A NEW METHOD FOR VERIFYING ATMOSPHERIC DISPERSION MODELS

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ABSTRACT
In urban areas, numerical dispersion models can be used for controlling and planning air quality. Due to existing NO_x, benzene and PM_{10} air pollution concentrations, which are within the range of regulatory limits, it is necessary that immission forecast be highly accurate. In regard to this, it is surprising that possible errors of dispersion models have not yet been analysed systematically and there is still no adequate tool to identify and assess the consequences of such errors. It will be shown that the results of immission and meteorological measurements done for 50 weeks at 6 measuring sites in the Rheinstrasse in Mainz can be used to form linear matrix equations which describe the dispersion within the street canyon. An analysis of the data set proves that the matrix equations are consistent and unambiguous. That means that the data set presented here can be used to verify numerical dispersion models in urban areas. A first verification, done with a common dispersion model, demonstrated that, for the Rheinstrasse, the calculated results agree with the measurements for most of the measuring sites. The difference between measured and calculated weekly standard deviation fell below 25%. The data set should now be applied to other models in order to ensure the ability of different numeric models to predict pollutant transport and mixing in urban areas. Those interested are asked to contact the authors.

Key words: Air pollution modelling. Immission, dispersion models, verification, benzene

INTRODUCTION

Numerical dispersion models nowadays can be used to control and plan air quality even in urban areas. For example, microscale dispersion models are used to ensure that traffic-induced benzene, soot (or PM10) and nitrogen dioxide pollution does not exceed regulatory limits. In contrast to single point measurements, numerical models can forecast the immission concentration for a whole area. This ensures that all locations which are possibly highly polluted are included and measurements can be made there to verify the forecast. Numerical models can be used, moreover, to analyse and compare the environmental impact of different traffic planning concepts. Due to the existing NO_x, benzene and PM_{10} pollution in urban areas which is within the range of regulatory limits, it is necessary that immission forecast be highly accurate. It is all the more surprising that dispersion model errors have not yet been analysed systematically and that there is still no adequate tool to identify and assess the consequences of such errors. This situation is profoundly unsatisfactory.

VERIFYING NUMERICAL IMMISSION FORECASTS IN URBAN AREAS

In the literature many examinations comparing numerical forecasts and measurements in urban areas are described (in Germany, e.g. Eichhorn et al. 1995, Schädler et al. 1996, Schädler et al. 1999). But most examinations compare air quality measurements only

- with the results of coupled emission- and dispersion models. Therefore it is not possible to distinguish the errors of one from the other
- on the basis of annual mean or 98 percentile immission without detailed background concentration information. Therefore errors due to different wind directions can be compensated and the accuracy of the annual mean depends on wind distribution and background concentration.

As will be shown in the following, numerical dispersion models can be verified for both annual mean and case-to-case wind directions without any need of input emission data. To do this it is necessary to measure the

- weekly mean immission of any substance for a longer period at a minimum of 2 sites, for example, on two opposite sides of a street with more or less uniform traffic strength
- wind direction and velocity within the examination area at an altitude where both are undisturbed by surrounding buildings
- background immission.

Measurements

The measurements presented here were made along the Rheinstrasse in Mainz for one year. Within the examination area the Rheinstrasse is a street canyon. Due to some gaps in the row of buildings, local wind- and immission distribution varies widely.

