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Spatial variation of modelled and measured NO, NO_2 and O_3 concentrations in the polluted urban landscape – relation to meteorology during the Göte-2005 campaign

J. Klingberg[1], L. Tang[2], D. Chen[2], G. Pihl Karlsson[3], E. Bäck[4], and H. Pleijel[1]

[1]Department of Plant and Environmental Sciences, University of Gothenburg, P.O. Box 461, 405 30 Gothenburg, Sweden
[2]Department of Earth Sciences, University of Gothenburg, P.O. Box 460, 405 30 Gothenburg, Sweden

[3] Swedish Environmental Research Institute (IVL), P.O. Box 5302, 400 14 Gothenburg, Sweden
[4] City of Gothenburg, Environmental Administration, Karl Johansgatan 23,
414 59 Gothenburg, Sweden

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Correspondence to: J. Klingberg (jenny.klingberg@dpes.gu.se)

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Abstract

Knowledge about temporal and spatial variations of the O_3 and NO_x relationship in the urban environment are necessary to assess the exceedance of air quality standards for NO_2. Both reliable measurements and validated high-resolution air quality models are important to assess the effect of traffic emission on air quality. In this study, measurements of NO, NO_2 and O_3 concentrations were performed in Gothenburg, Sweden, during the Göte-2005 campaign in February 2005. The aim was to evaluate the variation of pollutant concentrations in the urban landscape in relation to urban air quality monitoring stations and wind speed. A brief description of the meteorological conditions and the air pollution situation during the Göte-2005 campaign was also given. Furthermore, the Air Pollution Model (TAPM) was used to simulate the NO_x-regime close to an urban traffic route and the simulations were compared to the measurements. Important conclusions were that the pollutant concentrations varied substantially in the urban landscape and the permanent monitoring stations were not fully representative for the most polluted environments. As expected, wind speed strongly influenced measured pollutant concentrations and gradients. Higher wind speeds dilute NO_2 due to stronger dispersion; while at the same time vertical transport of O_3 is enhanced, which produces NO_2 through oxidation of NO. The oxidation effect was predominant at the more polluted sites, while the dilution effect was more important at the less polluted sites. TAPM reproduced the temporal variability in pollutant concentrations satisfactorily, but was not able to resolve the situation at the most polluted site, due to the local scale site-specific conditions.

1 Introduction

It is well documented that nitrogen dioxide (NO_2) and ozone (O_3) can adversely affect human health (Curtis et al., 2006). In the European Union Framework Directive on Air Quality Assessment and Management (1996/62/EC) and its First Daughter Directive

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(1999/30/EC) limit values for nitrogen dioxide (NO_2) concentration are defined as an hourly average of 200 $\mu g\,m^{-3}$ (~105 $nmol\,mol^{-1}$, 99.8-percentile) and an annual average of 40 $\mu g\,m^{-3}$ (~21 $nmol\,mol^{-1}$), to be achieved by 1 January 2010. Measurements and modelling indicate that many urban areas will have problems to reach the air quality standard for NO_2, especially close to major traffic routes (Carslaw et al., 2007; Pleijel et al., 2009).

The levels of NO_2 and O_3 are closely linked by the chemical coupling of O_3 with NO_x (NO_2+NO). O_3 levels are generally lower at ground level in streets than at rooftops or in the surrounding countryside due to the titration of O_3 by NO in car exhaust to form NO_2 (Fenger, 1999). Therefore reductions of NO_x emissions in the cities are frequently accompanied by an increase in the level of O_3. A better understanding of the relationships between O_3, NO and NO_2, as well as the influence of the state of the atmosphere is necessary to evaluate the exceedances of air quality standards (Clapp and Jenkin, 2001). In addition, both for air quality forecasting and for development of control strategies it is important to identify the factors controlling the NO_2 concentrations (Shi and Harrison, 1997).

The spatial variability of air pollutants is large in urban areas (Coppalle et al., 2001; Vardoulakis et al., 2005). Therefore exposure to air pollutants is strongly dependent on location. Cost, bulk of equipment, power supply, etc. often put practical limits to the number of air quality monitoring stations in a city. In many cities air pollutants are only measured at one or a few locations. It is therefore very important to assess the representativeness of these locations (Flemming et al., 2005). How far from traffic routes the local impact of traffic emissions reaches and to which amount these emissions affect the formation or destruction of ozone is not well known (Suppan and Schädler, 2004). Both measurements and validated high resolution air quality model calculations are useful to assess the effect of traffic emissions on air quality. Measurements are especially valuable to determine spatial and temporal variability of air pollution situations at relevant scales, while modelling makes it possible to produce scenarios and to identify relative importance of various processes and mechanisms.

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Progresses in fine scale meteorological and air chemistry modelling over the last decades have made it possible to fairly realistically model urban air pollution dynamics. One such model is The Air Pollution Model (TAPM), which is a three-dimensional, nestable, prognostic meteorological and air pollution model. Previous studies have shown that TAPM performs well in coastal, inland and complex terrain, in sub-tropical to mid-latitude conditions (Hurley et al., 2001, 2003, 2005). Chen et al. (2002) evaluated the meteorological performance of TAPM in Gothenburg, Sweden for a two year long meteorology only simulation. The results showed that meteorological variables from TAPM were in agreement with observations on yearly and daily time scales. A recent model intercomparison study between TAPM and MM5 (the PSU/NCAR mesoscale model) carried out in Gothenburg concluded that TAPM is comparable to MM5 and has better performance in urban areas (Tang et al., 2009), in terms of surface meteorological variables including temperature and wind which are important to air pollution dynamics. While TAPM's ability to realistically reproduce local meteorological conditions have been demonstrated and the simulations have been successfully used in urban air pollution studies (e.g. Johansson et al., 2008), its capability in reproducing local scale variability in pollutant concentrations has been tested to a lesser extent.

