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THE COPENHAGEN TRACER EXPERIMENT, WHAT DID WE LEARN?

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1. INTRODUCTION

In 1978 and 1979 a series of full scale experiments were carried out in Copenhagen to study atmospheric dispersion from elevated sources over urban areas (Gryning and Lyck, 1984). The number of experiments was considerably smaller than for the 10 year earlier St. Louis Dispersion Study (McElroy 1969) and it mainly covered atmospheric near neutral conditions. It was found that the spread of the plume scaled with the measured σ_v and σ_w. Due to its limited extent in time and atmospheric stability the Copenhagen experiment was not used to apply simple relationships for regulatory use as the St. Louis Dispersion Study, but formed an experimental basis for later developments on the path from the Pasquill stability classification towards the use of continuous parameterisations based on Monin-Obukhov scaling in regulatory modelling (Gryning et al., 1987). The Copenhagen experiments have been used extensively for model evaluations and form part of the Model Evaluation Kit of the harmonisation initiative (Olesen, 1994).

The experiment was carried out with the contemporary most modern turbulence instruments at a 200 m tall mast equipped with standard profile measurements of mean temperature, wind speed and direction. At that time profiles of turbulence measurements were not feasible, therefore turbulence was only measured at the release height (115 m). Time averaged measurements of both meteorology and tracer concentrations were published in Gryning and Lyck (1984) and Gryning et al. (1987); due to renewed interest the time series of the measurements were published in Gryning and Lyck (2002)

The interest for dispersion experiments on all scales, including the Copenhagen tracer experiment, hibernated from the beginning of the eighties but came to an abrupt wake up by the Chernobyl accident – initiating considerable modeling and measuring efforts for long-range dispersion. The interest mainly of funding bodies and policy makers for short range dispersion in urban settlements remained low although gradually emerged as a result of scattered terrorist attacks in urban settings. It increased dramatically after the terrorist attack on September 11, 2001 in New York City and Washington D.C. This also raised renewed interest for the data from the Copenhagen tracer experiment as reflected in the citations of the papers Gryning and Lyck (1984) and Gryning et al (1987) that reports the measurements, Fig. 1.

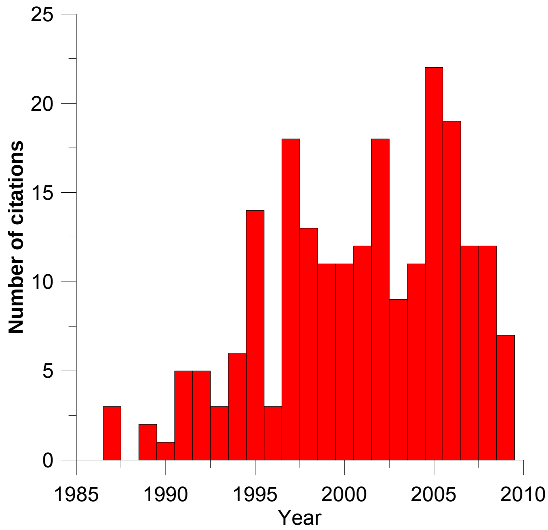

Figure 1. Citations indicating the time evolution in the use of the measurements from the Copenhagen tracer experiment.

I believe that some of the reasons for the long lasting interest for the Copenhagen tracer experiment could be that:

- the experiments were set-up to obtain data that were needed for the emerging efforts to parameterize dispersion in terms of Monin-Obukhov similarity. The data set includes among others the Monin-Obukhov stability length L and the height of the boundary layer z_i. These parameters were usually not derived/measured in the tracer experiments at that time.

- the measurements were carried out under well defined, stationary, flat and homogeneous conditions, avoiding complications such as complex terrain and land sea breezes which haunted many tracer experiments.
- a considerable effort was put into the processing of the measurements and the data-set was published in the reviewed literature – making the measurements easily accessible even today.