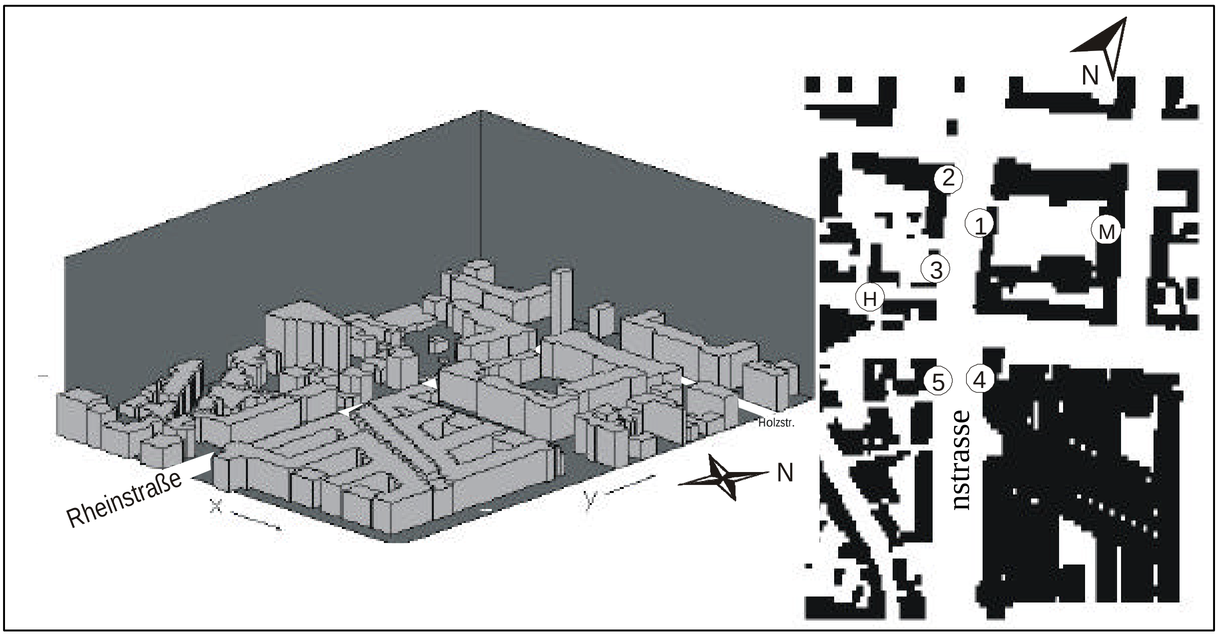

Fig.1: schematic representation of the examination area and location of measurement sites 1–5. The meteorology station M is situated on the roof of a building at site M and background concentration was measured at site H

Between July 1999 and October 2000, weekly mean benzene concentrations were determined at a height of 2.5 metres by the Landesanstalt für Umweltschutz und Gewerbeaufsicht Rheinland-Pfalz at 6 sites. Benzene was sampled with passive collectors and measured with a gas chromatograph. In order to determine accuracy, each site was equipped with 2 adjacent collectors which were analysed separately. For 18 weeks a gas chromatograph was situated right next to the passive collector at station 1. A comparison of the results of active and passive measurements yields an accuracy rate of better than ± 20% for the passive collectors (with the exception of 4 weeks).

Results of the measurements

First, for all 5 measurement sites, the background concentration observed at station H was subtracted. The result is the additional benzene concentration due to the traffic-induced emission in the Rheinstrasse and to the mixing and dispersion processes within the street canyon. The weekly mean concentration at different stations is influenced by the wind distribution in the given week and by the wind velocity. To eliminate the effect of different wind velocities, the immission concentration was standardised by multiplication with the wind velocity. Now the immission at one site should only depend on the distribution of wind velocity if the weekly emission is time independent. This is demonstrated by the following example. Figure 2 shows the wind distribution between 26 January and 16 February, i.e. for 3 different weeks.

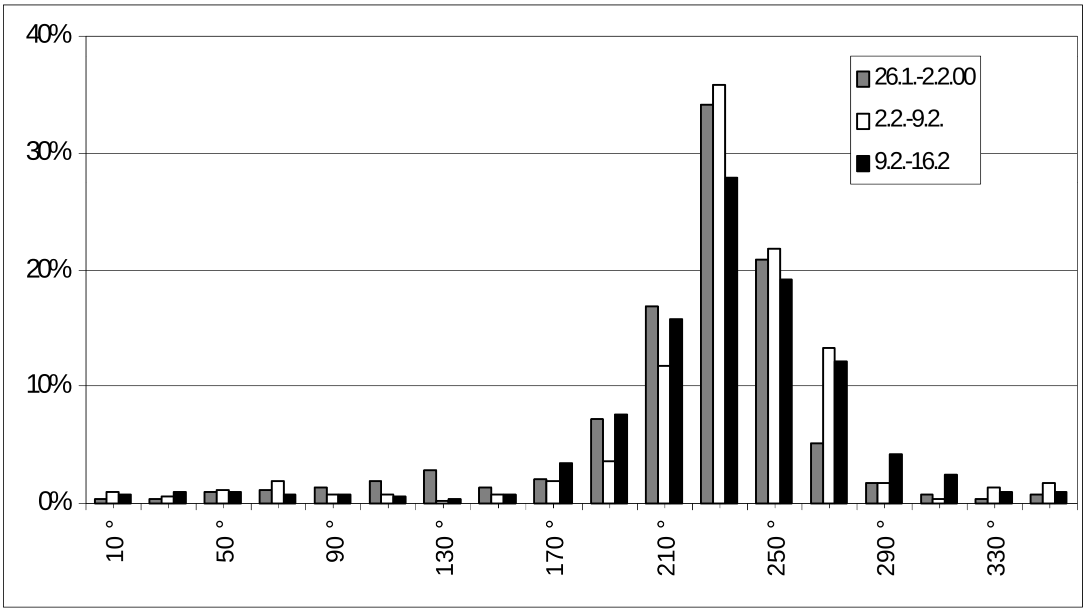

Fig. 2: Distribution of wind direction between 26 January and 16 February

In each of the three weeks, the wind distribution was very similar with mostly south-west winds. Because the standardised immission has to be independent from wind velocity, the weekly mean additional concentration at one site should agree within an accuracy range of ± 20% (measuring accuracy) for the 3 weeks. The prerequisite is a weekly mean constant benzene emission, i.e. a weekly mean constant traffic volume on the Rheinstraße. As can be seen from fig. 3, this is indeed the case. For every site the concentrations for the 3 different weeks remain constant within the error range.