The measurements and modelling in this study formed part of the Göte-2005 campaign (http://www2.chem.gu.se/~hallq/Gote_eng_2005.htm), which took place in Gothenburg, South-West Sweden, from 2 February to 2 March, 2005. The coordination of different research groups' measurements created a platform for cooperation and a common database with measurement data. Through coordination of unique competences, the overall goals of the Göte-2005 campaign were to (1) better describe the air pollution situation in Gothenburg, (2) increase the understanding of the fate of the air pollutants near the road, (3) provide a base for risk assessment, (4) test new measurement techniques and (5) evaluate air pollution models.

The objectives of the part of the Göte-2005 campaign described in the present paper were:

– Describe the general air pollutant and metrological situation in Gothenburg during

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the Göte-2005 campaign.

- Evaluate how the NO, NO_2 and O_3 concentrations varied in the urban landscape compared to permanent monitoring stations. The hypothesis was that there is a large spatial (and temporal) variability within the city, not fully resolved by the monitoring stations.
- Investigate how the NO_2 concentrations varied with wind speed at differently polluted sites. The hypothesis was that the influence of wind speed/turbulence on NO_2 concentrations is a balance between increased dilution and enhanced vertical transport of O_3 to oxidize NO to NO_2.
- Compare the observations with results from the TAPM model. The hypothesis was that the model simulations would correlate well with the corresponding observations, but not necessarily be able to reproduce dynamics at sites with very high pollution levels due to local scale variations in the site-specific characteristics.

2 Material and methods

2.1 Air pollution and meteorological measurements

Measurements of NO, NO_2 and O_3 concentrations were performed using passive diffusion samplers of the IVL type (Ferm, 2001) during five 5-day intervals from 2 to 27 February 2005, at eight different locations in Gothenburg. In addition, temperature (T) and relative humidity (RH) were measured with Tinytag (INTAB Interface-Teknik AB) sensors/loggers TGP 1500 (recording every 10 min) enclosed in self-ventilating radiation shields. The upper half of the radiation shield was black and the lower half had reflective cover. Similar instruments have been used to characterize local scale temperature variations within the city of Gothenburg (Upmanis and Chen, 1999). Six sites were located in an area with heavy traffic around Olskroksmotet, with varying distances

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and elevations in relation to this major traffic route, including a site in a nearby park. One site was co-located with the urban rooftop monitoring site Femman, which permitted comparison of passive sampler and Tinytag data with continuously operating monitors and meteorological observations (T and RH with Campbell Rotronic MP101 and wind speed with Gill Ultrasonic). One further site was a rural reference (Annekärr) situated about 25 km north-east of the Gothenburg city centre. If not stated otherwise, the measurement height was 2 m for the passive samplers and 1.5 m for T and RH measurements with Tinytags. At Femman, O_3 concentration was measured with an UV absorption monitor (Monitor Labs 9811), NO_x with a Tecan CLD 700 AL and PM_{10} with a TEOM 1400A. Further continuous NO and NO_2 data (Opsis DOAS system) were received from a measurement station nearby the major traffic route (Gårda) and a measurement station situated in a city street environment (Haga). The location of the measurement sites can be seen on the map in Fig. 1. Coordinates and further characteristics of the measurement sites are given in Table 1.

2.2 Evaluation of passive samplers and Tinytag data

One week before and three weeks after the measurement period the Tinytags, in their self-ventilated radiation shields, were kept at Femman in parallel with the Rotronic sensor, the latter expected to provide T and RH with high accuracy, for calibration. After correction a relationship close to 1:1 was obtained between the different Tinytags and the Rotronic for T. For example, the relationship between the Tinytag co-located with the Femman Rotronic the entire measurement period was $T_{\text{Rotronic}}=T_{\text{Tinytag}}+0.00004$, $R^2=0.95$. Calibration of RH close to 100% was complicated. Below 80% there was a relationship close to 1:1, but values above 80% could not be accurately corrected for all Tinytags because of occasional out of range values. One Tinytag was lost (stolen, site 2) after the second measurement period.

The performance of the passive diffusion samplers was tested by comparison with the instruments at Femman. For the entire measurement period the average deviation

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of the NO, NO_2 and O_3 samplers from the Femman instrument measurements were 25%, 5% and 1%, respectively. For reasons unknown, the NO samplers did not work properly at Annekärr suggesting very high concentrations at this rural site. Therefore NO values from this site were excluded.

2.3 TAPM configurations

The meteorology module of TAPM predicts the local scale flow, such as sea breezes and terrain induced circulation given the larger scale synoptic meteorological fields. The mean horizontal wind components are determined from the momentum equations and the terrain-following vertical velocity from the continuity equation. The air pollution module of TAPM consists of an Eulerian grid-based set of prognostic equations for pollutant concentrations. Gas-phase photochemistry is based on the semi-empirical mechanism called the generic reaction set (GRS) of Azzi et al. (1992), with the hydrogen peroxide modification of Venkatram et al. (1997). See Hurley (2005) for more details, including reactions, the specification of reaction rates and yield coefficients. In this study, TAPM was run from 2 to 27 February 2005 with three nested domains of 41×41 horizontal grid points at 10, 3, 1 km spacing for the meteorology and 31×51 horizontal grid (N-S direction by E-W direction) points at 1.0, 0.3, 0.1 km spacing for air pollution. All domains centred at the location (57°42′ N, 11°58′ E, Site 1/Femman in Fig. 1) and the innermost domains consist of the Gothenburg city centre. The lowest ten of the 40 vertical levels were 10, 25, 50, 75, 100, 150, 200, 250, 300, 350 m a.g.l., with the highest model level at 8000 m a.g.l. The initial and boundary conditions used for TAPM was six-hourly synoptic scale analyses at 1.0 degree in latitude and longitude spacing from the Australian Bureau of Meteorology. Observed winds at Järnbrott (approximately 7 km south-west of Gothenburg city centre) were assimilated as nudging terms and assuming a 10 km radius of influence, which improved the wind simulation. In the innermost model domain, the urban land use was dominant, but there are also pasture/herb-field-mid-dense (seasonal) and forest-low sparse (woodland). The terrain height, vegetation and soil type were from default model options based on public

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domain data available from the US Geological Survey. The monthly sea-surface temperature was extracted from model default database based on US National Centre for Atmospheric Research (NCAR) (http://dss.ucar.edu/datasets). Monthly varying deep soil volumetric moisture content was set to 0.38 $m^3\,m^{-3}$ from the European Centre for Medium-Range Weather Forecasts (www.ecmwf.int).

