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DESCRIPTION OF VERTICAL DISPERSION INFLUENCED BY ROUGHNESS ELEMENTS

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SUMMARY

A tentative method to include the dispersion effect of roughness elements is suggested.

A simplified equation for the horizontal variation in the moments of the vertical concentration distribution is used as a vertical diffusion model. The horizontal variation in the vertical dispersion parameter depend on the scale as well as on the intensity of turbulence.

The intensity of local eddy velocity components may be calculated in well defined wind conditions. Measurements should be required in weak wind situations.

At the top of the roughness elements the scale of turbulence is found to be proportional to the height of the elements according to results from studies on canopy flows.

With increasing height the scale of turbulence approach a constant value determined by the structure of the atmospheric surface layer.

The evaluation of the tentative model suggested in chapter two should include simultaneous measurements of local turbulence in the area of emission.

A further development of the statistical formulation close to the source and of the effect of the structure of the atmospheric boundary layer far from the sources may be needed. Existing result of dispersion experiments in a small town indicate that local data on turbulence statistics may be important 150 m downwind of a line source in stable winter situations. The inverse value of Monin-Obukhov length described the variation in vertical dispersion with the surface layer structure. The measurements were carried out 800-1400 m downwind of an emission of two tracer components.

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DESCRIPTION OF VERTICAL DISPERSION UNDER INFLUENCE OF ROUGHNESS ELEMENTS

1 INTRODUCTION

Increased mixing downwind of roughness elements influence the dilution of local emission as well as the dry deposition of pollution from distant sources.

When car traffic gradually became the main source of pollution near the ground, discrepancies have been observed between observed and estimated ground, level concentrations. The calculations compared well with measurements of SO_2-concentrations, however, calculated values systematically underestimated observed NOx-concentrations in urban areas in Norway. The discrepancies could either be caused by the description of emission or dispersion. Further development of both descriptions is probably necessary (Grønskei and Gram, 1988). The dispersion of low level sources over urban areas is known to be effective, and vertical dispersion parameters developed for urban areas were used (MacElroy and Pooler, 1968).

The dependence of dispersion on thermal stratification and on height above the ground over urban areas is not well documented. In Bergen as well as Oslo the concentrations in air pollution episodes were dependent on the strength of ground based inversion under similar emission conditions (Hanssen-Bauer, 1985; Grønskei, 1973). Referring to the dispersion classification scheme proposed by Gryning et al. (1986) further work is needed to clarify the dispersion over urban areas in stable atmospheric conditions as the surface layer theory may not apply below the height of about 50 m over urban areas.

In order to improve the methods for estimating the relative contribution to ground level concentration from elevated and ground level sources, tracer experiments were performed in a suburban area in the southern part of Norway as a part of the description of the pollution situation in 1983 and 1984.

In this report a description of surface layer dispersion assisted by a statistical diffusion description close to the source provide a tentative interpretation model for explaining the results of tracer experiments. In chapter three results of dual tracer experiments from one winter and one summer period are used to discuss parameters describing vertical diffusion.

2 FORMAL DESCRIPTION OF DISPERSION ADJACENT TO THE GROUND IN URBAN AREAS

2.1 DESCRIPTION OF DISPERSION OF EMISSION FROM GROUND LEVEL SOURCES

When vertical dispersion may be described by a turbulent diffusion coefficient K(z) and the horizontal wind velocity, the dispersion may be described by solving an equation for the gradient transfer by numerical methods.

For emission close to the ground the following simplification applies under conditions described in Appendix A and results of the dispersion experiments may be interpreted in terms of the following differential equation for the first moment ($\bar{z}$) in the vertical concentration vertical concentration distribution.

$$\frac{d\bar{z}}{dx} = \left[\left(\frac{K_z}{u}\right)_{\bar{z}} - \left(\frac{K_z}{u}\right)\right]\frac{1}{\bar{z}} + \frac{c(z_1)}{M}\left(\frac{K}{u}\right)_1 \qquad (2.1)$$

$\bar{z}$: The first moment of the vertical concentration distribution.

K_z : The vertical turbulent diffusion coefficient.

u : Horizontal wind speed.

$c(z_1)$: Concentration near the ground.

$\bar{M} = \int_{z_1}^{z_2} c \, dz = \bar{z}\,\bar{c}$ The vertical integrated C-profile.