2. COPENHAGEN TRACER EXPERIMENT

The atmospheric dispersion experiments were carried out in the Copenhagen area to investigate the dispersion process of a tracer released from an elevated source in the urban/residential area (Gryning and Lyck, 1984). The tracer sulphur hexafluoride, an inert gas tracer, was released from a tower at a height of 115 m and collected near ground level in crosswind arcs 2 to 6 km from the source, see Figure 1.

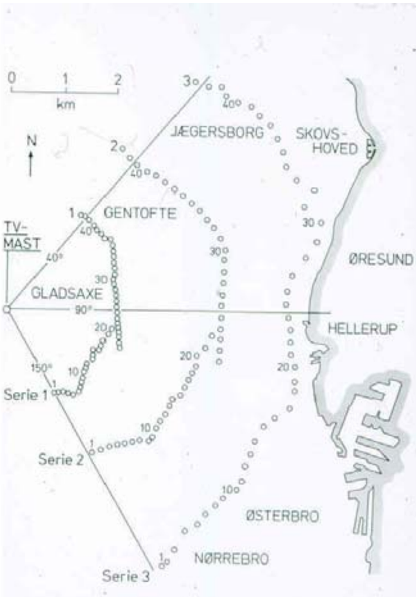

Figure 2: Tracer sampling-unit set up for the experiments in Copenhagen. Typically 20 locations in each arc situated in the actual plume direction for the individual experiments were used.

The tracer sampling time was 1 hour. The site in both the upwind and downwind directions was mainly residential. The meteorological measurements included turbulence at the height of the tracer release, profiles of temperature and wind along the mast and the standard routine radiosoundings launched 4 km northeast of the tracer release point. All tracer experiments were performed during daytime in neutral to slightly convective atmospheric conditions.

3. PLUME DISPERSION IN URBAN AREAS

The tracer experiment was modeled by a number of standard dispersion models that were developed in the 80ties. Figure 3 shows a comparison between simulated and measured tracer concentrations. It can be seen that some of the models (IFDM and INPUFF) reveal a fairly good agreement between model results and observations, and some (HPDM, IFDM, OML, UK-ADMS) show a clear under-prediction of the measured tracer concentrations.

It was argued by Rotach and de Haan (1996) that the under-prediction could be explained by the fact that the experiment was performed over a rough suburban surface and the urban character is not considered in these models. Taking into account the urban roughness sub-layer in a Lagrangian stochastic dispersion model Rotach and de Haan (1996) obtained good agreement between model simulations and measurements, Figure 4.

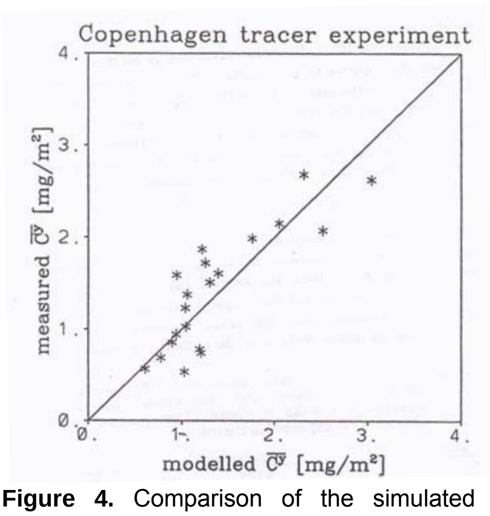

Figure 4. Comparison of the simulated and measured crosswind integrated ground level concentrations for the urbanized Lagrangian dispersion model of Rotach and de Haan (1996).

