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Integrated monitoring and assessment for air quality management in Hanoi, Vietnam

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Abstract. In relation to air quality management (AQM), Integrated Monitoring and Assessment (IMA) is defined as a combined usage of measurements and model calculations. Integrated air quality monitoring is monitoring based on results from air quality measurements from fixed monitoring stations, and results obtained from calculations with air quality models. IMA combines data from both modeling and measurements to improve assessment of air quality. A PhD research has been conducted during 2007-2010 with the aim to evaluate air quality models developed in Denmark in the context of AQM in Vietnam with Hanoi as case study area. The Operational Street Pollution Model (OSPM) model was adapted to the traffic and vehicle emission conditions in Hanoi, and model results were compared to measurement campaigns at three streets where limited measurement data were available. The OSPM model was also used for inverse modeling to estimate average vehicle emission factors based on the air quality measurement data. The OML model was used to assess the geographic distribution of air pollution in Hanoi based on an emission inventory for vehicle, domestic and industrial sources. OML model results for urban background conditions were compared to measurements from a passive sample measurement campaign and for hourly pollutant data from an urban background station. The analysis showed many limitations in input data and measurement data but also many opportunities for improving air quality assessment with the use of air quality models in combination with measurements.The paper outlines the concept of IMA and present results from the case study in Hanoi and further provides recommendations for future implementation of IMA in AQM in Hanoi with focus on the role of air quality models.

Keywords: Urban air quality management, integrated monitoring, dispersion modeling, OSPM model, OML model.

1. Introduction

In developed countries a strategy that combines monitoring and modeling so-called “integrated monitoring”[1] can provide a good understanding of information about air pollution conditions in a cost-effective way. This study uses this concept to carry out air pollution assessment and management in Hanoi, Vietnam. The impacts of climatic, meteorological, topographical and geographical conditions are also considered. This study also investigates ways to ensure successful implementation of air quality assessment and management by air quality models. The

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research provides a potential tool of assessment and management of air quality for Vietnam in protecting the urban areas from air pollutions. The research mainly focuses on dispersion models that are operational and applicable for assessment of urban background and street scales as there is a particular need to improve capacities in this area. Air quality models can be used to map concentrations where there are no measurements. The combination of monitoring and modeling (integrated monitoring and assessment) can be useful for a spatial description of air quality. Since models establish a link between emissions and concentrations they can be used to analyze the pollution contributed from different source (e.g. traffic sources emitting at ground level versus sources emitting at elevated level as industrial chimneys). Being a potential tool in air quality assessment and management, air quality modeling requires many input data on meteorology, emissions, topology etc., which is difficult to fulfill in Vietnam. Models can be used for backcast, nowcast and forecast, and air quality models may be used to evaluate different control options in scenario analysis.

In Vietnam, only limited monitoring of air quality is conducted in few locations. In the two largest cities (HoChiMinh City and Hanoi), some air quality models have been applied in some specific cases but they have not been validated against monitored air quality data. A monitoring network should ideally provide air pollution data of high temporal solution and high accuracy. Monitoring data is useful to follow trends and assess compliance with air quality standards. Analysis of data can also provide insight into the sources of air pollution. However, the establishment and operation of monitor stations are expensive and can only be expected to be established in few locations. Therefore, modeling is a powerful tool because it can estimate the pollution level at any locations [2]. Air pollution modeling has proved successful as a management technique. Air quality models attempt to simulate the physical and chemical processes in the atmosphere that may involve transport, dispersion, deposition and chemical reactions that occur in the atmosphere to estimate pollutant concentrations at a downwind receptor location. Fundamentally, different models have been developed in the way they parameterize the physical and chemical processes. They have been developed for different scales from transboundary air pollution, to urban background and street scale, and for different sources: traffic or industrial sources [3,4].

The cities of developed countries and developing countries are very different. Nevertheless, developing countries could learn from experiences of developed countries. Such experiences still require some modifications to match with the local conditions. The first step towards formulating the concept is to design a case study that applies to a certain situation. The study investigates ways to apply dispersion models as a tool for air quality assessment and management in Vietnam. This research will potentially contribute to Vietnam in protecting the air quality in urban areas. It could also contribute to the technology transfers and international cooperation between developed and developing countries for environmental protection and sustainable development.

2. Integrated Monitoring and Assessment of Urban Air Pollution

Urban Air Quality Assessment requires a method to analyze the relations between air quality models and actual measurements. The Integrated Monitoring and Assessment (IMA) tool is defined as the combined use of measurements and model calculations. This concept has been analyzed and validated with model and measurement data for the past 20 years in the Department of Atmospheric Environment (ATMI), National Environmental Research Institute (NERI), Denmark. It is now widely applied at NERI and in many other environmental research institutes with monitoring responsibilities. IMA uses the best data both from modeling and measurements. The combined results are found to reflect the actual situation more precisely compared to a situation where only modeling or measurements were used. Measurements are important for evaluation of air quality and measurement data is very crucial for validation of models. On the other hand, model calculations are also used in interpretation of measurements to identify measurement errors. The main advantages of IMA in air quality management are to improve the data quality, enhance the understanding of processes and optimize allocated resources [1,5] (see figure 1).

