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EXPERIMENTAL AND NUMERICAL STUDY OF THE DISPERSION AND TRANSPORT OF AUTOMOBILE EXHAUST GASES FROM HIGHWAYS

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SUMMARY

This paper describes examples of modelling and of measurements of the dispersion and transport of exhaust gases from automobiles on a highway. Model runs were performed by a large-eddy-simulation model. The measurements were carried through by the DLR environmental research aircraft lee-side of the highway between München and Augsburg.

INTRODUCTION

Due to a strong increase in traffic density in the last 10 years, a considerable contribution of air pollution in the Federal Republic of Germany is produced by automobiles in cities and on roads. These emissions lead to serious problems of nitrogen oxides impact and of photochemically produced oxidants. Efforts should be made to answer the question of the distribution of the automobile emissions of a line source on a local and regional scale. One part of the emissions is distributed within the atmospheric boundary layer and transported on a regional scale, another part is handed over into the free troposphere, and the third part is deposited on the ground and vegetation.

During the day one can assume that the boundary layer is well mixed, whereas during the night a stable boundary layer is predominant. Since traffic density is higher during the day we are particularly interested in air pollution dispersion during the development of the convective boundary layer. For this purpose both numerical simulations and aircraft measurements have been carried out.

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To resolve the turbulent eddies in the convective boundary layer a large-eddy-simulation model is used. A short model description and obtained results are presented in the first section. First results on the distribution of air pollution components leeside of the highway Munich - Stuttgart obtained from airborne measurements are presented in the second section.

Numerical Simulation

The distribution of pollutants in the convective boundary layer cannot be simulated by conventional k-theory-models (Sun, 1986 (ref. 4)). As the covariance of temperature and concentration is an important factor for producing the countergradient flux in a convective layer, models using second order closure technique are essential.

A micro- and mesoscale model (MESOSCOP) has been developed (Schumann et al, 1987 (ref.3)) to study the turbulent transport in the stratified boundary layer among other things by means of a large-eddy simulation (LES) model. The turbulence parametrization of this LES-version of the model is described in detail by Schmidt 1988 and Schmidt and Schumann 1989 (refs. 1 - 2). The model makes use of the Monin-Obuchow relation for calculating the turbulent momentum and heat flux at the surface as a function of a prescribed surface heat flux or a surface-temperature and roughness-length. The model covers a domain of typically 8 km in the two horizontal directions and 2.4 km in the vertical direction. To resolve the turbulent eddies a gridspace of 50 to 100 m in all three directions is necessary.

For this study an additional prognostic equation for a passive and nonreactive tracer gas has to be solved besides the basic model equations. To simulate the transport and dilution of a pollutant released from a continuous line source at the ground the concentration flux $\overline{w'c'}$ was set to a constant source rate Q at the lower boundary. We assumed an infinite line source in the y-direction (Fig. 1) and an environmental background wind U of 4 m s^{-1} transverse to the line source.

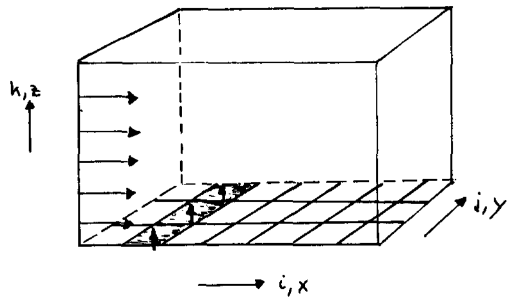

Fig. 1. Line source in the model domain and environmental wind U.

The initial value of the concentration c is set equal zero. A periodic boundary condition is applied at the lateral boundary. At the outflow, upper and surface boundary Neumann conditions are prescribed. At the inflow boundary c is set equal zero.

The numerical simulated cross-wind integrated concentration is shown in Fig. 2, after 30 min and 60 min. integration time. The plume is carried upward by the well organized updraft of convection. There is a local maximum at the height of about 1 000 m, near the top of the mixed layer. This result is in agreement with laboratory experiment of Deardorff 1978 and Willis and Deardorff 1983 (refs. 5 - 6), where a local maximum was also found in the upper mixed layer.