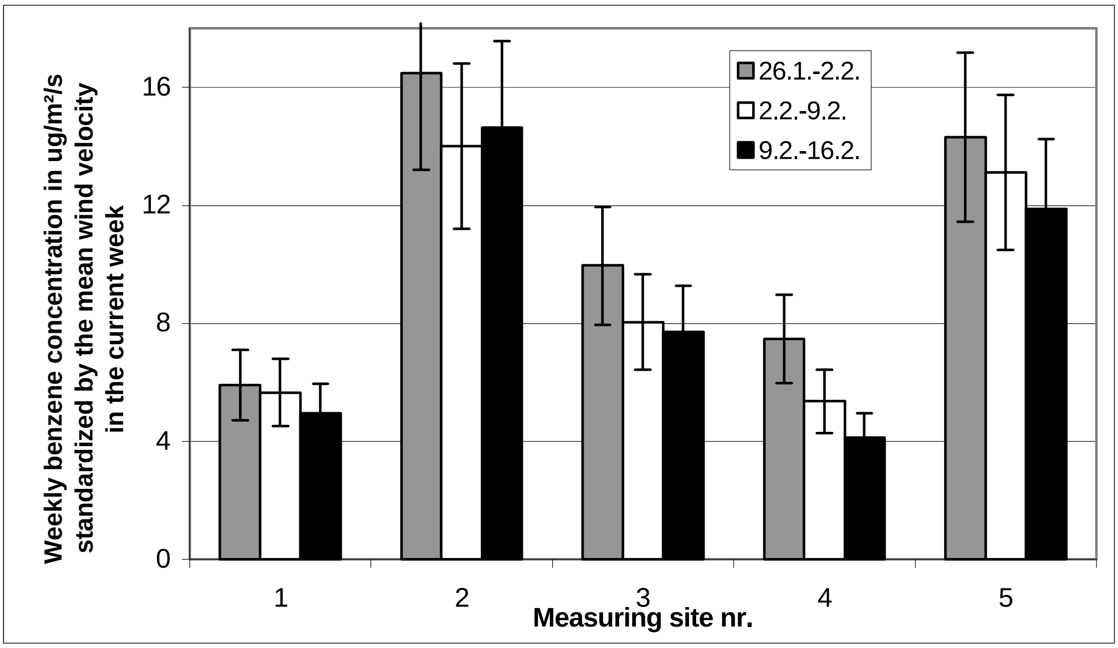

Fig. 3: Distribution of additional standardised benzene concentration in µg/m²/s at sites 1 to 5 from 26.01 and 16.02 standardised by the weekly mean wind velocity

For westerly winds, leeward measuring sites 1 and 4 show lower concentrations than sites 2 and 5, which were to windward. This is the typical airstream pattern for perpendicular winds in a street canyon. At site 3, the street canyon is interrupted and therefore lower concentration occurs than at sites 2 and 5. Similar results were observed for winds from easterly directions, when sites 1 and 4 have higher and sites 2 and 5 lower immission concentrations. This is not shown here; for more detail see Zenger and Weißenmeier (2001).

Data base to verify dispersion models

Dispersion models yield the immissions for fixed conditions, i.e. an emission E, a wind direction k and a wind velocity u. The weekly mean is obtained by weighting the results under individual meteorological conditions with the frequency of their occurrence. Assuming that the street emission is not correlated with wind velocity or direction within the week, the concentration mean for the week j C(j) results from the following equation

$$C_i(j) = \sum_{k=1}^{18} H_{k\,(j)} \cdot u_k(j) \cdot \quad I_{i\,k} \cdot E\,(j)/(u \cdot E) \qquad \text{(eq.1)}$$

Here, wind direction is broken down into 18 divisions of 20 degrees.

C_i (j): weekly mean additional immission concentration at site i in the week j

H_k (j): frequency of wind direction k in week j

u_k (j): mean wind velocity for wind direction k in the week j

I_{ik}: normalised immission, measured at site i, with a wind velocity u from direction k and an emission E. Also a result of dispersion models under these conditions.

E(j): weekly mean real emission in the street for the week j

E, u: unit emission and wind velocity used to calculate I_{ik} .

Assuming the weekly emission to be time independent, i.e. traffic strength does not change from week to week, $E_{(j)}/(u \cdot E)$ can be moved in front of the sum to be a constant A. This results in

$$C_i(j) = A \cdot \sum_{k=1}^{18} H_k(j) \cdot u_k(j) \cdot I_{i\,k} \qquad \text{(eq.2)}$$

If the data set measured at the Rheinstraße is consistent, it must be possible to calculate the weekly immission C_i (j) by using a set of normalised immission concentrations I_{ik} and equation 2.