The traffic route passing through Olskroksmotet, located in the north-east of the city centre, is one of the busiest roads in Gothenburg (see Fig. 1). Data on the number of vehicles and their average speed on the highway were received from the Swedish National Road Administration's website (www.vv.se). Estimated emission factors for NO_x based on the Swedish National Road Administration's information system EVA 2.2 were received from the City of Gothenburg, Environmental Administration. Thereafter the emission rate of NO_x for each hour of the day was calculated (Fig. 2). Carslaw (2005) has found evidence of an increasing NO_2/NO_x emissions ratio from about 5–6 vol% in 1997 to about 17 vol% in 2003 in London. Pleijel et al. (2009) investigated the NO_2/NO_x emission ratio in Gothenburg and found it to be approximately 15 vol%, which was used in this study.

In this study, the hourly NO_2 and O_3 concentrations at the Femman rooftop monitoring site were used as urban background values. Emissions of volatile organic compounds (VOC) were not considered in this study since there is generally insufficient time available for reactions including VOC to become important on the small geographical scale of a few kilometres (Carslaw and Beevers, 2005). However, the urban background of VOC was given by setting the smog reactivity, R_{smog} as 0.5 nmol mol^{-1} in the model. As a result, TAPM predicted the hourly average for NO_2, NO_x and O_3 provided with the estimated emission rate of NO_x at Olskroksmotet.

To evaluate the TAPM against the observations the explained variance (R^2) was calculated:

$$R^2 = 1 - \frac{\sum(\mathrm{obs}_i - \mathrm{pred}_i)^2}{\sum(\mathrm{obs}_i - \mathrm{obs}_{\mathrm{mean}})^2}$$

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where obs represents observations and pred the corresponding prediction. An R^2 close to 1 means a small deviation from the 1:1 line. Also a linear regression ($y=kx+m$) was made between model and observations. The explained variance according to the regression (r^2) is always higher than R^2. If r^2 is significantly higher than R^2 there is a systematic error in the model.

3 Results

Table 2 describes the meteorological conditions during night and day, separately for weekdays and weekends, and for the total Göte-2005 period. For the interpretation of air pollution data it was important to know that no systematic meteorological differences between weekdays and weekends had arisen by unfortunate coincidence. There were no major differences in meteorology between weekdays and weekends during the measurement period. In general, the Göte-2005 campaign was characterised by relatively cloudy and windy weather, with partial snow cover. Temperature inversions were not strongly developed during the campaign. Consequently, air pollution concentrations did not grow very large. For example, NO never reached concentrations higher than 316 nmol mol^{-1} at rooftop level (Femman), 550 nmol mol^{-1} at Gårda and 307 nmol mol^{-1} at Haga during Göte-2005, while this pollutant reached 670 nmol mol^{-1} at Femman during an inversion episode in February 2004 (Janhäll et al., 2006).

Table 3 shows the mean concentration of air pollutants during night and day, separately for weekdays and weekends, and for the total Göte-2005 period. It is clear that the concentrations of NO and NO_2 were higher on weekdays compared to weekends during daytime also at rooftop level, emphasizing the important impact of the traffic. As a consequence, the O_3 concentrations were lower on weekdays compared to weekends, due to stronger titration of O_3 by NO in weekdays. The Swedish air quality standard for NO_2 of 90 μg m^{-3} (~47 nmol mol^{-1}) averaged over an hour was exceeded 6 h during the Göte-2005 campaign at the rooftop level monitoring station (Femman), mainly in the first few days of the measurement period. Closer to the traffic the number

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of exceedances was larger. At the Gårda monitoring site the air quality standard for NO_2 was exceeded 11.5% (80 h) of the hours and at the Haga monitoring site 5.3% (37 h) of the hours during the Göte-2005 period. In general the PM_{10} concentrations were low during the period except for an episode in the end of February with the maximum concentration of 212 $\mu g\,m^{-3}$ during one hour. It was the only day during the period when the air quality standard of 50 $\mu g\,m^{-3}$ averaged over a day was exceeded (64 $\mu g\,m^{-3}$).

3.1 NO, NO_2 and O_3 concentrations in relation to location of monitoring site

Figure 3 shows the mean variation in O_3, NO and NO_2 concentrations between the different sites during the measurement period. The Femman monitoring site was relatively low in NO and NO_2 compared to most of the other urban sites, with the exception of the park site. For instance, the 25-day average of NO_2 was 13.1 nmol mol^{-1} at Femman, while 24.7 nmol mol^{-1} at the site closest to the traffic route. The rural site was however much lower in NO_2 compared to the urban sites, only 3.1 nmol mol^{-1}. The variation of NO in the urban landscape was larger. Concentrations of NO at the most polluted site (site 4) were approximately eight times higher than at the Femman rooftop monitoring station and nearly twice as high as at the Gårda monitoring station. For NO_2, being largely a secondary pollutant, the concentration at the most polluted site was twice as high as the urban background, Femman, and for O_3 the concentration was approximately 30% lower in the most polluted site compared to Femman. There was a clear negative effect of NO emissions on the O_3 concentration at the most polluted sites, while the variation in O_x (NO_2+O_3) between sites was relatively small, the range being between 32.4 nmol mol^{-1} at the rural site and 41.6 nmol mol^{-1} at the most polluted site.

The diurnal variation in the NO/NO_2 system differed substantially between the rooftop monitoring site (Femman) and the monitoring sites nearby a traffic route (Gårda) and at the urban street level station (Haga) as can be seen in Fig. 4. On

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weekdays the diurnal cycle at Gårda was characterized by two peaks of NO concentration corresponding to the morning and afternoon rush hours. The morning peak was larger due to less air mixing at this time of the day than at the afternoon peak. The morning peak during weekdays can also be seen at Femman and Haga. Less traffic, which was more evenly distributed over the day, resulted in no pronounced peaks and in NO_2 concentrations larger compared to the NO concentration during large parts of the day during weekends.