Pasquill (1976) suggested that the dispersion in the surface layer followed a simplified form of equation 2.1. For the concentration distribution close to the ground we have:

$$c(z_1) = \frac{2}{\pi}\bar{c}$$

$$\frac{d\bar{z}}{dx} = \left[\left(\frac{K}{u}\right)_{\bar{z}} - \left(\frac{\pi-2}{\pi}\right)\left(\frac{K}{u}\right)_1 \right] \frac{1}{\bar{z}} \tag{2.2}$$

When the K and u variation with height is known, the equation may be used to estimate vertical diffusion. The different empirically determined σ_z-formulas may be interpreted as vertical variation of K/u by using the equation 2.2.

2.2 THE DESCRIPTION OF TURBULENCE CLOSE TO THE GROUND IN URBAN AREAS

The urban surface layer is characterized by the influence of

- the roughness elements that may be ordered along lines (buildings along streets).
- horizontal variation in the heat balance close to the ground.

Accordingly the urban surface layer may be expected to vary with roughness geometry. In many problems it is suggested to treat the influence of roughness elements as a transition zone to regular surface layer theory. This approach applies for the description of the wind and temperature profiles. The turbulent structure in the transition zone becomes particularly important for the dispersion from ground level or elevated sources.

Several studies on canopy flow and on dispersion of exhaust pollution in street canyons provide useful information on the structure of turbulence close to the ground. Yamartino and Wiegand (1986) proposed a simplified model for the dispersion of exhaust emission in street canyons. The proposed formula for the standard deviation of the turbulent velocity components σ_i reads:

$$\sigma_i = f(x,z)\ [A_m\ (S_r^2 + \alpha^2\ V_r^2)^{1/2} + (A_c + A_u h)] \quad \text{Unit: m/s} \qquad (2.3)$$

$$h = S + N_a\ e_a/B \qquad \text{Unit: kW/m}^2$$

S : total solar radiation.

$$S_r^2 = U_r^2 + W_r^2 \qquad \text{Unit: m/s}$$

U_r : horizontal velocity component perpendicular to the road.

W_r : vertical velocity component

V_r : horizontal velocity component along the road.

h : total heat flux

N_a : traffic intensity i.e. number of cars per time unit.

e_a : heat loss per vehicle per length unit of the road.

B : width of the road.

$\left.\begin{matrix} A_m \\ \alpha \end{matrix}\right\}$: Dimensionless factors of proportionality describing mechanical turbulence.

A_u : Factor of proportionality for thermally generated turbulence. Unit: $[m^3/(kW \cdot s)]$.

A_c : Turbulence observed at night with calm wind conditions and no traffic.

According to the evaluation of the coefficients in the formula, the thermally generated turbulence is of minor importance only when the sun intensity is low.

Meteorology department of Risø National Laboratories in Denmark performed measurements of turbulence at 10 m height in an urban area (Lillestrøm) in Norway. When the wind speed was above 1 m/s the standard deviation of the eddy velocitiy component in vertical direction (σ_w) increased with wind speed according to a simplified formulae 2.3b When the wind speed was lower than 1 m/s, the σ_w- values were normally distributed around 0.135 m/s as shown in Figure 1.

$$\sigma_w = 0.2\ (ff - 1.0) + 0.2 \qquad (2.3b)$$

ff: wind speed in m/s.