Consistency of the data set

For every site i, the measurements in the Rheinstraße over a period of 50 weeks k can be interpreted as a system of 50 linear equations with 18 unknown variables I_{ik}. This also can be seen as a matrix equation:

$$Ci_{(1)} = A \cdot \left(H_{1(1)} \cdot u_{1(1)} \cdot I_1 + H_{2\,(1)} \cdot u_{2\,(1)} \cdot I_2 + \ldots + H_{18\,(1)} \cdot u_{18\,(1)} \cdot I_{18} \right)$$

$$Ci_{(2)} = A \cdot \left(H_{1(2)} \cdot u_{1(2)} \cdot I_1 + H_{2\,(2)} \cdot u_{2\,(2)} \cdot I_2 + \ldots + H_{18\,(2)} \cdot u_{18\,(2)} \cdot I_{18} \right) \qquad \text{(eq.3)}$$

etc. ....

$$Ci_{(n)} = A \cdot \left(H_{1(n)} \cdot u_{1(n)} \cdot I_1 + H_{2\,(n)} \cdot u_{2\,(n)} \cdot I_2 + \ldots + H_{18\,(n)} \cdot u_{18\,(n)} \cdot I_{18} \right)$$

Only 18 wind directions are taken into account, because the analysis was made in steps of 20 degrees. The matrix equation 3 was solved by using an explicit numerical algorithm explained more in detail in Zenger and Weißenmeyer (2001).

Solving this equation resulted in the vector I_{ik} at all 5 measuring sites. By inserting this vector in equation 3, it should be possible to calculate the concentration time series C_i (j) by using the wind distribution $H_k(j) \cdot u_k(j)$ only. As can be seen in fig. 4, at site 1 the measured benzene additional concentration correlates well with the result obtained from eq.2 by using the vector I_{ik}. Except for 6 weeks, all predicted weekly mean immission concentrations agree with the results gained from measurements within the measuring accuracy of ± 20%.

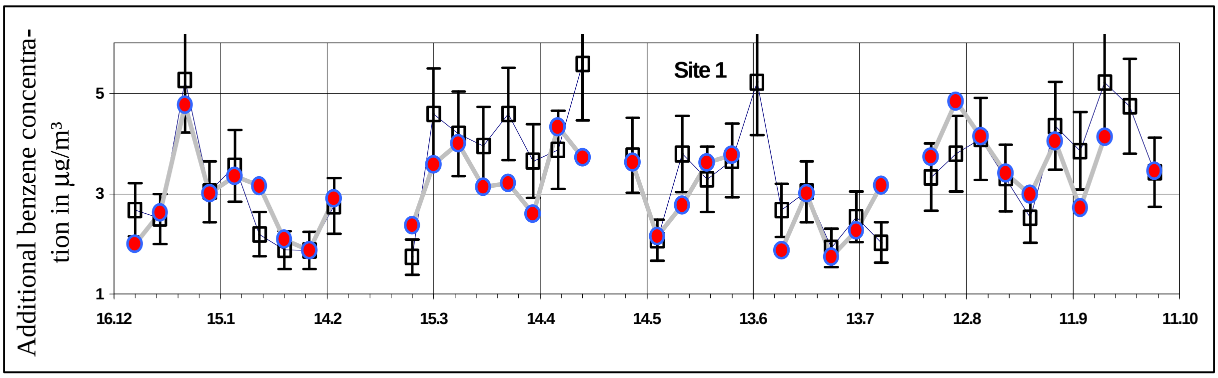

Fig. 4: Time series of measured (o) and calculated ( ) additional benzene concentration in µg/m³ for site 1. Calculated results were obtained using equation 2 or 3 with the solving vector I_{ik}

This is the principle of the verification method. Any immission vector obtained by dispersion models for the Rheinstrasse building configuration can be used as described before.

First test to verify a numerical dispersion model

In a first test, the data set was used to verify the results of a common dispersion model often employed in Germany. In order to do this, the area map was digitised and formatted as required by the model. Differential GPS measurements were used to check the exact position of the buildings and measurement sites. The calculations were done for every site i and for 18 wind directions k. The vector I_{ik} resulted. Inserting I_{ik} in equation 3 makes possible a direct comparison between the modelled and measured time series. The test demonstrated that, for the Rheinstrasse, the result of the numerical model agrees well for all 50 weeks with the actual measurements for the sites 1, 2, 4 and 5. The difference between calculated and measured weekly standard deviation is lower than 25% for all sites except site 3. There is an inexplicable lack of agreement.

The data set should now be applied to other models in order to ensure the ability of different models to predict immission concentrations. Those interested are asked to contact the authors.

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