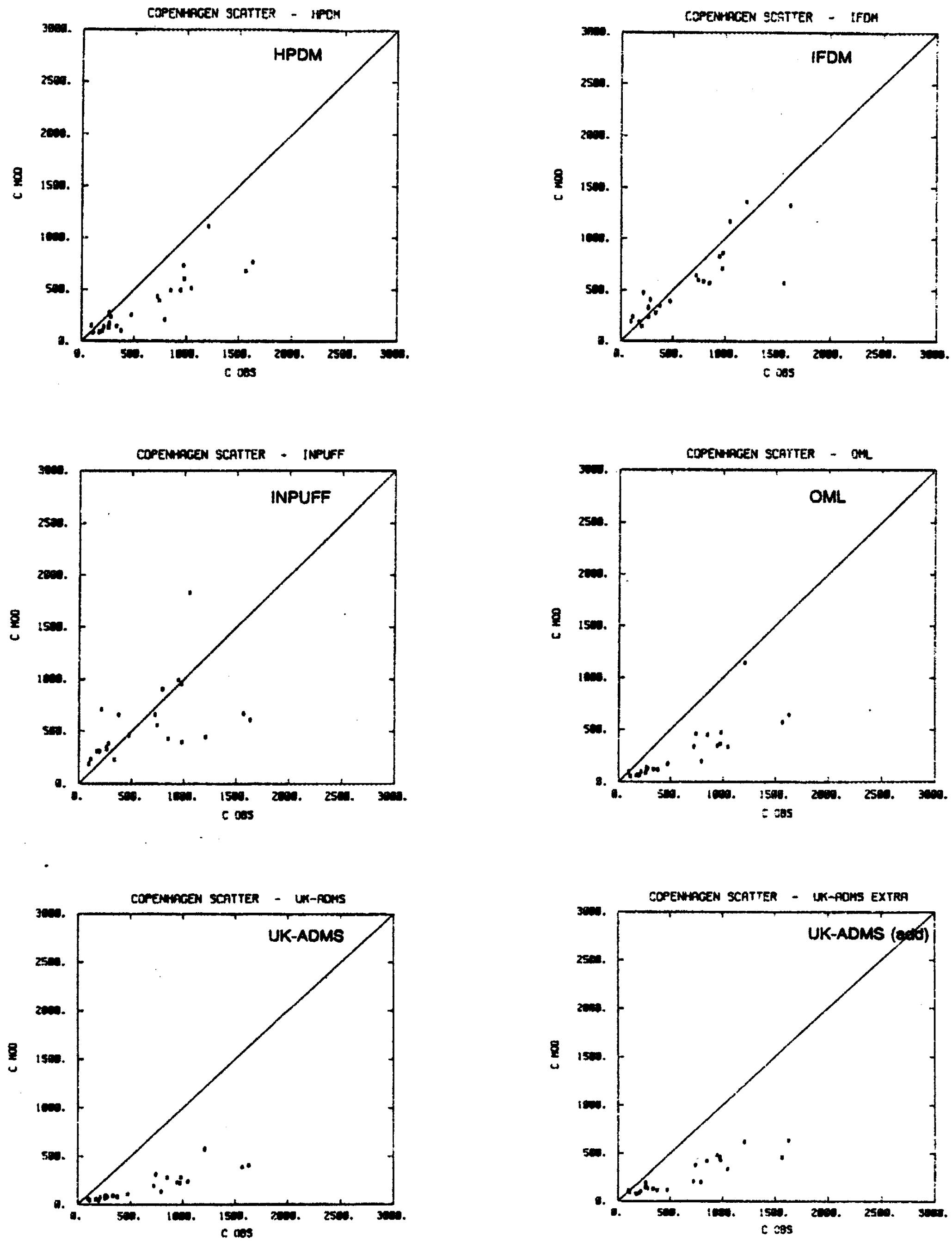

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Figure 3. Comparison of a number of commonly used applied dispersion models with the measurements from the Copenhagen tracer Experiment (Olesen, 1995).

3.1 Basic modelling

In the following the dispersion will be simulated by use of the on-site meteorological measurements, either indirectly through parameterizations of the turbulence or by direct measurements of the turbulence parameters.

Aspects of the lateral spread of tracer plumes, σ_y, and the maximum concentration $C_{\max}$ as a function of distance in urban areas will be investigated. The Copenhagen experiment represents an elevated source and near neutral and convective meteorological conditions with relatively high wind velocities.