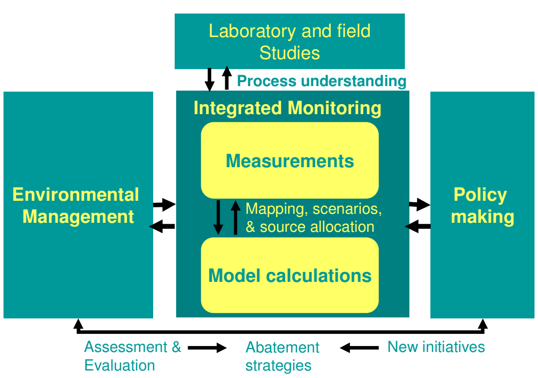

Figure 1. Integrated Monitoring and Assessment Framework. (source:[1]).

IMA can provide optimal use of resources and the best basis for environmental management and decision making. It is a useful tool to study processes and optimize allocated resources for urban air pollution assessment. Integrated air quality monitoring is based upon atmospheric measurement results usually from fixed stations and those calculated from air quality models.

In this research, the concept of IMA is used within: (a) The ambient air concentrations at the monitoring sites, (b) source apportionments and (c) validation of air quality models.

The model calculations are used to provide air quality levels at locations where measurements are not available. The results from the air pollution models are used in the interpretation of actual measurements, and also to provide information on pollution sources.

Within this study, the model calculations are also used to obtain the following: (a) Mapping of pollutant concentrations in GIS map, (b) distribution among local contributing sources, and (c) distribution among different contributing sectors.

2.1. Urban air pollution description

Urban air pollution description and appropriate dispersion models applied is described in the figure 2:

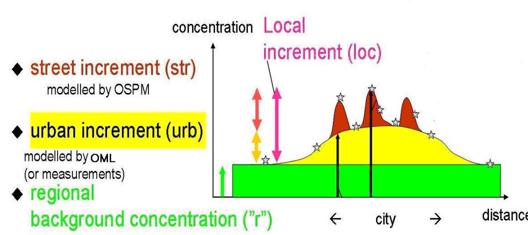

Figure 2. Urban air pollution description and dispersion models applied. (source [6]).

The regional background concentration is the contribution from distant anthropogenic and natural sources to the urban air pollution levels. A monitor station located in rural areas outside the city in question would represent regional background concentrations. Regional or long-range transport chemistry models can calculate regional background concentrations.

The urban background concentration represent air pollution levels in the city e.g. at roof tops or in parks that are not strongly influenced by close by sources. A monitor station located at the a roof top in the central part of a city could represent urban background concentrations. The urban background increment (difference between urban background and regional background) is a result of emission sources in the city such as vehicle transport, domestic cooking and smaller industries which have low release heights. A dispersion mode like the OML model can calculate urban background models [7].

The street increment (difference between street concentrations and urban background) is due to the vehicle emissions in the street and the often restricted dispersion conditions due to surrounding buildings. Emission from vehicle fleet is the main source of air pollution inside cities. Therefore, the pollution level from roadside is the highest in the urban areas. The dilution increases with wind speed, especially in urban areas where the highest concentrations generally appear at low wind speeds (below 2 m/s). A monitor station located at curb side in a street canyon can represent street concentrations. A street model like the OSPM model can model the street increment [6,8].

As indicated above, a monitoring strategy should ideally include at least one monitor station in each of the environments: Regional background, urban background, and street with corresponding model capabilities.

2.2. Hanoi case study

Hanoi is the capital and located in the northern part of Vietnam. It covers an area of 921 km^2 and has a registered population of about 3.5 million inhabitants [9]. The annual average temperature was 24.5^oC, annual average relative humidity of 77%, and annual average wind speed of 1.16 m/s (Lang Monitoring Station, Hanoi). Low wind speeds in combination with high temperatures and sunlight and high emissions cause elevated air pollution levels (photochemical smog) in the urban areas.

Targets for future improved air quality weredefined based on international standards and recommendations of the CAI-Asia initiative [10]. A systematic analysis of the technical and institutional requirements to develop from the current to the future situation was carried out based on the theoretical and methodological frame developed. The transition will focus on required changes in air quality assessment and management strategies and techniques with special focus on selection, adaptation and application of air quality models in the Integrated Monitoring and Assessment concept.

Two of the identified air quality models are applied and adapted to the conditions in Hanoi based on available input data (OSPM and OML models). Validation studies were carried out that also compared model results and measurements, and evaluate possible discrepancies. Potentials and shortcomings of the models and input data were analyzed. The spatial variation of urban background concentrations was modeled as well as detailed modeling in specific streets. Consultation workshops for consultants and stakeholders of involved institutions were also held in Hanoi in 2009 in order to evaluate findings and recommendations.

