H14-222
AIR POLLUTION LEVELS AT COPENHAGEN AIRPORT ESTIMATED BY MEASUREMENTS AND NESTED REGIONAL EULERIAN, LOCAL GAUSSIAN PLUME AND CFD MODELS

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Abstract: At Copenhagen airport an occupational health problem has been investigated concerning the air quality for the workers at the airport. Therefore the hourly air pollution levels have been measured and modelled at different locations at the Danish Airport for the year 2010. Measurements were conducted both at the apron close to the aircraft handling area and the terminal buildings where most of the workers are exposed and in the open fields close to the border of the airport in order to estimate the background levels at the airport. The modelling is based on a very detailed emission inventory (down to 5 m resolution in the handling area) for the airport together with emission data for stationary and mobile sources outside the airport in a 10x10 km^2 domain. The inventory describes the emission coupled to the use of different runways and taxiways depending on the meteorological conditions. The hemispheric Eulerian model, DEHM, the Gaussian point and area/volume source model, OML, and the CFD model, MISKAM, that take into account the complex building configuration have been employed in a nested way. The modelled concentrations are divided into the contribution from regional sources, local sources outside the airport, aircraft main engines, auxiliary power units (APU), ground support equipment and airport vehicle traffic in order to define the various source contributions and develop an appropriate reduction strategy. Modelled annual mean concentration of NO_x and NO_2 are presented and validated against measurements. The OML calculations including the apron emissions at a resolution of 50 m are compared with MISKAM calculations using the 5 m resolution.

***Key words:** Airport air quality, airport emissions, dispersion, OML, Gauss plume, MISKAM, CFD.*

INTRODUCTION

Focus on airport emissions and the contribution to air pollution have increased the recent years. Airports are typical located close to or inside major cities and may not only impact the surroundings but also the airport staffs are exposed. Measurements of air pollution inside and in the surroundings of the airports are used to study the air quality. However, measurements alone are often not sufficient for source apportionment and thus atmospheric dispersion calculations of the emissions from the airport and the surrounding sources become very important. The source apportionment gives important information on which sources are mainly responsible for the observed pollution levels and where to implement reduction efforts in case air quality limit values are exceeded. For Copenhagen Airport, Denmark such an air quality study has been conducted for the year 2010 with focus on then apron where it is assumed that workers are most exposed to air pollution. Several air pollutants were included in the study, but only the annual NO_x and NO_2 results are presented here. Similar studies have been performed for Heathrow Airport (Carruthers et al., 2008) and Zurich Airport (Duchene et al., 2007).

METHOD

The calculated concentrations for the airport and the surrounding neighbourhoods are based solely on emissions inventories and on three one-way nested atmospheric dispersion models - no background measurements are included. The CFD model MISKAM (Eichhorn et al., 2010) is applied for the concentration calculations at the complex central part of the apron in a domain of about 700x1100 m^2. The MISKAM domain is located inside a domain of 10x10 km^2 where the Gaussian plume model OML (Olesen et al., 2007) is applied, see Figure 1. Outside the OML domain the Danish Eulerian Hemispheric Model, DEHM (Christensen 1997, Frohn et al., 2003) is applied.

Figure 1. Map of the south-eastern part of Copenhagen where the airport is located. The blue square marks the OML domain of 10x10 km^2 and the red rectangle marks the MISKAM domain. Red dots are positions of measurements.

DEHM is a 3D long-range atmospheric chemistry-transport model with a grid resolution of 5.6 km over Denmark. It provides an hourly time series of concentrations of NO_x, NO_2 and O_3 for the OML model at the upwind border of the OML domain. The applied concentrations are averaged values of the boundary layer. It is assumed that these averaged values are reasonable estimates of the ground concentration at the apron near the centre of the OML domain as a possible incoming vertical concentration profile will be mixed at that distance. The emission inventory for NO_x and NO_2 used by DEHM is for the Danish area a high resolution (1x1 km^2) inventory (Plejdrup et al., 2011), for Europe a EMEP inventory (50x50 km^2) and for the rest of the hemisphere EDGAR2000 and GEIA.

The DEHM model uses hourly meteorological data from the numerical weather prediction model MM5 (Grell et al., 1995). MM5 also supply the OML and MISKAM models with meteorological data that is modified with measured wind direction at the airport.

