 ppb and 150 ppb, for the northern and north-western parts of the city, respectively. Then, until 1400LT the wind direction is the same wind direction than at 1300LT. However the wind speed is very strong (two times stronger than at 1300LT), which pushes rapidly the $O_3$ plume to go up to the north and north-west of the city. Fig .15(c) shows that at 1500LT the plumes leave the basin of HCMC through the north and north-west. The $O_3$ concentrations remain low in the city. Then, at 2000LT the wind direction is the same wind direction than at 1000LT. At 2000LT, there is not solar radiation coming to the earth which prevents $O_3$ production and promotes the destruction of $O_3$, especially in the north-western part of the city.

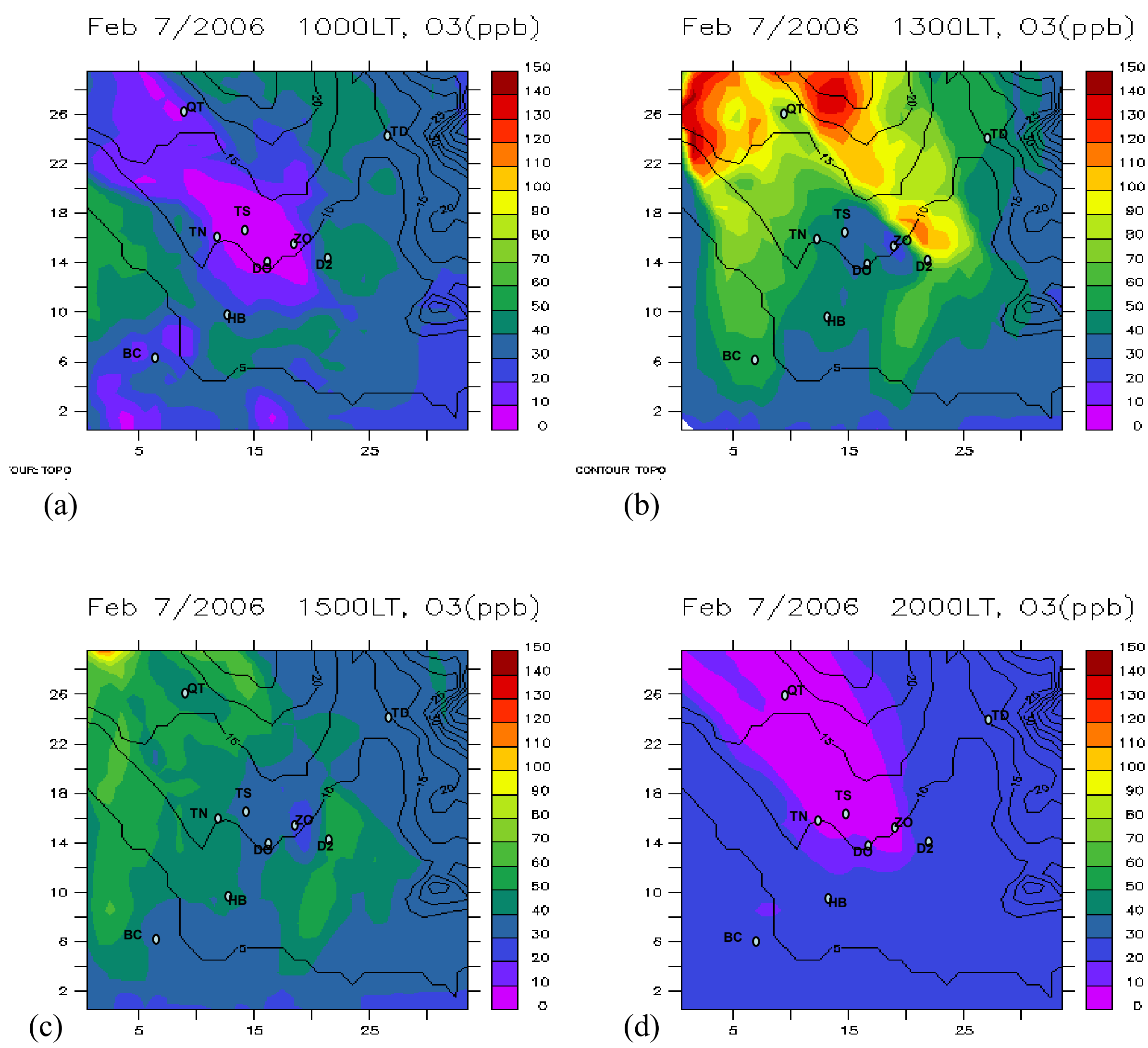


Fig. 15. Map of $O_3$ concentrations (ppb) at ground level in the domain of 34 km x 30 km, at 10LT00 (upper left panel), 1300LT (upper right panel), 1500LT (lower left panel) and 2000LT (lower right panel), 7th Feb 2006 and measurement stations. The different colours are the $O_3$ levels.