2.3. Regional and urban background air quality measurements

In Hanoi, air quality data are neither systematically collected nor well documented. Therefore, it is a challenge to provide regional and urban background data for dispersion models. The quality assurance and quality control (QA/QC) are not well maintained. In this modeling study, data from a measurement campaign using passive sampling techniques by Swiss-Vietnamese Clean Air Program [11]are used to analyze the current air pollution situation, and to evaluate the hourly urban background data from the Lang station for use as model input data. The campaign using passive sampling was conducted during two periods in 2007. The mean values of the passive sampling measurements were presented in figure 3.

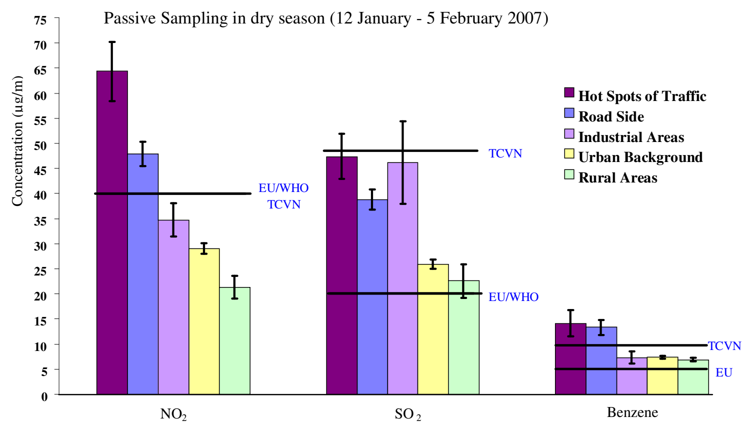

Figure 3. Mean concentrations and standard deviation of NO_2, SO_2 and benzene for five site categories in dry season of 2007 using passive sampling compared to Vietnamese standard, WHO and EU air quality limit values. (Source [12]).

Average values from the passive sample measurements are used to represent the general air pollution level in the urban background and regional background (figure 3) and to down-scale (adjust) the hourly measurements at the Lang Station (Figure 4a, 4b). The Lang Station is an urban background monitor station which is located in the central part of Hanoi. The Lang Station was assessed to have too high concentrations to represent the urban background. The Lang Station is the only monitor station that has hourly data that is a requirement for air quality modeling. The measurements from 12 January to 5 February 2007 are representative for the dry season and the measurements from 18 August to 12 September 2007 are representative for the wet season. Those months which belong to the dry season (November, December, January, February, March and April) will be adjusted by measurements from 12 January to 5 February 2007. The other months from May to October which belong to the wet season will be adjusted by measurements from 18 August to 12 September 2007. The adjusted time series will have the mean value equivalent to the mean value of the campaign using passive sampling. A sample of the correction was presented in figure 4a, 4b.

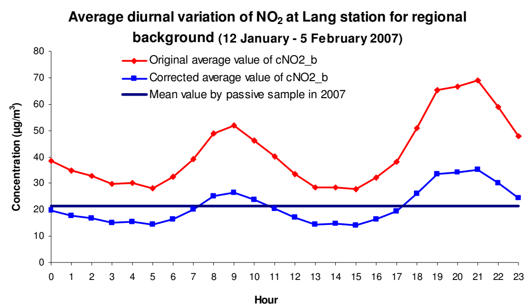

Figure 4a. Illustration of the construction of hourly regional background data-dry season 2007. (source [13]).

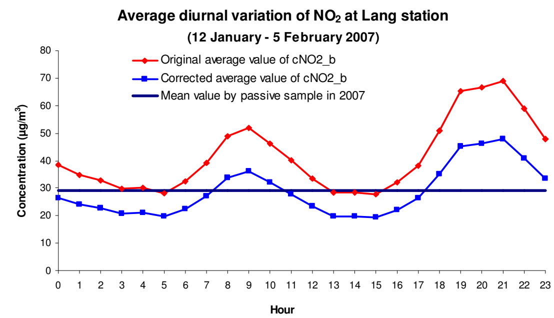

Figure 4b. Illustration of the construction of hourly urban background data - dry season 2007. (source [13]).

The adjusted hourly data were used as input data (regional background for OML model and Urban background for OSPM model) and as a compared data set for Urban background model outputs by OML model.

2.4. Street air quality measurements

In Hanoi, there is no fixed air pollution monitoring station at street level. Instead, available street measurements in Hanoi from 5 locations were used to evaluate the model outputs calculated by the OSPM model. The street measurements in 2004 were obtained during a project by Asian Institute of Technology [14]. The measurements mainly focused on the benzene (BZN) concentrations on both sides of the streets (S1 and S2). The project also measured NO_X, NO_2, NO, SO_2, and CO in some hours of the day. The hourly traffic was counted at the same time as air pollutants were measured. The street measurements in 2007 were carried out by the SVCAP project [11]. The campaign using passive sampling technique focused on NO_2, SO_2, and BNZ. The campaign was used to compare with the mean value of the dispersion model outputs.