The OML model is a local-scale Gaussian plume model for point and area/volume sources. The model is based on boundary layer scaling (friction velocity, Monin-Obukhov length, heat flux, mixing height etc.) instead of relying on Pasquill stability classification. Three different emission inventories are used in the OML domain. The road emissions of NO_x and NO_2 are from a Danish road database (Jensen et al., 2009). Emissions are aggregated into 250 m squares in the major part of the domain and into 50 m squares north of the apron, where a nearby motorway is located. The temporal variation of the emission depends on, hour of the day, week-day, and month. Other mobile and stationary sources are from the above mentioned 1 km^2 Danish inventory. In this inventory the sources are split into SNAP code categories each also having its own temporal emission variation depending on hour, week-day, and month. OML uses a very detailed airport emission inventory created in this study. The inventory is based on flight operations from four typical days, for the four possible runways: 22L+22R, 04L+04R, 12, and 30 and is described in detail later. The wind speed and direction at any hour determine which one of the four runways is used.

The emissions are split on four different types of sources: jet engines, auxiliary power units (APU's), ground handling equipment and airport road traffic. The emissions are for each hour aggregated into 5 m squares for the apron area and 50 m squares for the rest of the airport. For the OML calculations the 5 m squares are aggregated into 50 m. The plume rise from jet engines and APU is not taken directly into account, but are treated as volume sources with a height of 8 m. Ground equipment is also treated as volume source with a height of 4 m. The chemical reactions for NO, NO_2 and O_3 is accounted for in OML by a photochemical reaction scheme dependent on transportation time identical to the one used by the OSPM model (Berkowicz, 1998 and 2000) and the necessary global radiation is from measurements in Copenhagen.

The OML runs are performed in two setups. In one setup all emissions are included and this is used for the concentration mapping of NO_x and NO_2 for the entire airport. In the other setup the emissions inside the MISKAM domain is not included and this setup is used to calculate a time series of the NO_x concentrations at the monitor B4 (Figure 2) that serves as background concentrations for subsequent MISKAM calculations for B4.

Figure 2. Map of Copenhagen Airport with positions of the three monitors (red dots): West and East at the border, and B4 at the apron close to the handling areas.

MISKAM is a CFD-model (Computational Fluid Dynamics) that describes the complex air flow and turbulence around buildings and the dispersion of air pollution. However, it only simulates neutral atmospheric conditions and can not simulate the effects of the buoyancy or momentum from e.g. the jet engines and APU's. For the latter an initial vertical distribution of the emissions from 0 to 5 m is assumed. The horizontal initial spread is contained in the emission inventory due to hourly averaging of the moving sources. The setup of the MISKAM calculation grid (about 1100 m x 700 m x 500 m, Figure 3) was successfully validated against sonic measurements in the terminal building wake near monitor B4 (not shown).

In order to save computing time MISKAM is run for 36 different wind directions (10, 20,…, 360 degrees) for one wind speed and for the four different types of sources in the airport mentioned above. In total 144 model runs are performed applying an average diurnal emission rate for each grid cell and source type. To describe the temporal variation of the emission rates hourly patterns for each source type are constructed that are geographically homogeneous for the MISKAM area.

The final hourly time series of NO_x for the whole year is calculated using the actual wind direction and source type to pick one of the 144 scenarios and scale it proportional to the common emission rate at the actual hour and the inverse of the actual wind speed.

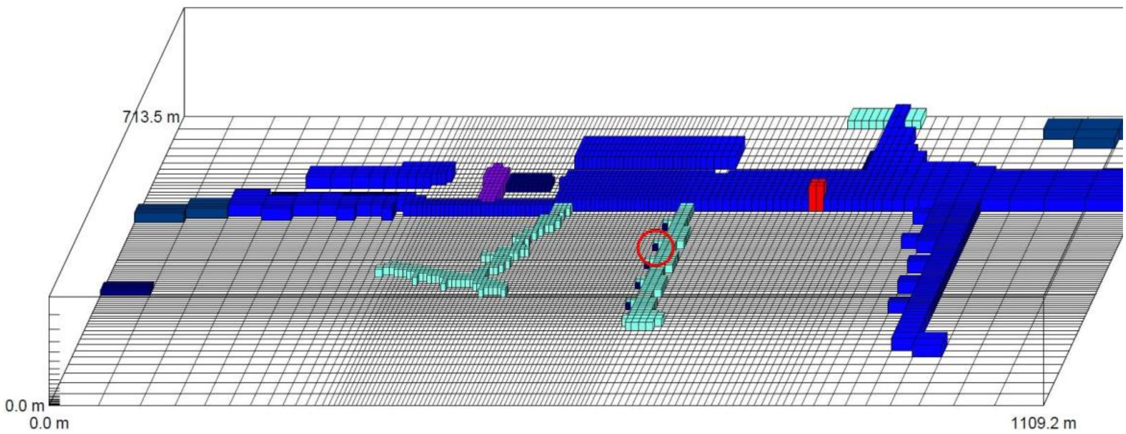

Figure 3. Layout of the MISKAM grid covering the central part of the apron and the terminal buildings. The colours of the buildings refer to different heights. The read circle marks the location of monitor B4 .