In conclusion, 6th – 8th February 2006 is a period which is representative for one of the highest $O_3$ episodes during the dry season of the year in HCMC. The primary pollutants show highest values in centre of city where the highest density of traffic is found. Therefore, the huge part of population in the centre of HCMC is living with unfavorable conditions due to high concentration of primary pollutants. However, in the case of secondary pollutant we can see that it has most favorable conditions for the population living in the centre of HCMC and unfavorable for the population living in the north and north-west of HCMC. Once the models were shown able to reproduce and understand the principal characteristics of pollution in HCMC, it is very useful to study different strategies to reduce pollution for the city in the future.

### 4.4 Air pollution abatement strategy

For over 15 years, a lot of studies to evaluate air pollution abatement strategies have been carried out by using air quality models (Metcalfe et al. 2002; Palacios et al. 2002; Zarate et al. 2007 and to cite a few). The previous section shows that it is urgent to establish emission control scenarios for HCMC. Over some recently years, the results of air quality monitoring have shown that the pollutants exceeded regularly the standard limits in HCMC due to the emissions from the traffic source (HEPA, 2005; HEPA, 2006). The local government has started to design some emission control plans for traffic in HCMC. The plans are designed for the year of 2015 and 2020. The two emission control plans are named: (1) Emission reduction scenario for 2015 and (2) Emission reduction scenario for 2020.

The main ideas are that in 2015 the HCMC government will perform many activities to control air pollution concerning the road traffic source (Trinh, 2007): (1) controlling the emission of all vehicles (Thang, 2004), (2) the first metro line will be finished at the end of 2014 (Bao du lich, 2008) and (3) HCMC government will add 3000 new buses during 2006-2015 (Tuong, 2005).

For the year of 2020, four metro lines will be constructed (metro system will replace 50% of total motorcycle) (Bao du lich, 2008) and the number of buses will be increased to 4500 during 2006-2020 (Bang et al., 2010).

**Spatial distribution of $O_3$**

The impacts of two strategies on the levels of troposphere $O_3$ in HCMC are shown in Fig .16(a) and Fig .16(b). If HCMC follows the reduction plan: (i) For the year of 2015, the reductions for the HCMC grid area as a whole are 3.3% for CO, $SO_2$, and $CH_4$. There is an increase in NOx emissions of 8%. Mean values of $O_3$ are reduced from 28.5 ppb to 28.0 ppb and the maximum from 150 ppb to 136 ppb on 7th Feb. (ii) For the year of 2020, the reductions for HCMC grid area as a whole are 8.6% for CO and 12.5 % for $CH_4$, there are increases in NOx, $SO_2$ and NMVOC emissions of 20.1%, 7.6% and 6.2%, respectively. Mean values of $O_3$ are reduced from 28.5 ppb to 27.6 ppb and the maximum from 150 ppb to 120 ppb for 7th Feb.

The highest reduction of $O_3$ concentration is found at the same place of the principal $O_3$ plume for both abatement strategies. A deeper analysis of this reduction will be discussed by plotting the $O_3$ concentration variable with respect to time and its uncertainties. In this research, we select some stations where we find the maximum of $O_3$ reduction, the medium of $O_3$ reduction and the minimum of $O_3$ reduction. The MA, D2 and HB stations are chosen for the maximum, medium and minimum reduction zones, respectively (Fig .16 (a)). Their results are shown in the following section.