3.2 TAPM simulations

Figure 5 presents the modelled and observed mean NO, NO_2 and O_3 concentations at the seven sites close to the traffic route (Olskroksmotet) during the Göte-2005 period. The O_3 concentration showed the best agreement between the model simulation and observations with a R^2 of 0.44. The TAPM tended to overestimate NO_2. The NO concentration showed more scattering and therefore a lower R^2. The passive sampler detection limit for NO is higher compared to NO_2 and O_3, which could be an explanation for the large intercept of the regression line between observed and modelled NO concentration in Fig. 5d. TAPM successfully reproduced the relationship between NO_x and O_3 observed by the passive samplers. The highest NO_x concentrations were found closest to the emissions at the traffic route. The model also showed the lowest O_3 concentrations close to the road due to NO titration. Figure 6 shows the modelled diurnal cycle of NO, NO_2 and O_3 at site 6 (the most NO polluted site according to TAMP) which was also satisfactorily reproduced. Two peak daily values of NO and NO_2 correspond to two traffic rush hours with large emissions. The O_3 concentrations were lowest at peak NO_x concentrations.

3.3 Spatial variation of air pollutants in relation to wind speed

The difference in O_3 concentration between the most polluted site 4 and the rooftop monitoring site Femman shows a statistically significant ($p<0.05$) correlation ($r^2=0.86$)

with wind speed. The concentration difference was larger at higher wind speeds. The O_3 concentration increased with wind speed at both sites, but the increase was more rapid at Femman, reflecting a stronger coupling with the more O_3 rich air layers aloft at that site and the larger consumption of O_3 in reaction with NO at the more polluted site. The effect of wind speed on the NO_2 concentration ratio of the polluted urban landscape and the Femman rooftop monitoring site is shown in Fig. 7. Higher wind speeds act to dilute NO_2 due to stronger dispersion, but also lead to an enhanced vertical transport of O_3, which produces NO_2 through oxidation of NO. The oxidation effect dominated at the two most polluted sites, while the dilution effect was more important at the less polluted sites.

A similar pattern was found when looking at the modelled data. Figure 8 shows the average NO_2 ratio between the different sites and the Femman monitoring site divided into wind speed classes. The sites have been ranked depending on how NO polluted they were according to the model. The least polluted site 7 had approximately the same level of NO_2 as the Femman monitoring site rather independently of wind speed. At the more polluted sites the NO_2 concentration was 1.5 times that of Femman in calm or windy conditions. At medium wind speeds of 2 to 3 $m\,s^{-1}$ the NO_2 ratio ($[NO_2]_{site\ 4}/[NO_2]_{Femman}$) increased to 3 at the most polluted sites. At higher wind speeds dispersion was the dominating process also at the most polluted sites. In the class with the highest wind speeds (6–7 $m\,s^{-1}$) the average NO_2 ratio increased again. This result is probably caused by the fact that only 4% of the hours (25 h) belonged to this class and occurred almost exclusively during daytime when the emissions are higher.

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4 Discussion

4.1 Spatial and temporal variation in pollutant concentration

The results clearly indicated large spatial and temporal variations in pollutant concentrations even though the windy weather situation during the measurement period did not promote extreme differences between locations. One way of describing the spatial representativeness of measurement sites is the concept of air quality regimes. Pronounced differences in magnitude and range of observed concentrations at different sites can be considered as different regimes of air quality. Flemming et al. (2005) identified six different air quality regimes (from "rural" to "severely polluted street") by hierarchical clustering based on the medians of daily means from measured NO_2 at 400 monitoring sites in Germany during 1995–2001. The Gårda monitoring site of the present study was similar to the severely polluted urban environments in Germany with typical daily averages above 60 $\mu g\,m^{-3}$ (Flemming et al., 2005). The pronounced diurnal cycle with two daily maxima during morning and evening rush hour also placed Gårda in Flemming's severely polluted street category. The Femman and Haga monitoring stations were comparable to Flemming's urban and polluted urban categories, respectively. The NO concentrations followed the amount of traffic more closely than NO_2 and therefore varied more between measurement sites. Fenger (1999) also found that the NO concentration follows the amount of traffic more closely than NO_2, the concentration of which is partly determined by the available O_3 supplied from outside the city to oxidise NO.

The increasing O_3 concentration with increasing distance from the traffic route was in agreement with measurements in Toronto, Canada (Beckerman et al., 2008). According to Sillman (1999) significant removal of O_3 during daytime occurs in the vicinity of large NO emission sources (through the reaction $NO+O_3 \rightarrow NO_2+O_2$), where the NO_x concentrations reach 50 $nmol\,mol^{-1}$ or higher, equal to or greater than ambient O_3 concentrations. The measurements in this study also showed a significant decrease

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in O_3 concentrations closest to the traffic route where the NO_x concentration reached 50 nmol mol^{-1} or higher. At the most polluted site (site 4) the reduction in O_3 concentration was on average 10 nmol mol^{-1} compared to urban background, which is in the same range as what Suppan and Schädler (2004) found in a modelling study of the impact of highway emissions on ozone in Germany. At the same time our measurements showed a doubling in NO_2 concentration at the most polluted site compared to urban background which was in agreement with the results of Palmgren et al. (1996) from Copenhagen.