The study is based on well-known and commonly used semi-empirical estimates that as starting point take Taylor's famous formula for plume dispersion (Taylor, 1921):

$$\sigma_y = \sigma_v t \, f_y(t/T_y) \qquad (1)$$
$$\sigma_z = \sigma_w t \, f_z(t/T_z)$$

where t is travel time of the plume and f_y and f_z are functions of the dimensionless travel time where T_y and T_z are Lagrangian time scales for the lateral and vertical dispersion processes. The approximations

$$f_y = \left(1 + \sqrt{t/2T_y}\right)^{-1} \qquad (2)$$
$$f_z = \left(1 + \sqrt{t/2T_z}\right)^{-1}$$

are often recommended for applied dispersion modelling (Gryning et al., 1987). For ground-level sources $T_y = 200$ s is recommended and $T_y = 600$ s for elevated sources and when the vertical extent of the plume is larger than 10% of the depth of the mixing layer. For unstable atmospheric conditions $T_z = 300$ s.

When measurements of σ_w and σ_v are not available, these parameters can be obtained from parameterisations. Following Batchvarova and Gryning (2006) we apply the parameterisations (Gryning et al., 1987):

$$\sigma_w^2 = u_*^2 \left[1.5 \left(\frac{z}{z_i} \right)^{2/3} \left(\frac{w_*}{u_*} \right)^2 \exp\left(-2 \left(\frac{z}{z_i} \right) \right) \right] + u_*^2 \left[1.7 - \left(\frac{z}{z_i} \right) \right] \qquad (3)$$

where the convective velocity scale is

$$w_* = \left((g/T) \overline{w'T'} \, z_i \right)^{1/3},$$

with g for the acceleration due to gravity and T for temperature and

$$\sigma_v^2 = 0.35 w_*^2 + (2 - z / z_i) u_*^2 \quad . \qquad (4)$$

The expressions (3) and (4) have been tested in the report of the COST Action 710 (Cenedese et al., 1998) and found to work well for a variety of data sets. Figure 5 illustrates the performance of the parameterizations on the Copenhagen experiment

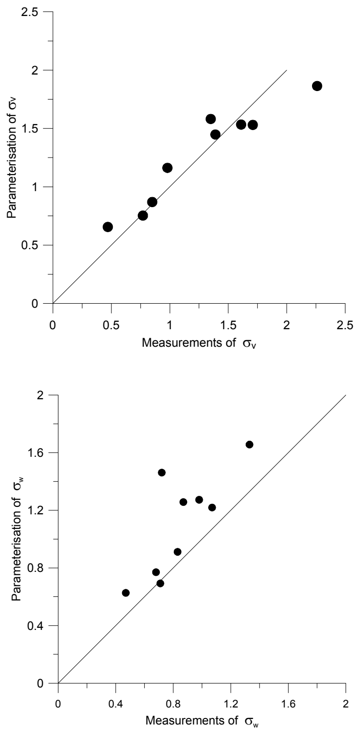

Figure 5. Measured and parameterized values of σ_v (upper panel) and σ_w (lower panel) based on the measurements at 115 m for the Copenhagen experiment (Batchvarova and Gryning 2005).

3.2 Lateral dispersion

The simulation of the lateral spread is performed in two ways. In the first one we use the observed σ_v values. For the Copenhagen experiment observations at the tracer release height (115 m) are used. Figure 6 shows the measurements and model simulations of σ_y using measured values of σ_v (upper panel) and parameterized values of σ_w (lower panel). In both cases the agreement with the measurements is within a factor of two.