AIRPORT EMISSIONS

As mentioned above the very detailed airport emission inventory is based on flight operations for four typical days with use of the four possible runways: 22L+22R, 04L+04R, 12, and 30. The cell sizes are 5m x 5m for the whole airport and with a vertical cell height of 10 m for landing and take-off.

Flight operations contain information on type of aircraft, gate, on-block and off-block time, start and landing time and runway. The digitalisation of aircraft movements are divided into taxi (before start/queuing/after landing), take-off, climb-out, approach and landing. Time in each grid cell is determined from documentation from the airport and further assumptions regarding e.g. the preferable taxi ways, taxi, landing and take off speed, and landing/take off deceleration /acceleration.

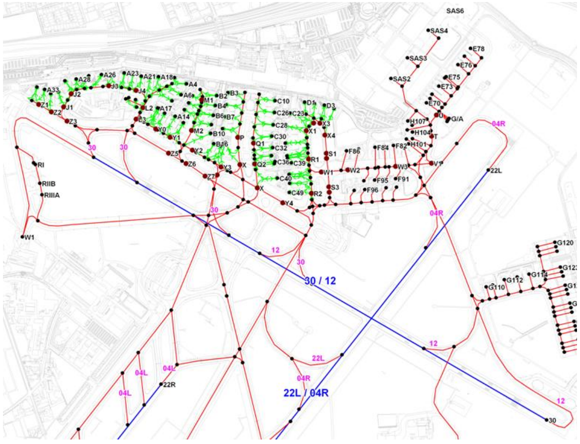

Figure 4. Map of the northern part of CPH Airport with marked tracks of landing and take-off (blue), taxi (red) and dock-in and push-back (green). Dots are gates or waypoints.

For APU (auxiliary power units) the engine load and the duration of use are taken from the ICAO (International Civil Aviation Organization) Airport Air Quality Guidance Manual (doc. 9889).

Figure 4 shows the aircraft tracks for landing/take-off, taxi, and gate approach /push-back. The aircraft track is up to 100 m above ground during landing and climb-out.

The type of handling gear, equipment age, engine size, engine loads and the duration of use are based on information provided by the handling companies in the airport. The handling situations are divided into four groups depending on aircraft size. The handling area is assumed to occur at one side of the aircraft and occupy an area equal to the length and the width of the aircraft wing. For the handling equipment with diesel engines the emission factors are grouped according to the EU legislation for non road (Stage I-IV), road transport (Euro I-V) and other older engines.

The fuel consumption and NO_x emission factors for aircraft engines are from the ICAO Engine Exhaust Emission Database (www.caa.co.uk; jet engines) and the Swedish FOI (www.foi.se; turboprops). NO_2 emission fractions are from Herndon et al. (2004). For APU the NO_x emission factors are from ICAO (doc. 9889), NO_2 emission fractions are from Schäfer et al. (2003) and fuel consumption factors are from LASPORT (LASat for airports, Janicke 2010).

Baseline emission rates for main engines, APU and handling gear are derived from the emission factors and time spend in each cell. For each cell the hourly fuel consumption and emissions are calculated as the product of the emission rate (g/s) and the time (s) duration for each of the activities.

RESULTS AND DISCUSSION

Figure 5 shows the average NO_2 concentrations calculated with OML in a 150 m grid. The highest levels are found at the start positions for take-off at the two main runways. For areas where airport staff is working the highest exposure is found at the apron. Here, the measured level at station B4 is 24 µg m^{-3}, which is lower than the calculated value of about 30 µg m^{-3}. Local maxima are found along the east-west oriented motorway just north of the airport where the irregular pattern is due to the coarse calculation grid. There is a concentration gradient from north-west to south-east because of emission from Copenhagen to the north-west.