4.2 Performance of TAPM

It has been demonstrated that the TAPM can be a tool to investigate the impacts of meteorological conditions on air pollutants at regional and urban scales. The results in this study showed that the model was able to reproduce the daily variations of NO, NO_2 and O_3 concentrations at local scale. However, the air pollution module of TAPM, with the smallest resolution of 100 m, restricts the performance of the model at a specific site near the traffic route. The NO concentration west of the traffic route (site 1 to 3) was underestimated by TAPM which might be due to the fact that emissions from nearby roads and other emission sources were not included in the TAPM simulations. The difference between modelled and measured air pollutant concentrations was largest for NO at site 4. This site was located only 8 m from the traffic route in the road canyon which restricted air mixing and dispersion of air pollutants. The measurements at this site showed a very high concentration on NO which is likely to be very local and site-specific. A drawback in the comparison of measurements and TAPM was that the measurements and model simulations did not have the same time-resolution. While the TAPM simulations gave hourly concentrations the measurements only had a time-resolution of five days. Furthermore, in order to obtain good model results, a high-quality emission inventory is necessary (Hurley et al., 2001).

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4.3 Wind speed and NO_x-O_3 interactions

Many factors influence the NO_x and O_3 concentrations in the urban landscape. Based on measurements of NO_x, O_3 and meteorology, Shi and Harrison (1997) developed a model to analyze and predict NO_x and NO_2 concentrations in London. They found that primary emissions and wind speed were the most important factors influencing NO_x concentration. In addition, the reaction of NO with O_3 was a major factor influencing NO_2 concentrations.

The measurements in this study clearly indicated that the NO_2 concentration in relation to urban background responded differently to increasing wind speed depending on the degree of pollution at the site. At the most polluted sites the NO_2 concentration ratio increased with increasing wind speed while at the least polluted sites the NO_2 concentration ratio decreased. Due to the limited amount of data the correlations were not statistically significant but the same pattern was shown by TAPM. Two processes are of importance and in delicate balance. Higher wind speeds act to dilute NO_2 due to stronger dispersion, but also lead to an enhanced vertical transport of O_3, which produces NO_2 through oxidation of NO. Palmgren et al. (1996) found the background O_3 level to be the limiting component for the occurrence of high levels of NO_2 in Danish urban streets. In the urban background in Denmark the limiting component for formation of NO_2 was often the available amount of NO and not O_3 as in the streets.

The results shown in this paper illustrates the complexity of the temporal and spatial air pollution variations in the urban landscape. The importance of measurements and knowledge about the measurement site characteristics and representativeness are emphasized. Also it has been shown that TAPM has the potential to be an important tool in evaluating air quality problems in Gothenburg and other cities with similar characteristics.

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5 Conclusions

Important conclusions from the present study were:

- The Göte-2005 campaign was characterised by relatively cloudy and windy weather resulting in no strongly developed temperature inversions. Consequently, air pollution concentrations did not grow very large during the campaign.
- The most polluted site had considerably higher levels of NO_x, especially the primary pollutant NO, compared to the urban rooftop continuous monitoring station Femman. The most polluted site also had considerably higher levels of NO compared to the most polluted continuous monitoring site, Gårda. Thus the permanent monitoring stations were not fully representative for the most polluted environments in Gothenburg.
- Pollutant concentrations and pollutant gradients in the urban landscape were strongly dependent on the wind speed. The effect of wind on NO_2 concentration in urban areas was a delicate balance between stronger dispersion at high wind speeds (diluting NO_2) and enhanced vertical transport of O_3 to oxidize NO to NO_2 by stronger winds. The latter effect was strongest at more polluted sites, while the first dominated at less polluted sites.
- TAPM reproduced the relation of NO, NO_2 and O_3 satisfactorily as well as the site differences under different wind speed. However, TAPM was not able to resolve the NO situation at the most polluted site, due to local scale site-specific conditions.

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Table 1. Site names, coordinates, site characteristics, mean, maximum and minimum temperature (T, °C) and the fraction of time (%) with relative humidity (RH) above 80% based on measurements with Tinytags.

Site	Coordinates	Site type	Mean T (°C)	Max/Min T (°C)	Time fraction RH>80% (%)
1. Femman	57°42.522′ 11°58.236′	Rooftop monitoring site (30 m above street level)	−0.6	5.8/−7.5	59
2. Skansen Lejonet	57°42.853′ 11°59.346′	15 m above ground, ~200 m west of Olskroksmotet			
3. Mast	57°42.943′ 11°59.545′	~100 m west of Olskroksmotet	−0.9	4.2/−7.4	59
4. Road	57°42.960′ 11°59.574′	Closest (~8 m) to traffic route, west of Olskroksmotet	−0.7	4.1/−7.0	59
5. Railroad	57°42.708′ 11°59.834′	Along traffic route, ~400 m south of Olskroksmotet	−0.5	6.1/−6.9	59
6. Olskroken	57°42.828′ 11°59.700′	~15 m from traffic route, east of Olskroksmotet	−0.8	5.5/−7.4	72
7. Lunden	57°42.697′ 12°00.031′	Hillslope park site, elevated in relation to traffic route	−1.2	3.8/−7.6	77
8. Annekärr	57°51.901′ 12°19.080′	Rural	−1.8	4.6/−8.1	84
Gårda	57°42.059′ 11°59.676′	Along traffic route, ~1 km south of Olskroksmotet			
Haga	57°41.949′ 11°57.645′	City street environment			

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Table 2. Mean and standard deviation of temperature (T, °C), relative humidity (RH, %), wind speed (wind, m s^{-1}) and global radiation (radiation, W m^{-2}) during the Göte-2005 campaign (2 February to 2 March) based on measurements at rooftop level in the city centre (Femman). Temperature difference (ΔT, °C/10 m) was measured at site Lejonet, a positive value implies a temperature inversion. Daytime is 06:00 to 18:00. Weekdays N=252 (21×12), weekend days N=96 (8×12) and total period is N=696 h.

	Weekday		Weekend		Total period
	Day	Night	Day	Night	
T	−0.7±3.4	−1.8±3.2	0.0±2.6	−0.8±2.8	−1.0±3.2
RH	79±11	83±9	81±16	85±13	82±12
Wind	5.0±2.3	4.5±2.3	4.9±2.5	4.3±2.7	4.7±2.4
Radiation	91±97	0	86±107	0	45±84
ΔT	−0.1±0.8	0.5±0.6	−0.1±0.8	0.7±0.7	0.2±0.8

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Table 3. Mean and standard deviation of NO, NO_2, O_3 (nmol mol^{-1}) and PM_{10} ($\mu g\, m^{-3}$) during the Göte-2005 campaign (2 February to 2 March) based on measurements at rooftop level in the city centre (Femman), a site close to a traffic route (Gårda) and a site in a city street environment (Haga). Daytime is 06:00 to 18:00. Weekdays N=252 (21*12), weekend days N=96 (8*12) and total period is N=696 h.