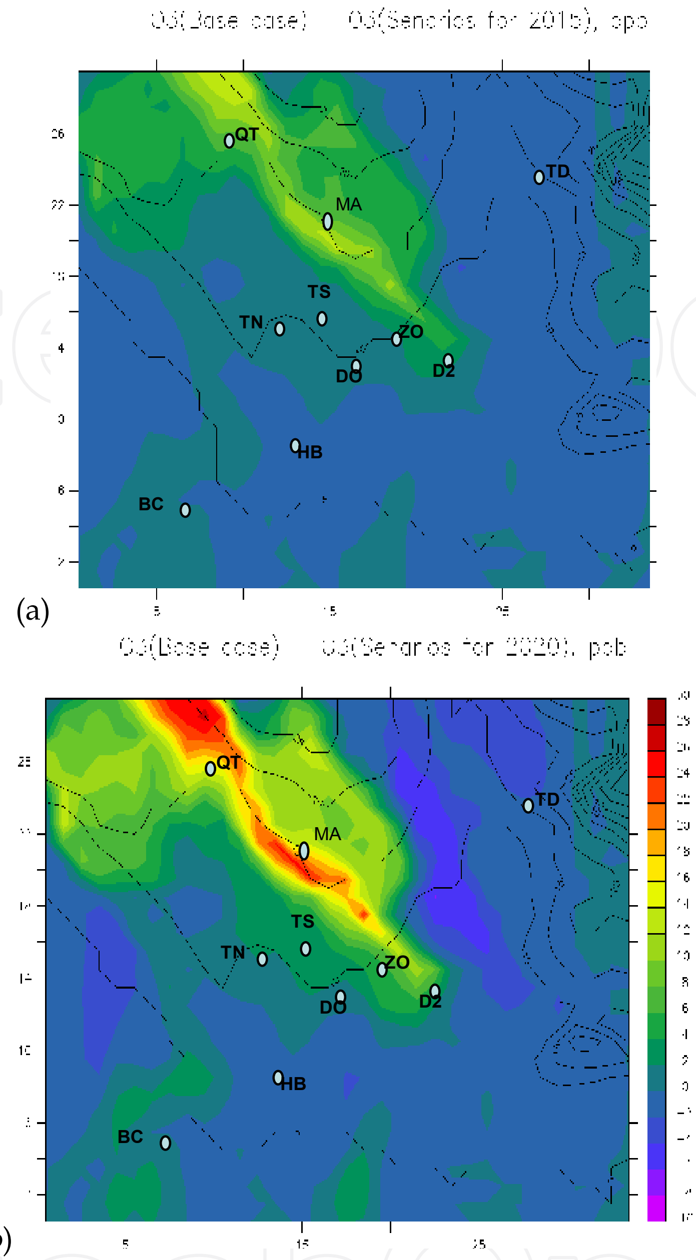


Fig. 16. Effect of two strategies on $O_3$ concentration (ppb) fields for the 7th Feb 2006 at 1300LT ground level. Figure 16(a) represents the reduction of $O_3$ concentration in 2015 from the ozone concentration in 2006. Figure 16(b) represents the reduction of $O_3$ concentration in 2020 from the ozone concentration in 2006. The measurement stations are shown in Fig. 13.

**Analysis of $O_3$ at different measuring stations**

Strategy in 2015: Figure 17(a, b, c)-upper panels shows the reduction of $O_3$ concentrations ($\overline{\Delta O_3}$ in equation 4) in 2015 from the $O_3$ concentration in 2006 and its uncertainties ($\sigma_{\overline{\Delta O_3}}$ in equation 5) in different stations (we consider the standard deviation as the uncertainty).

The Delta $O_3$ ($\overline{\Delta O_3}$) and uncertainties of $O_3$ ($\sigma_{\overline{\Delta O_3}}$) presented on Fig .17 are calculated using equations (4) and (5). These values are calculated from 100 MC simulations for the base case and 100 MC simulations for each strategy.