2.5. Dispersion modeling

The OSPM model was adapted to the traffic and vehicle emission conditions in Hanoi, and model results were compared to measurement campaigns at five streets where limited measurement data were available. The OSPM model was also used for inverse modeling to estimate average vehicle emission factors based on the air quality measurement data. The OML model was used to assess the geographic distribution of air pollution in Hanoi based on an emission inventory for vehicle, domestic and industrial sources. OML model results for urban background conditions were compared to measurements from a passive sample measurement campaign and also for hourly pollutant data from an urban background station.

Emission data for Hanoi and measurements of NO_X, SO_2, CO, and BNZ are collected from previous studies [11, 14-16]. Hourly metrological data and air quality monitoring were taken from Lang Station.

3. Result and discussions

3.1 Air pollutant emissions per vehicle category

The vehicle distribution and the average emission contribution of the different vehicle categories in the five streets used in the model evaluation study are calculated based on traffic data (ADT) and emission factors. The results are shown in Figure 5:

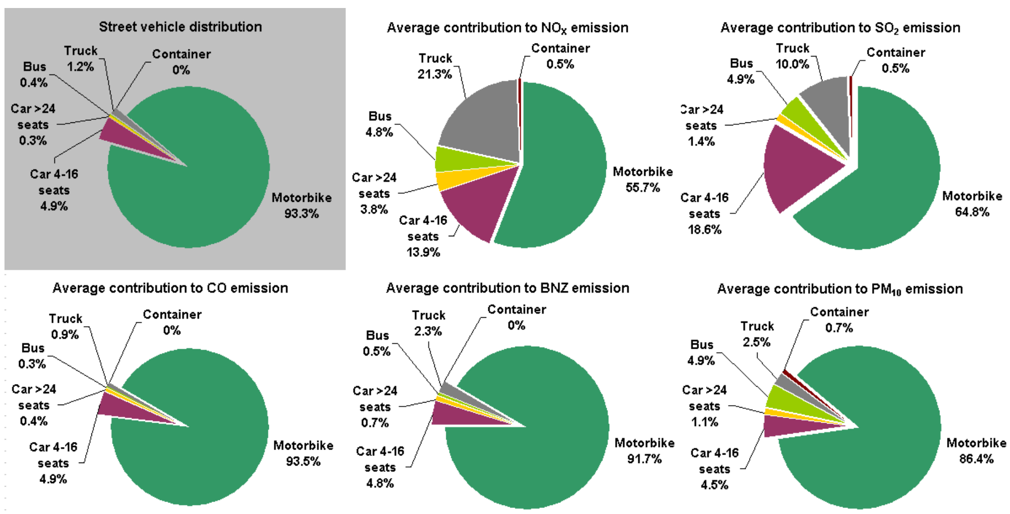

Figure 5. Average contribution (%) to emission of NO_X, SO_2, CO, BZN and PM_{10} from each vehicle category for five streets in this model evaluation study. The vehicle distribution (%) is shown in the top left chart (source [13]).

Motorbikes are the dominant type of vehicle in Hanoi. They contribute 92-95% of all vehicles. They are also the main source of emissions in the streets. Motorbikes contribute 56% of NO_X, 65% of SO_2, 94% of CO, 92% of BNZ, and 86 % of PM_{10} exhaust emissions. The "Trucks" and the "Car 4-16 seats" also have relatively large contributions to NO_X and SO_2 emissions. Trucks contribute 21% of NO_X and 10% of SO_2 emissions, and "Car 4-16 seats" contribute 14% NO_X and 19% of SO_2.

3.2. Comparison of measured and modeled results

The OSPM model was used to model the hourly concentrations of NO_2, SO_2 and CO at location of road side of selected streets in Hanoi. The five selected streets are representative for the traffic condition in Hanoi. TruongChinh (TC) is the outer ring road level 2 of the city road transport system. NguyenTrai (NT) is the main road (arterial road) that connects Hanoi centre to the south west areas. DienBienPhu (DBP) is another main street in the centre of the BaDinh district of Hanoi; LeTrongTan (LTT) and ToVinhDien (TVD) are located in ThanhXuan district representing inner city streets. The Lang Station is an urban background monitor station which is located in the central part of Hanoi

Observed and modeled CO concentrations for the TC Street by OSPM model are shown as diurnal variation in Figure 6.

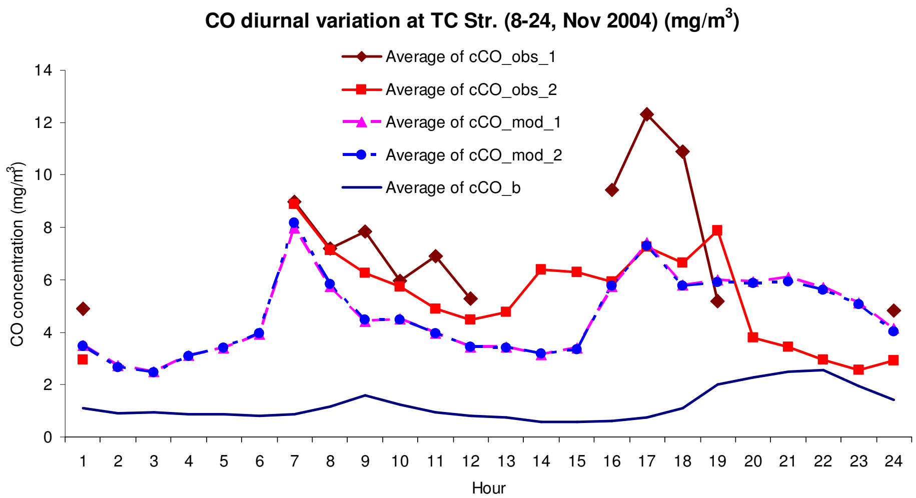

Figure 6. Modeled and observed diurnal variation of CO concentrations for the TC Street in Hanoi by OSPM model. “mod” refers to modeled street concentrations, “obs” to observed street concentrations and “b” to urban background concentrations (source [12]).