	Weekday		Weekend		Total period
	Day	Night	Day	Night	
NO (Femman)	15±31	8±24	4±3	8±18	10±25
NO_2 (Femman)	17±9	12±9	9±4	12±9	13±9
O_3 (Femman)	24±10	27±13	29±10	25±14	26±11
PM_{10} (Femman)	28±19	21±15	22±20	21±34	24±21
NO (Gårda)	76±77	36±51	21±20	29±32	49±62
NO_2 (Gårda)	34±13	23±13	19±9	21±13	26±14
NO (Haga)	36±39	21±33	18±14	21±26	26±34
NO_2 (Haga)	23±12	17±12	14±7	19±12	19±12

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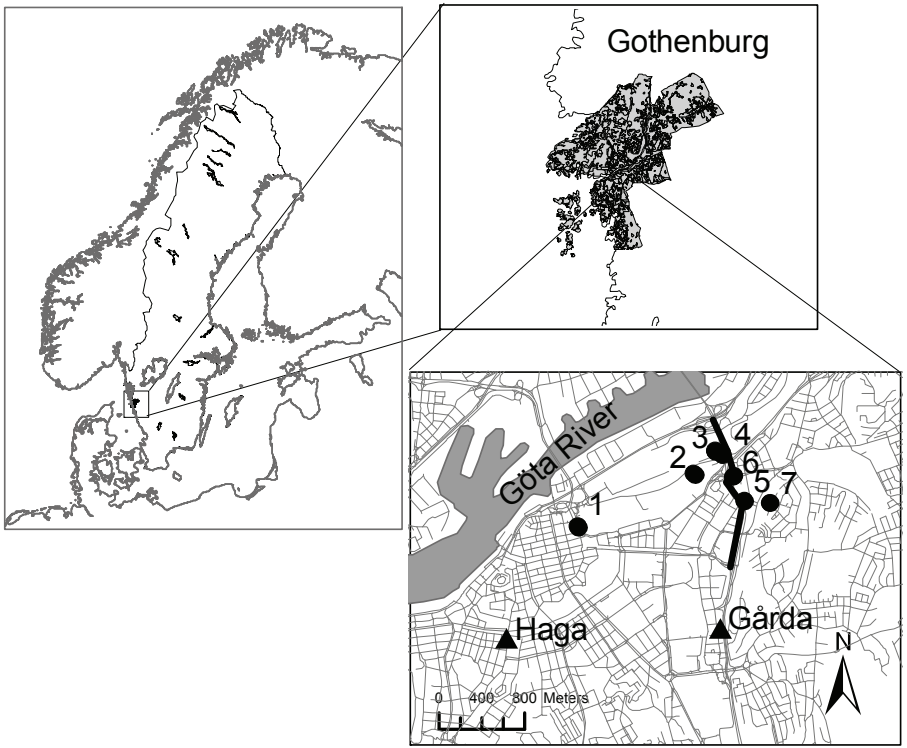

Fig. 1. The location of Olskroksmotet and the position of the measurement sites in Gothenburg. Site 1 (Femman), Gårda and Haga are permanent monitoring sites.

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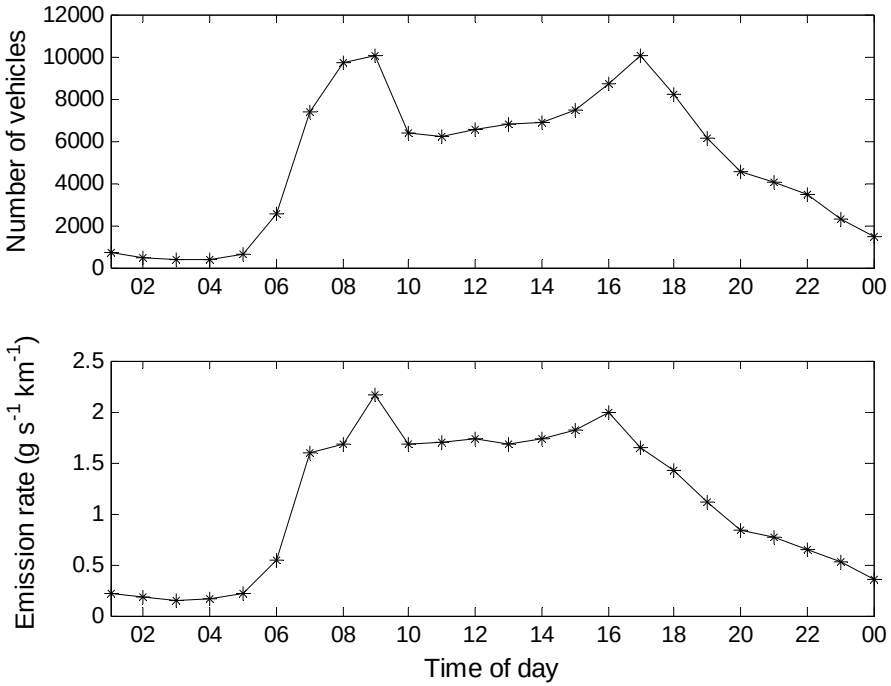

Fig. 2. Diurnal variation of vehicle number and emission rate of NO_x at Olskroksmotet used in the TAPM model.