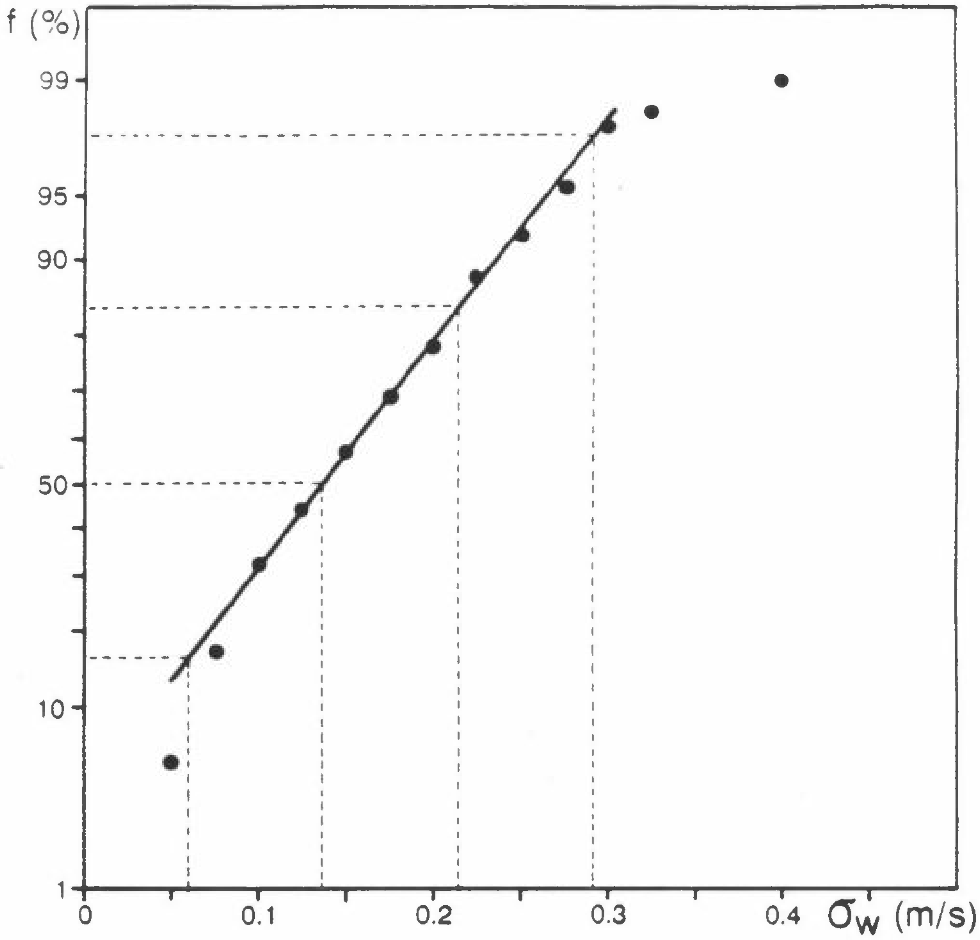

Figure 1: The standard deviation of vertical eddy velocity σ_w. The cumulative distribution when the wind speed is lower than 1 m/s.

Several authors have indicated that ventilation of street canyons may be described by a time constant rather than a diffusion process (Lamb, 1978; DePaul and Sheih, 1985). The observations indicate that the scale of turbulence determining pollution dispersion from street canyons approach a finite value above the roof level.

The atmospheric surface layer is characterized by wind and temperature profiles but also by the turbulence statistics close to the ground. In pollution situations the wind speed are low and the shear stress terms are in some situations of minor importance. The other process important for the generation of turbulence is the horizontal variation in heat balance introducing a separate length scale. The amplitude of horizontal variation in temperature may be a source of vertical mixing.

2.3 ON THE USE OF TURBULENCE DATA FOR THE DESCRIPTION OF DISPERSION

The equation 2.2 have been used for the further discussion of dispersion of emission near the ground. Using the definition of drag coefficient C_D and turbulence length scale λ, the equation may be reformulated

$$C_D \equiv \left(\frac{u_*}{\bar{u}}\right)^2 \text{ and } \lambda \equiv \frac{K_z}{u_*} \tag{2.4}$$

u_* : friction velocity. Unit: m/s.

$$\bar{z}\,\frac{d\bar{z}}{dx} = \lambda(z)\ C_D^{\,0.5}\ (\bar{z}) - \frac{\pi-2}{\pi}\,\lambda(z_1)\ C_D^{\,0.5}\ (z_1) \tag{2.5}$$

According to the surface layer similarity theory

$$C_D^{\,0.5} = \frac{0.36}{\ln\left(\frac{z}{z_0}\right) + 4.7\left(\frac{z}{L}\right)}$$

z_0 : roughness length.
L : Monin Obukhov length.

The drag coefficient decrease with increasing height and the vertical variation has to be taken into account in very stabel situations.

Considering the horizontal variation in a Gaussian concentration distribution as a result of ground level emission:

$$\frac{1}{2}\,\frac{d\sigma_z^{\,2}}{dx} = \frac{\pi}{2}\,((\lambda(\bar{z})C_D(\bar{z})^{0.5} - \frac{\pi-2}{\pi}\,\lambda(z_1)\ C_D^{\,0.5}(z_1)) \tag{2.6}$$

In the literature empirical data have been used to provide information on the vertical variation in λ in different meteorological situations. Studies on canopy flow have given the following estimate of the length scale close to the ground Bache (1986):

$$\lambda(h) = C_D^{0.5} \frac{h}{\alpha}$$

h: height of the roughness elements

α: coefficient depending on the structure of the surface. A small value means high scale of turbulence and an effective penetration of wind.