Observed and modeled CO concentrations for TC Street have similar variation corresponding to the diurnal variation of CO emissions (figure 6). The modeled diurnal variation of CO concentrations shows peaks in the morning and afternoon rush hours and also relatively high concentrations during the evening.

This diurnal variation fits well with the diurnal variation of motorbikes which are the dominant source to CO emissions (Figure 6). The model predicts almost the same concentrations for opposite sides of the street (S1 and S2). This is also expected due to the long modeling period, the low buildings on both sides (height of 4 m) and the low wind speeds. It is also seen that the street increment (difference between street and urban background concentrations) is considerable. The observed diurnal variation of CO concentrations of side 2 show a similar diurnal pattern as the modeled variation although observations are somewhat higher during the day and lower during the evening. The observed CO concentrations of side 1 during the morning and night fit well with that of side 2 but during 16h-18h concentrations are much higher for no obvious reason, probably due to special traffic or meteorological conditions during the measurements or uncertainties in the measured data.

The modeled diurnal concentrations of SO_2 and BNZ show similar patterns as for CO. It is not possible to present observed diurnal variations of SO_2 and BNZ due to the very limited number of observations. Modeled and observed daily mean concentrations of SO_2, CO and BNZ for the TC, DBP and NT streets, and SO_2, NO_2 and BNZ for the LTT and TVD streets are shown in Figure 7.

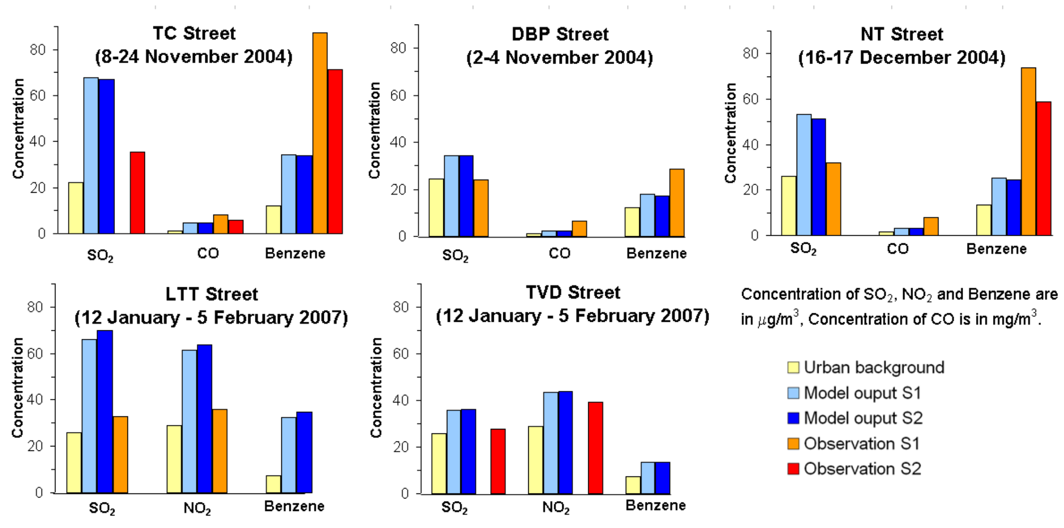

Figure 7. OSPM modeled (at two street sides S1 and S2) and observed daily mean concentrations for the five selected streets. Urban background concentrations are also provided for reference (source [12]).

Modeled concentrations overestimate observations up to a factor of two for SO_2. The smallest overestimation is for the two streets with low traffic levels (DBP and TVD). However, for DBP street the SO_2 street observations are lower than the background concentrations, which are not consistent and can never be reproduced by the model. The systematic overestimation indicates that the SO_2 emission factors may be too high. Analysis of the limited data on diurnal variation of observed SO_2 concentrations also shows that other sources than vehicles may contribute to SO_2 concentrations.

For CO the modeled concentrations underestimate observations up to a factor of two for the streets of DBP and NT and less for TC. The systematic underestimation indicates that the CO emission factors might be too low.

For NO_2 the modeled concentrations overestimate observations up to a factor of two for the busy LTT Street whereas modeled and observed levels are similar for the TVD street that has low traffic levels. It is not logical that the observed street concentrations are similar at the LTT and TVD streets when the LTT street has about 10 times higher traffic levels than the TVD street. This indicates uncertainly on the NO_2 measurements.