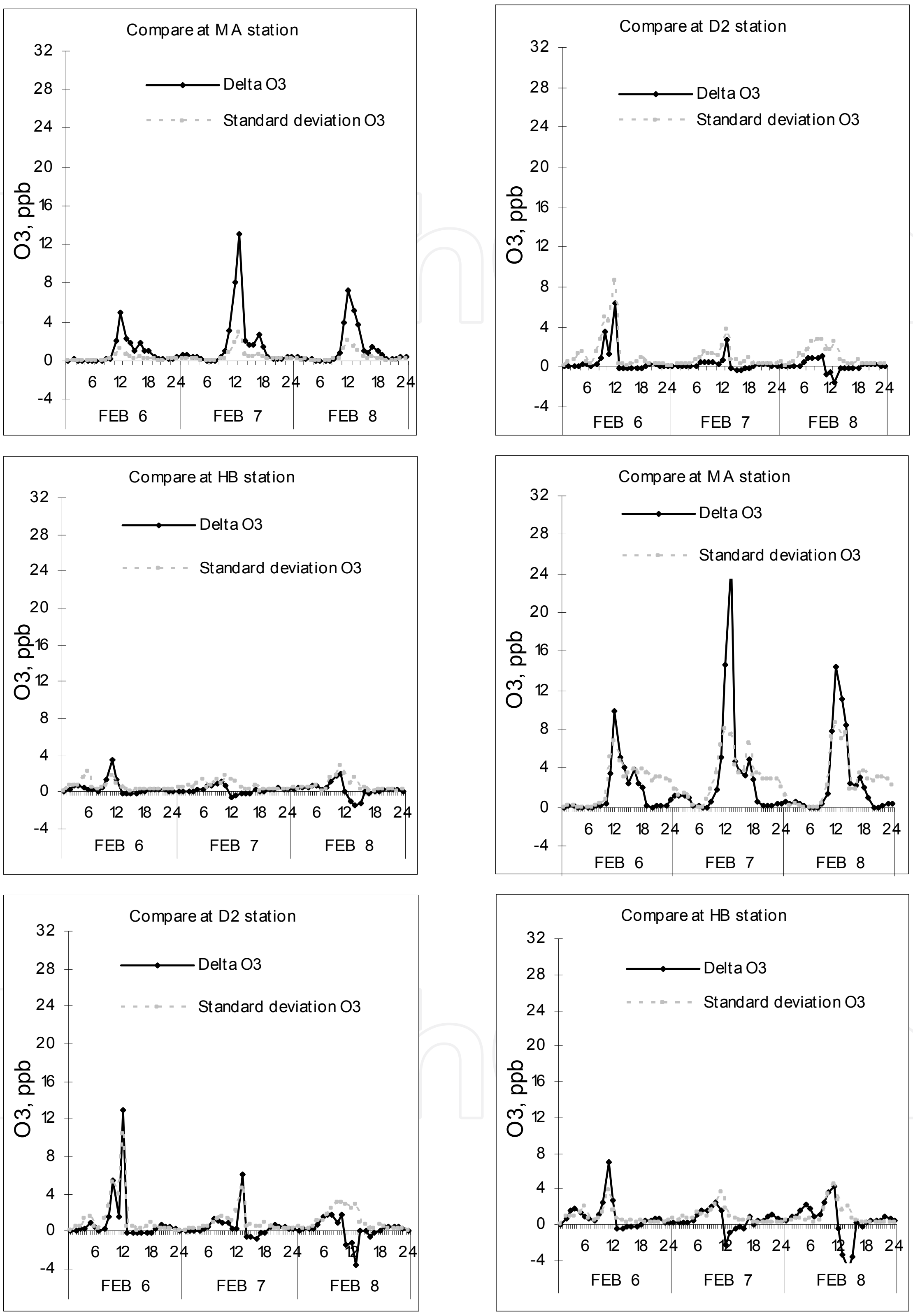


Fig. 17. Reduction of $O_3$ (in ppb) in 2015 (strategy in 2015; Fig .17 (a, b, c)_upper panels) and in 2020 (strategy in 2020; Fig .17 (d, e, f)_lower panels) from the $O_3$ concentration in 2006 and its uncertainties. The results are plotted for the first layer near the ground during the selected episode (on 6th - 8th Feb) at MA, D2 and HB stations.

$$\text{Delta } O_3 = \overline{\Delta O_3} = \frac{\sum_{i=1}^{100}(O^i_{3\_Base\ case} - O^i_{3\_2015})}{100} \quad (4)$$

where: i is the number of simulation

$O^i_{3\_Base\ case}$ is the $O_3$ concentration of base case (2006) for the ith simulation

$O^i_{3\_2015}$ is the $O_3$ concentration of strategy in 2015 for the ith simulation,

$$\text{Standard deviation of } O_3 = \sigma_{\overline{\Delta O_3^*}} = \sqrt{\frac{\sum_{i=1}^{100}(\Delta O^i_3 - \overline{\Delta O_3})^2}{99}} \quad (5)$$

Where: $\Delta O^i_3$ is the difference in $O_3$ concentration between the base case and the strategy in 2015 for the ith simulation.