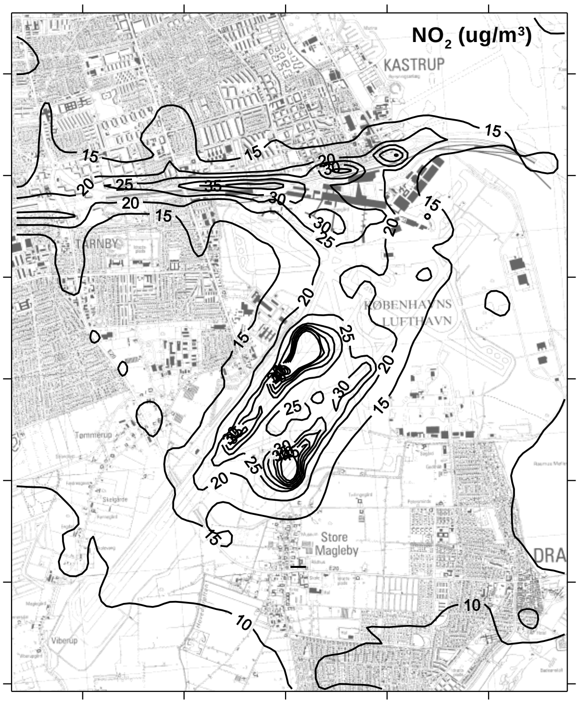

Figure 5. The average NO_2 concentrations for the year 2010. Maximum contour lines are 50 µg m^{-3}. Red dots are positions of monitors. Scale: 1 km between tick marks.

The map of NO_x concentrations is shown in Figure 6. The concentration pattern is similar to that of NO_2.

For NO_x a comparison of OML calculations and measurement is performed at the three monitor stations and this is shown in Figure 7. The contributions to the total concentration levels are split into the different groups of sources. The sources are: jet engine, APU, handling, road traffic inside the airport, all other sources in the 10x10 km^2 OML domain and the background from DEHM. For the apron monitor B4 the same comparison is shown for the MISKAM calculations.

For the West monitor OML calculate a concentration of 20.6 µg m^{-3} which is in very god agreement with the measured vale of 21.3 µg m^{-3}. 22 % of the total concentration is due to the airport emissions of which the jet engines constitute about 2/3.

At the East monitor the OML under estimates the measured level of 24.8 µg m^{-3} with 1/3. A possible reason could be that some very local sources are not included in the inventory or that some of the emissions are underestimated e.g. emissions due to the airside and landside perimeter road traffic or from the parking area to the east. Another explanation could be that the station is located relatively close to the eastern border of the OML domain and that the incoming background concentration has a pronounced vertical gradient (instead of the assumed constant profile) due to the ship traffic three kilometres away.

At the apron monitor B4 both OML and MISKAM over estimate the concentration. The calculated values are 62 µg m^{-3} and 67 µg m^{-3} respectively compared to the measured 37.5 µg m^{-3}. Calculations show that the handling contributes with about 45 % of the level, and this is most of all because the handling area of the two nearest gates is only about 30 m away. The contribution from sources outside the MISKAM domain calculated with OML for aircraft engines, APU's, handling and traffic are 3.9, 0.1, 0.3, and 0.1 µg m^{-3} respectively. The large over prediction could be due to the estimated operating times for the handling procedures used in the emission inventory are too long or the emission factors for the equipment are too high.

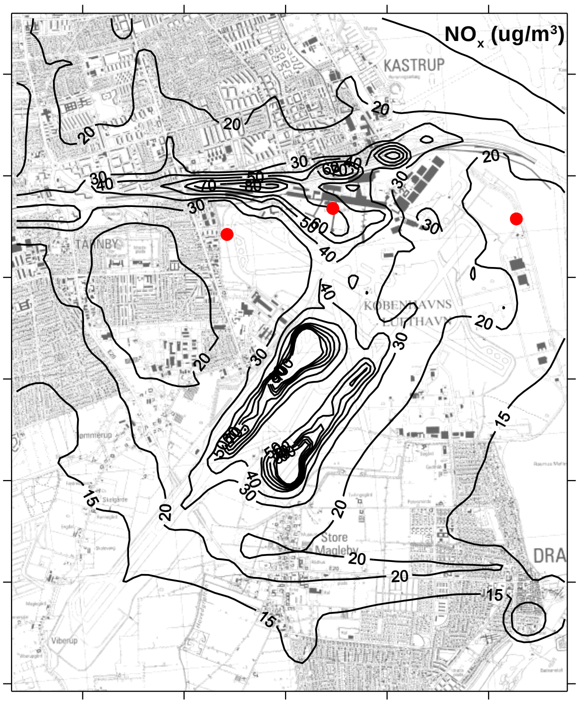

Figure 6. The average NO_x concentrations for the year 2010. Maximum contour lines are 100 µg m^{-3}. Red dots are positions of monitors. Scale: 1 km between tick marks.