For BNZ the modeled concentrations underestimate observations up to a factor of about two for the busy streets of TC and NT and less for DBF that has lower traffic levels. The systematic underestimation indicates that the BNZ emission factors may be too low. Furthermore, the urban background concentration of BNZ was estimated based on observed correlations between BNZ and CO in Denmark and transferred to Hanoi taking into account differences in the content of BNZ in petrol. In addition, the assumptions of BNZ emission factors for other vehicles than motorbikes for Vietnam conditions are based on a 1999 data set for Denmark according to emissions from the European emission model COPERT. It is obvious that these assumptions about the urban background and emission factors are highly uncertain.

The OML model was used to model the hourly concentrations of NO_2, SO_2 and CO at location of the Lang station. The values of model outputs for NO_2, SO_2, CO at the Lang

Station are compared with the monitoring data from the Lang station for an evaluation of the performance of the model.

The correlation between modeled and observed NO_2 concentrations for the Lang station location is presented in figure 8:

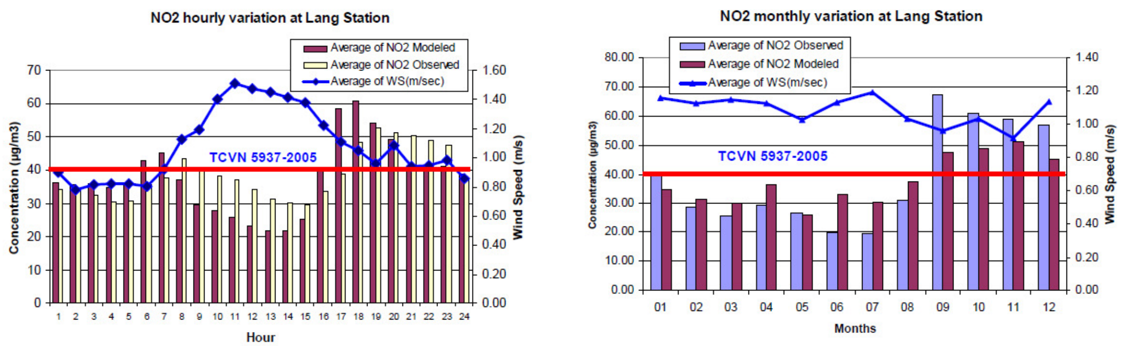

Figure 8. NO_2 modeled vs. NO_2 observed at the Lang Station in 2007 ($\mu g/m^3$) by OML model. (source [13]).

The diurnal and monthly variations of NO_2 are influenced by the meteorology conditions. As expected the concentration is low when the wind speed is high and vice versa but the picture is not clear as other factors also play a role. In the modeling it was assumed that the seasonal and day of the week variation in emissions was constant but this may not be the case and may partly explain difference in modeled and observed results. At the Lang station receptor point, NO_2 concentrations were lowest during the day and highest during at the evening and night. NO_2 concentrations were highest during the dry season. Compared to the Vietnamese standard 5937-2005: Air quality – Ambient air quality standards the limit value (40 $\mu g/m^3$) as an annual mean is just exceeded. The Vietnamese standard is equivalent to the EU and WHO standards.

The correlation between modeled and observed SO_2 concentrations for the Lang station location is presented in Figure 9

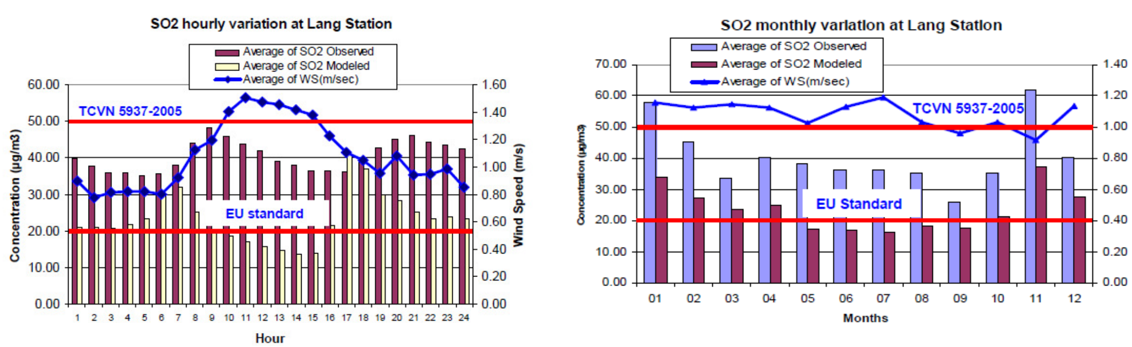

Figure 9. SO_2 modeled vs. SO_2 observed at the Lang Station in 2007 ($\mu g/m^3$) by OML model.(source [13]).

The diurnal and monthly variations of SO_2 are also influenced by the meteorology conditions. The correlation between modeled and observed SO_2 concentrations at the Lang station location shows a need to correct the emission factor and the time variation of SO_2. Compared to Vietnamese standard 5937-2005, SO_2 concentrations are below the standard at the Lang station. However, compared to EU and WHO Standards, the average measured and modeled concentrations are higher than the standard.