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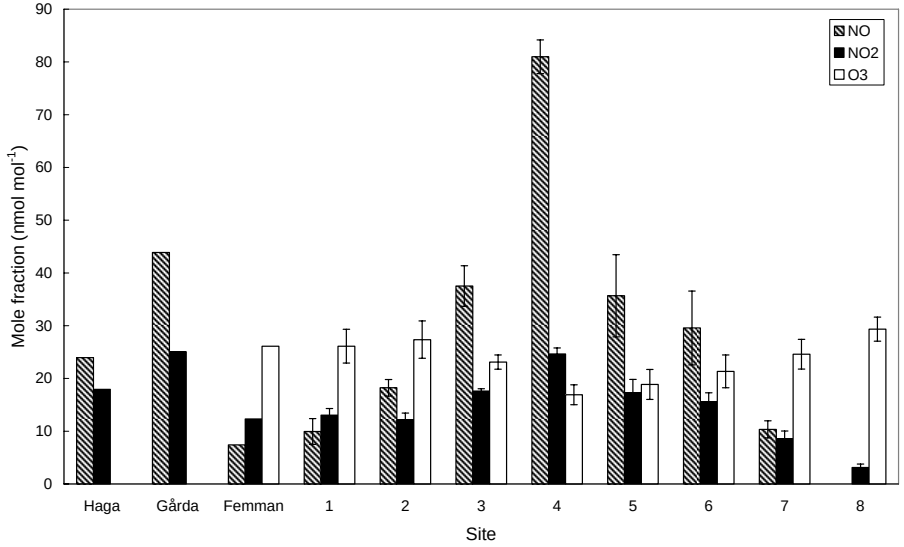

Fig. 3. Average pollutant conditions at the different sites, 2 to 27 February measured by passive diffusion samplers (site 1–8) and continuous instruments (Haga, Gårda and Femman). Site 1 was identical to Femman, but using passive diffusion samplers. Error bars show standard error.

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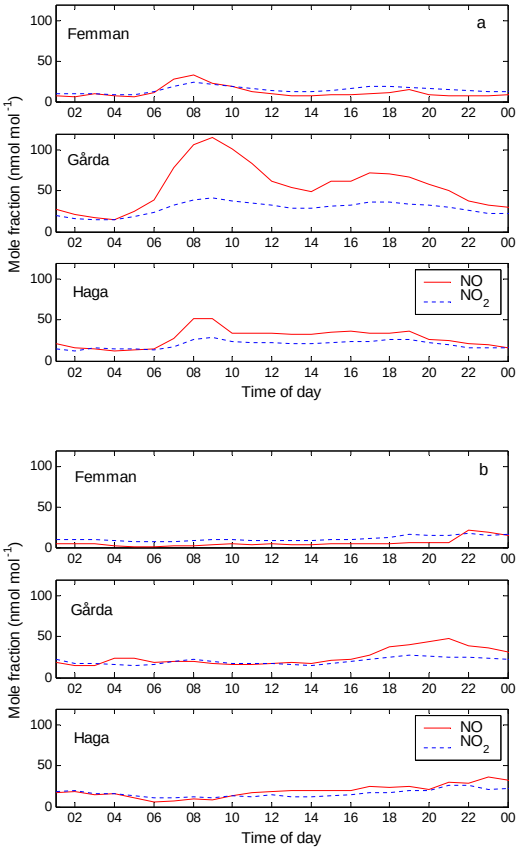

Fig. 4. The average diurnal cycle of NO and NO_2 at the urban monitoring sites during the Göte-2005 period (2 February to 2 March) for **(a)** 21 weekdays and **(b)** 8 weekend days.

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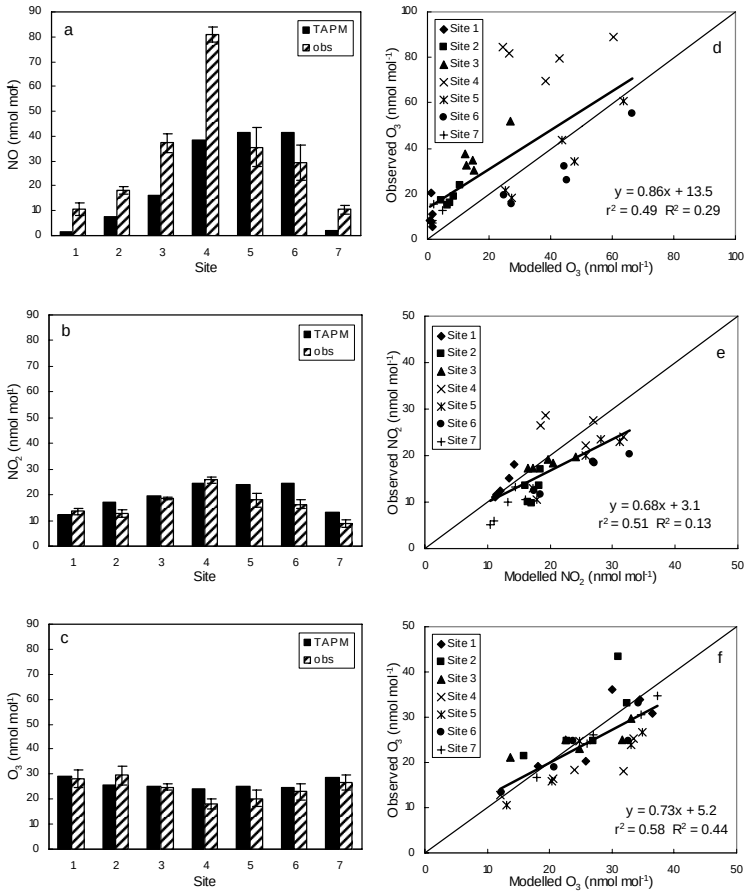

Fig. 5. Modelled and observed O_3, NO_2 and NO at seven sites during the Göte-2005 period (2 to 27 February).