Another explanation to the overestimation of concentrations is of course that the plume rise from the jet engine and APU may not be accounted for sufficiently, although the jet engine and APU only contribute with 12 % and 10-15 % respectively. The major jet engine emissions occur at the runway during take-off and with the apron more than 1 km away it was assumed that the plume rise was of minor importance at that distance, where the vertical mixing is about 100 m. However, Carruthers et al. (2007) stress the importance of plume rise from jet engines and estimate that the plume centreline from an aircraft at halt and full power ready to take-off could rise about 100 m at a distance of 1 km. As the aircraft speed increases during take-off the plume rise becomes less important. APU plume rise was not reported. An analysis of concentration vs. wind speed for monitor West (not presented here) shows that for wind direction from the runway 22R (135-185°) concentrations increases with decreasing wind speed indicating that plume rise is of minor importance, opposite to findings by Carruthers et al. (2007).

A third simple explanation to a minor part of the overestimation of jet engine and APU contribution is the applied emission factors in real operation are lower than the ICAO LTO definitions as also mention by Duchene et al. (2007) an references herein.

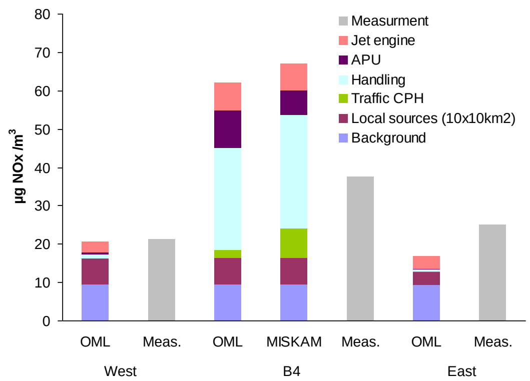

Figure 7. Average NO_x concentrations modelled with OML and MISKAM compared with measurements at the stations West, B4 and East for the year 2010

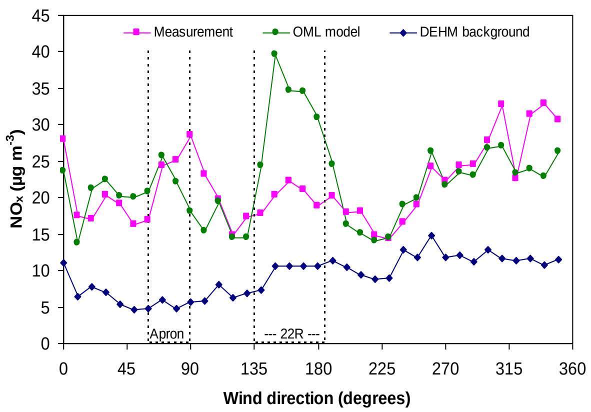

Figure 8. Average NOx concentrations modelled with OML compared with measurements at the station West for the year 2010 as a function of wind direction. The DEHM background concentrations are also included in the OML concentrations.

It is, however, obvious that either the estimated jet engine emissions or the OML treatment of jet engine plume rise is incorrect. This is visible in Figure 8 where NO_x concentrations modelled with OML are compared with measurements at the station West as a function of wind direction. The directions 135-185° from the monitor to the part of runway 22L with major emissions during take-off are marked at the figure. For these directions towards runway 22L OML over predicts the concentrations. For all other directions the calculated and the measured concentrations match reasonable well.

It was previously argued that the emission from handling was too high, but no overestimation is observed in the direction towards the apron (60-90°). This is not a contradiction because the handling emissions are still much smaller than emissions from the jet engines and both sources are located at almost the same distance.

In summary this comprehensive study of the air pollution levels at the Copenhagen Airport shows that the combination of regional and local scale dispersion models is able to estimate the background (station West) level of NO_x reasonable well. The modelled concentration level at the apron is overestimated mainly due to overestimation of emissions from ground handling. Including a better treatment of the plume rise from jet engines and APU's might improve the results.

ACKNOWLEDGEMENT
This study has been financed by Copenhagen Airports.

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