The correlation between modeled and observed CO concentrations for the Lang station location is presented in Figure 10:

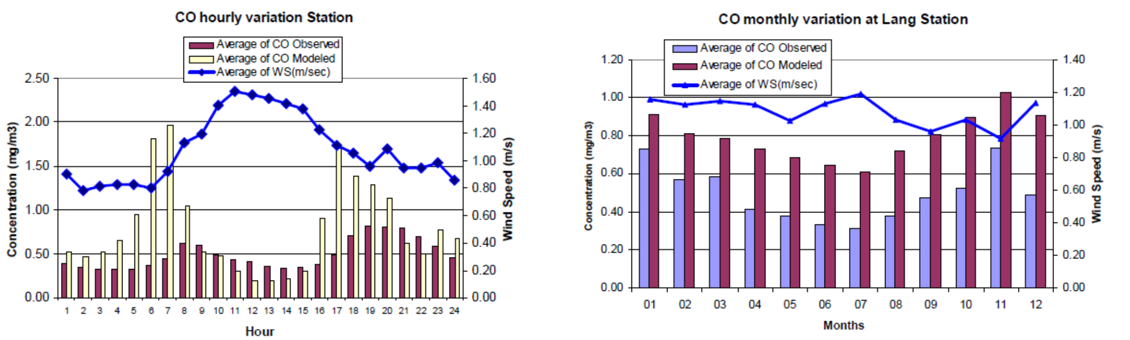

Figure 10. CO modeled vs. CO observed at the Lang Station in 2007 (mg/m^3) by OML model.(source [13]).

For this modeling study, CO measurements were not available for the campaign using passive sampling or for the regional background. The time correlation between modeled and observed CO concentrations for Lang station receptor point is poor since the modeling input data were not validated. However, the hourly mean values and monthly mean value correlated with the wind speed data.

The OML model was also run with the receptor points for all the center points of a 1 km x 1km grid applied to the whole city. This data is used to describe the spatial variation of the annual mean concentration of NO_2 and SO_2 in Hanoi. The spatial variation of modeled results for NO_2 and SO_2 are shown in Figure 11.

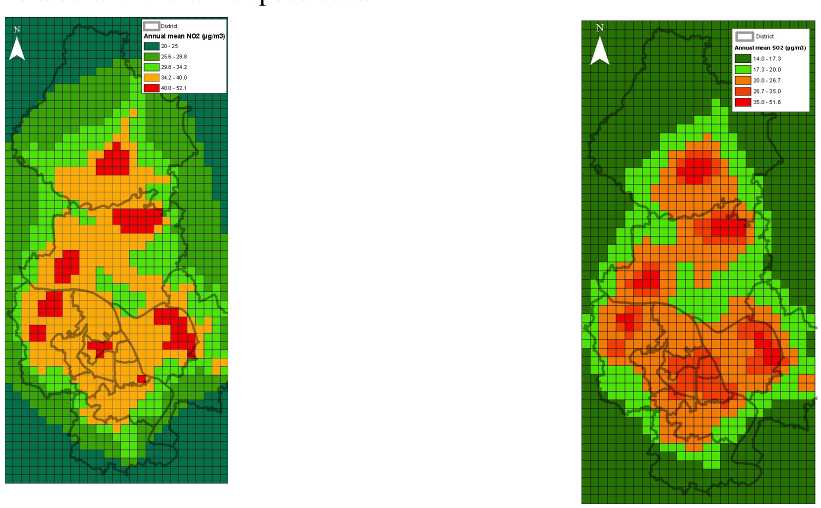

Figure 11. Spatial variation for annual concentrations of NO_2, SO_2 in Hanoi in 2007.(source [13]).

The spatial distribution of the annual mean values in Figure 11 show that the city center is highly polluted by NO_2 and SO_2. The pollution is higher in the locations where the industrial areas are located. NO_2 is mostly emitted from traffic. In fact, emission of NO_2 was shown to closely relate to the spatial distribution of traffic. SO_2 emission represents the domestic cooking source and was also found to correlate to the spatial distribution of residential areas. Such strong correlations between pollutant concentrations and the distribution of emission sources indicate the dependence of pollution level upon the proximity to emission sources.

4. Conclusions

A systematic evaluation of dispersion models as a tool for air quality assessment and management in a Vietnamese context was conducted with focus on technical as well as management aspects. The research studied the application of dispersion models in line with the Integrated Monitoring and Assessment (IMA) concept. The research mainly focused on the application and evaluation of Operational Street Pollution Model (OSPM) and Operational Meteorological Air Quality Model (OML), which are operational and applicable dispersion models for assessment of street and urban background air quality.

The OSPM model was applied in Hanoi for five selected streets and evaluated against air quality measurements. The model was also used to estimate average vehicle emission factors based on backward calculations. The motorbike is the dominant vehicle type in Hanoi as it constitutes 92-95% of all vehicles. It is also the main source of emissions in the streets. Analysis of the modeled and observed diurnal variation of CO for one street showed that the OSPM model generally reproduced the diurnal variation. The model evaluation also showed that the OSPM model, given the applied input data, overestimated daily mean concentrations of SO_2 and CO and underestimated concentrations of NO_2 and benzene. The most likely reason is uncertainties in emission factors. However, NO_2 measurements are also likely to be uncertain.