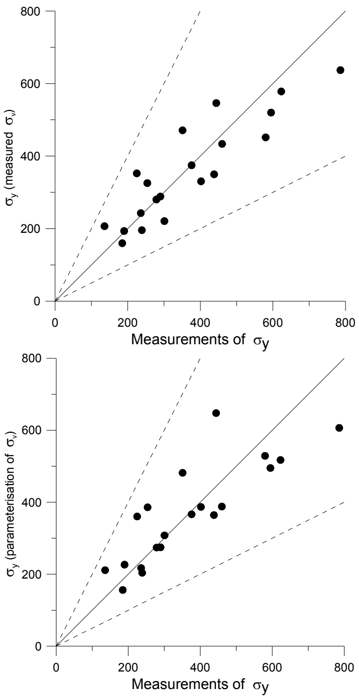

Figure 6: Measured and modelled values of σ_y for the Copenhagen experiment. The upper panel shows simulations based on measurements of σ_v at 115 m. The lower panel shows simulations using parameterized values of σ_v, also at 115 m. The lines show the 1:1 relationship and its factor of two ranges (Gryning and Batchvarova 2005).

Thus in an urban environment applied expressions for the lateral spread, originally developed and tested over flat, homogeneous terrain, resulted in agreement for the Copenhagen experiment better than a factor of two, which is similar to the uncertainty reported for flat terrain.

3.3 Maximum concentrations

Here a very simple modelling approach to the very complex dispersion process of the urban area is applied.

For the Gaussian plume model the ground-level centreline concentration $C_{\max}(x)$ at downwind distance x can be expressed as:

$$C_{\max}(x) = \frac{Q}{\pi \sigma_y \sigma_z u} \exp\left(-\frac{h^2}{2\sigma_z^2}\right) \tag{5}$$

where h is the tracer release height, and Q the release rate. Figure 7 illustrates the results from a comparison between model simulations and measured tracer concentrations from the Copenhagen experiment.

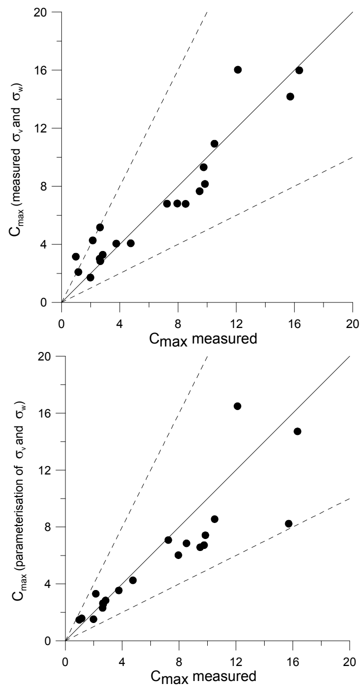

Figure 7: Measured and modelled normalized values of the maximum concentrations for the Copenhagen experiment. The upper panel shows simulations based on hourly measurements of σ_v and σ_w at 115 m. The lower panel is obtained by using parameterized values of σ_v and σ_w, also at 115 m. The lines show the 1:1 relationship and its factor of two ranges (Gryning and Batchvarova 2005).

The measured arc-wise maximum concentration has been compared to the modelled centreline concentration. The value of

σ_y and σ_z was derived from expressions (1) and (2) using $T_y = 600$ and $T_z = 300$ s. The upper panel in Figure 7 illustrates the comparison when the measured values of σ_v and σ_w were applied in the expressions for σ_y and σ_z. The lower panel refers to the case when the parameterized values of σ_v and σ_w were applied. The agreement can be seen to be within a factor of two on both cases.

4.CONCLUDING REMARKS

The tracer experiment was simulated by a number of applied models developed for regulatory purposes in the 80ties and based on Monin-Obukhov similarity. Some of the model simulations underestimated the measured tracer concentrations, other showed quite good agreement. The under-prediction by some of the models likely is due to the lack of accounting for the effect of the urban roughness sub-layer.

We applied simple models based on measured and parameterized turbulence for the lateral and vertical atmospheric dispersion in an urban environment and found an agreement of about a factor of two between model results and measurements. This result can be considered very promising in view of the complex structure of the urban boundary layer. It is generally considered that any attempt to model the dispersion in the urban atmospheric boundary layer better than a factor of 2 on the hourly scale is quite a hopeless task.

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