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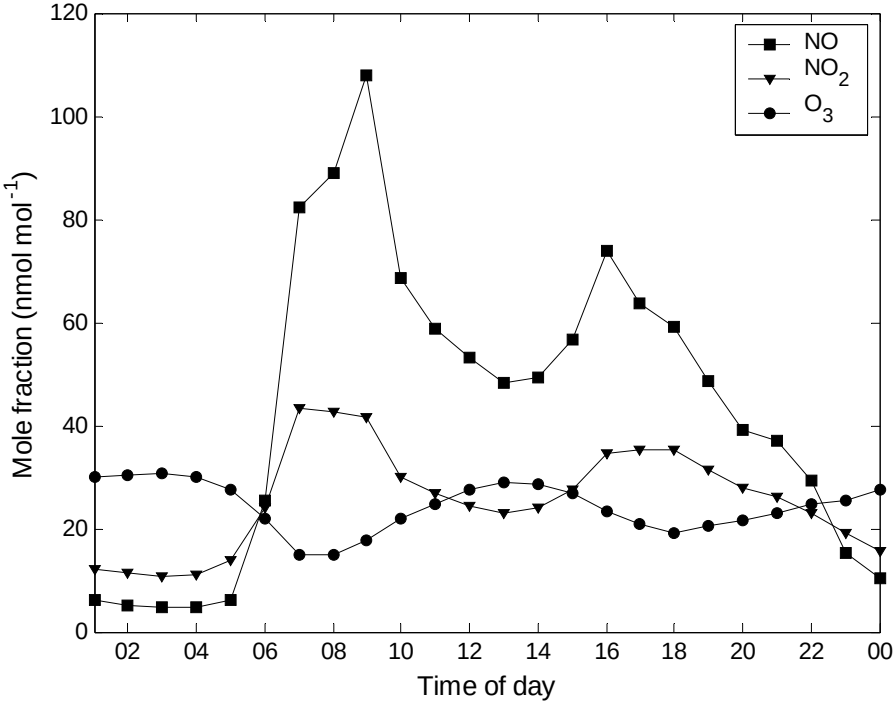

Fig. 6. Diurnal cycle of NO_2, NO and O_3 concentration at site 6 from 2–27 February 2005 modelled with the TAPM model. Site 6 was the most NO polluted site according to the model.

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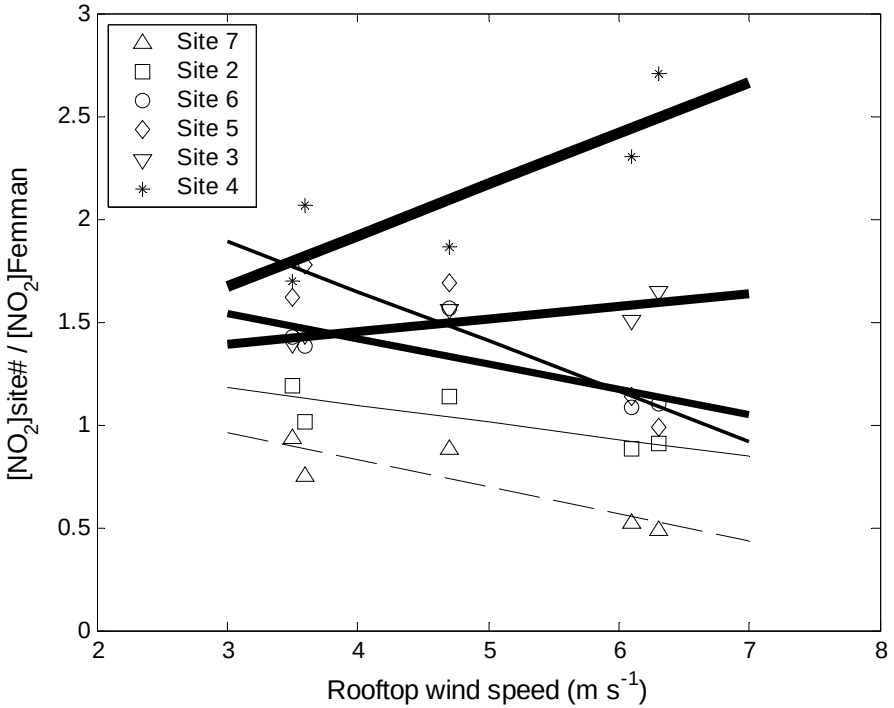

Fig. 7. NO_2 concentration ratio of sites 2 to 7 and the rooftop monitoring site Femman in relation to wind speed. Line thickness reflects the order of the sites with respect to NO pollution. (Thickest line belongs to the most NO polluted site 4 and thinnest line to the least NO polluted site 7).

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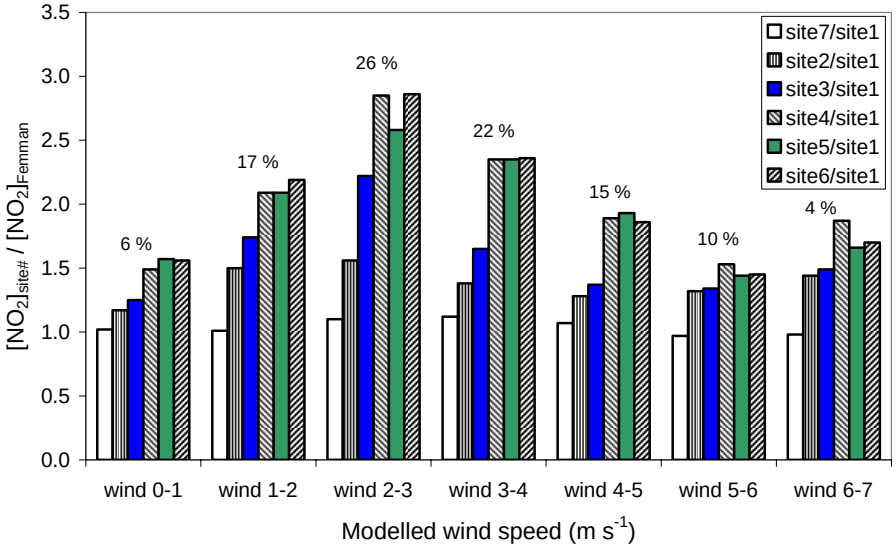

Fig. 8. NO_2 concentration at site 2 to 7 averaged for different wind speed categories and divided with the rooftop site Femman. Above the bars is the percentage hours included in each wind category given. All data come from the TAPM model.

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