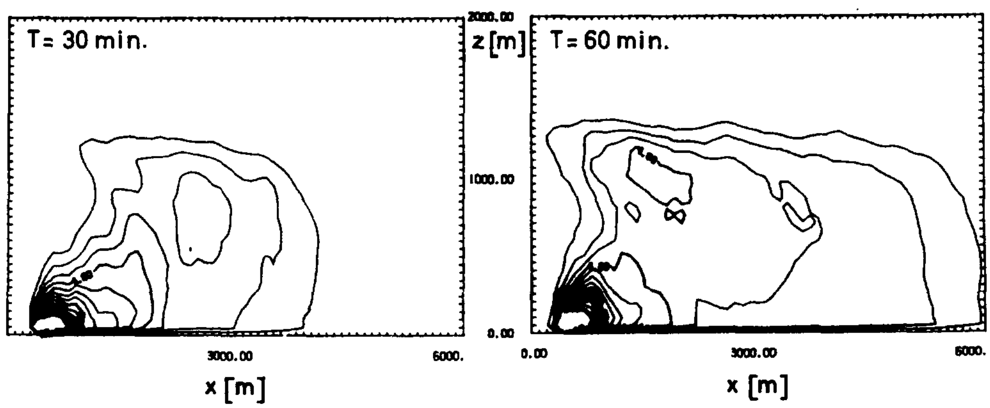

Fig. 2. Cross-wind integrated concentration after 30 min and 60 min integration-time.

Aircraft measurements of automobile exhaust gases

Usually automobile exhaust gases from roads or highways are measured by fixed or mobile ground stations and by instrumented towers (e.g. Chock, 1977, Cadle et al. 1977, Rao et al. 1979, Sistla et al. 1979, Rodes and Holland, 1981, Esser, 1982, Baumann, K. 1987, Kuhler et al. 1988 (refs. 7 - 14)). However, knowledge on the three-dimensional dispersion in the atmospheric boundary layer from measurements is poor, because the installation and operation of instrumented towers is expensive and, therefore, limited within the close range of the highway (max. 1 km). Thus little is known about the behaviour of exhaust gases at height ranges above 150 m and at larger distances.

In order to obtain data on pollution distribution and meteorological conditions within extended height and distance ranges from the highway, particularly for validation and verification pur poses of dispersion models, measurements should be performed by instrumented aircraft. We made measurements of NO, NO_x, SO_2, O_3, Aitken particles and visibility and of meteorological parameters like air temperature, humidity, and air pressure by means of a Queen Air Be-65 airplane at the highway between Munich and Augsburg in Bavaria (Paffrath, D. and Peters, W., 1983 (ref. 15)).

An example of the results of concentration and meteorological parameters measurements along traverses across the highway is shown in Fig. 3. Mean flight altitude was 50 m above ground. Crossing points are denoted by arrows (1), (2), (3) and (4). Flight paths (1) - (2) and (3) - (4) are downwind, flightpath (2) - (3) is upwind of the highway.

Maximum values of NO_x between 50 and 90 ppb and of NO between 30 and 50 ppb were measured above the crossing points (2), (3), (4). There we also find peak values of Aitken particle concentration. These particles are emitted by automobile engines too. On the other hand ozone concentrations are reduced for about 20 ppb below background ozone near these points which is due to the oxidation of NO to NO_2 thereby reducing the ozone to molecular oxygen. No correlation can be detected between SO_2 and nitrogen oxi-