The highest uncertainties of $O_3$ reduction appear at the same time of the highest $O_3$ reduction at 1200LT - 1400LT of each day (Fig .17). The highest reduction of $O_3$ concentration at MA, D2 and HB stations during 6th - 8th Feb are 14ppb, 6.7ppb and 3.9ppb, respectively. However, the highest uncertainties of $O_3$ reduction at MA, D2 and HB stations are 3ppb, 9ppb and 3.5ppb respectively. Therefore, the uncertainties of $O_3$ reduction are in general similar to the $O_3$ reduction. We can not conclude that the change in $O_3$ concentration is due to the impact of the emission control plan, because the change can probably be due to the impact of uncertainties of input parameters.

For the evolution of primary pollutants of the strategy in 2015, the concentrations of NOx in simulations will increase 7% than those were in 2006. However, the concentrations of CO and $CH_4$ decrease around 10% and 8%, respectively than those were in 2006. In conclusion, there is very little impact of the emission control plan in 2015.

Strategy in 2020: Figure 17 (d, e, f)-lower panels shows that the highest uncertainties of $O_3$ reduction ($\sigma_{\overline{\Delta O_3}}$) also appear at the same time of the highest $O_3$ reduction ($\overline{\Delta O_3}$) at 1200LT - 1400LT of each day. In general, the $O_3$ concentration in 2020 is lower than the $O_3$ concentration in 2006. The highest reduction of $O_3$ concentration at MA, D2 and HB stations during 6th – 8th Feb are 23.5ppb, 13.4ppb and 7.8ppb, respectively. While, the highest uncertainties of $O_3$ reduction at MA, D2 and HB stations are 8.2ppb, 11ppb and 5.1ppb, respectively. The $O_3$ reduction is higher than the uncertainty of $O_3$ reduction in all stations. It means that the change in $O_3$ concentration is due to the change in emissions from the emission control plan.

For the evolution of primary pollutants of the strategy in 2020, the concentrations of NOx in simulations will increase 16% than those were in 2006. However, the concentrations of CO decrease around 7% than those were in 2006. In conclusion, this emission control plan in 2020 has strong impact on the primary and secondary pollutants in HCMC.

## 5. Summary and key recommendations

In this chapter, the state of the art for studying urban air pollution was reviewed and discussed. Air in the large cities is polluted, especially in developing cities. Road traffic is the main source of pollution in cities. The environmental managers strongly need for air quality management systems to help them control air quality in the cities. The available air quality management system is discussed. Emission inventory is the most important part in air quality management system as it is the mostly used tool to identify the pollution source. However there are a lot of difficulties to be faced when we generate EIs. In this chapter, we also present an example of generation an EI for developing cities where there are not enough available data. The results of EI are used as input parameters for air quality modeling. Then we present many Air pollution abatement strategies over HCMC as a case study of developing cities.

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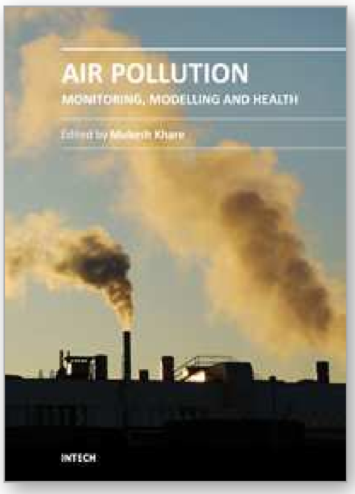


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Air pollution has always been a trans-boundary environmental problem and a matter of global concern for past many years. High concentrations of air pollutants due to numerous anthropogenic activities influence the air quality. There are many books on this subject, but the one in front of you will probably help in filling the gaps existing in the area of air quality monitoring, modelling, exposure, health and control, and can be of great help to graduate students professionals and researchers. The book is divided in two volumes dealing with various monitoring techniques of air pollutants, their predictions and control. It also contains case studies describing the exposure and health implications of air pollutants on living biota in different countries across the globe.