The OML model was applied to evaluate the air pollution level of NO_2, SO_2 and CO at urban background scale. OML modeled outputs were evaluated against passive sampling measurements and hourly data from the Lang Station. The OML model was also used to map the spatial distribution of air pollution for the whole Hanoi. The annual average concentrations of NO_2 and SO_2 were mapped in a GIS spatial map on a 1x1 km^2 grid resolution as an example of predicting the pollution levels related to the emission sources and meteorological conditions. The modeled spatial variation of air pollution by OML is a useful result based on a combination of emission data on GIS, modeled output results and measurement. Based on these data, environmental authorities and policymakers can describe the air pollution levels and its sources and developments for the environmental management and sustainable development of urban planning. The modeled spatial variation of SO_2 and NO_2 presents the possibility of using a simple model like the OML model with a GIS map as a sufficient tool for mapping of air pollution levels. The OML model can also be used to predict future concentrations if the future emissions can be predicted.

In the Integrated Monitoring and Assessment (IMA) framework, dispersion models can provide the information of pollution level at any location as required. The result from air pollution models can be used in the interpretation of monitoring and campaign measurement data. Modeling provides a link between the emission inventory data and the monitoring data. If the emission inventory, meteorology data and all of its inputs were perfect, the air quality model would predict measured pollutant concentrations from high quality monitor stations with high certainty. In Hanoi, as a case study of a developing country, these perfect conditions cannot be expected, so the three components (emission inventory, monitoring, and modeling) are used together in an integrated approach of adjustment, evaluation, and refinement. Each tool is used to help in identifying the shortcomings of the others and to identify what improvements are needed. This is an adapted IMA concept applied for developing countries.

5. Recommendations

The OSPM model study for streets in Hanoi also revealed the challenges of applying dispersion models in a context where high quality model input data and high quality measurements are unavailable. Better input data will indeed enable the model describes the actual pollution level better at street scale.

The emission factors of vehicles in developing countries are inadequately managed compared to emission models such as COPERT 4 (EU) or MOBILE 6 (USA). An experimental study on the emission factors for all vehicle categories reflecting the Vietnamese conditions should be conducted. The street types should be categorized according to their corresponding vehicle volume. Such data must be annually updated to a GIS database.

Due to the low wind speed condition and street configurations, Traffic produced turbulence (TPT) is a significant contributor to the circulating of air pollution at the street scale. More studies should be conducted on the influence of motorbikes on TPT as motorbikes are the dominant vehicle category in Hanoi.

The traffic and other relevant data for the road network must be regularly managed and maintained on a GIS map for local scale modeling (OML model) of air pollution from traffic. The analyzed trend of traffic development should be updated annually for sustainable urbanization.

Fuel used in the industry should be changed from fossil coal and kerosene oil to gas as this is a cleaner fuel. The detail parameters of those sources should be well updated and documented annually for dispersion modeling. It is possible to manage the industrial sources (due to the low stack height) as an area sources. Before an adequate emission inventory can be developed, the emissions can be estimated based on the fuel consumptions or production amount reported by industries. Using the emissions from industries based on production is more adequate in estimation the emission from this source since those data are reported annually to the municipal authorities. The ideal solution for this is to stop using fossil fuel to reduce the emissions. The other possible solution to this is to move polluting factories out of the residential areas. New location of polluting factories should be downwind. In Hanoi, the main wind directions are South East and North East. Therefore, from a meteorological point of view, new and existing factories using polluting fuels should be relocated to areas North West or South West from Hanoi center.

The emission from domestic cooking by household fuel consumption is not fully representative for all areas in Hanoi. Only low income groups use “hand-fired coal” for cooking whereas high income groups use natural gas and electricity for cooking. These richer households produce less emissions and less degradation of air quality. Estimation of the emissions per capital in Hanoi based on each residential area is recommended. The hand-fired coal should not be used for domestic cooking in the urban areas and incentives to reduce the use of this fuel should be developed.

In this research, the directly emitted NO_2 fraction of vehicle NO_X emission was assumed to be 5% following the European conditions in the 1990s similar to the conditions in Vietnam in 2010s. Studies should be undertaken to estimate the directly emitted NO_2 fraction more accurately.

Taking the sunny and hot weather in Hanoi into account, a study on the relation between NO_X, NO_2, NO and O_3 are also recommended to evaluate if the simple photo chemistry assumed in the OSPM and OML models are sufficient for Hanoi conditions.

The validation studies of air quality models using updated emission inventory and high quality measurement must be made.

Modeling human exposure and estimation of the heath impacts of air pollution in Hanoi need to be carried out soon. After all above mentioned activities are done.

Hanoi also requires more studies on the institutional aspects of air quality management especially with regard to developing a platform for air quality management activities, capacity building, legal framework and enforcement.

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