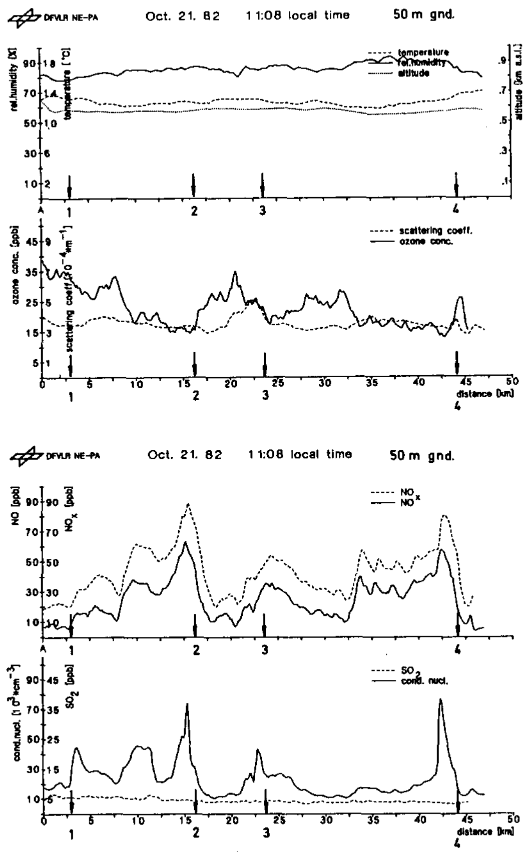

Fig. 3. Example of plots of meteorological parameters and concentrations of pollutants along a flight path crossing the highway

des. SO_2 concentrations are rather low (5 ppb) and nearly constant, which demonstrates that the SO_2-emission by traffic is small although diesel fuel contains considerable sulfur amounts. No significant correlation can be seen between scattering coefficient and nitrogen oxides because the nephelometer responds to large particles and the production of large particles in automobile engines is rather small compared with the background particle content of the air.

The flights were performed at different heights 50 m, 110 m, 180 m and 270 m above ground. From the results x_a two-dimensional NO_x-isoline distribution downwind of the highway was obtained by an interpolation technique (Fig. 4).

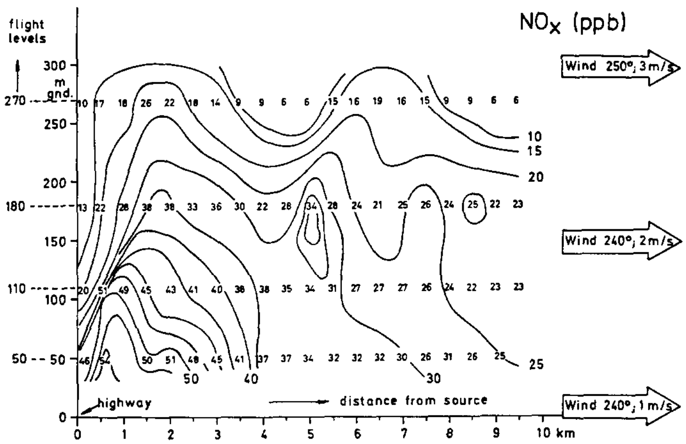

Fig. 4. NO_x concentration isoline plot downwind of the highway

It can be seen that the exhaust gases are dispersed upwards up to about 300 m above ground at a distance between 1 and 2 km from the source. This is due to low wind velocites associated with convective processes. At 180 m a second maximum is found at a distance of about 5 km.

From the position of the maximum concentration with reference to the position of the source and from horizontal wind speeds one can estimate mean vertical velocities of NO_x dispersion:

at 50 m gnd: 8 cm/s
at 110 m gnd: 40 cm/s
at 180 m gnd: 24 cm/s
at 270 m gnd: 50 cm/s

The following mass fluxes could be estimated from the concentrations and wind velocities:

	mean conc. upwind ppb	mean conc. downwind ppb	mass fluxes g/s/km
NO	10	35	10
NO_2	13	18	3
NO_x	23	53	13
SO_2	5	5	0

CONCLUSIONS:

It could be shown that the concentration field of automobile exhaust gases downwind of a line source (highway) can be simulated quite well by a large-eddy simulation model which has been developed at the DLR Institute of Atmospheric Physics. In addition the concentration field of a highway in Bavaria was determined by means of an instrumented aircraft.

With the measurements one can validate the simulation models and obtain initial values for these models. This shall be done by combined ground and aircraft measurements of exhaust gas components, of meteorological and turbulence parameters and of deposition processes during different weather situations up- and downwind of a selected line source.

The aim of a planned project is to quantify the fractions of exhaust gases which undergo deposition on the surface, longway transport in the boundary layer on mesoscales and handover to the free troposphere.

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