When $\sigma_z \lesssim \lambda$ the turbulence characteristics close to the point of emission determine the dispersion and different formulas have been suggested for σ_z i.e. Venkatram et al., 1984.

$$\sigma_z = \frac{\sigma_w t}{(1+t/2T_L)^{0.5}} \tag{2.7}$$

$$T_L = \frac{\lambda}{\sigma_w}$$

$$\frac{1}{\lambda} = \frac{1}{\lambda_n} + \frac{1}{\lambda_s}$$

$$\lambda_n = \varkappa z_r, \ \lambda_s = \gamma^2 \ \sigma_w/N$$

$$\varkappa = 0.36; \ \gamma^2 = 0.26.$$

$$N = (\frac{g}{T} \frac{\partial\Theta}{\partial z})^{0.5}$$

Figure 2 show the variation of λ with height above the ground. Different assumptions about the turbulence structure in the atmospheric surface layer are considered.

Two curves marked L=10 m and L=100 m represent the scale of turbulence described by the atmospheric surface layer theory. The curves marked λ_s= 18.5 m and λ_s= 116 m follow Venkatram (1983) results for high and low σ_w -values with different temperature increases with height (0.001-0.01) deg/m. The variation of scale in neutral atmospheric conditions is given as a straight line marked λ_n in the figure. Further the scale of turbulence at the height of the roughness elements in a small town marked λ (10 m) is indicated by a vertical line. This value varies with the penetration of wind between the roughness elements and also with the drag coefficient.

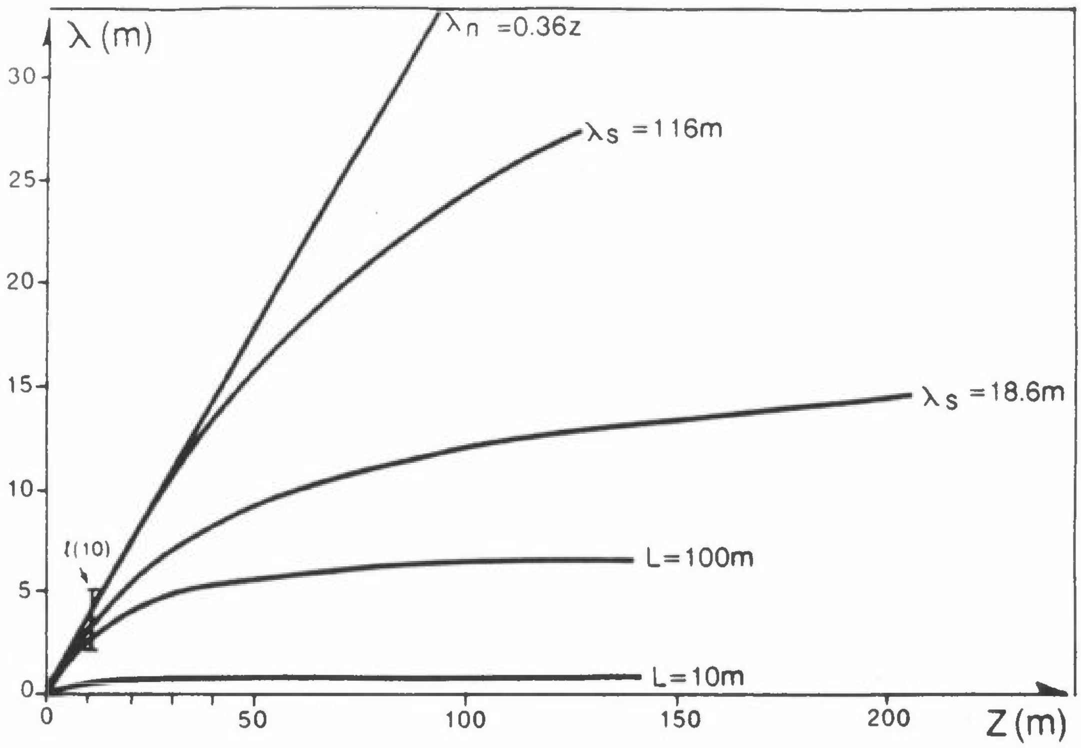

Figure 2: The scale of turbulence under different atmospheric surface layer structure.

Yamartino and Wiegand (1986) indicate that σ_w is dependent both on wind speed and on the heat balance.

When the scale of the plume is larger than the scale of turbulence close to the ground, equation 2.6 takes into account the vertical variation in scale of turbulence.

A smooth combination of the equations 2.6 and 2.7 for dispersion calculation would be obtained when the functions for σ_z are continuous and have a continuous derivative at the point of transition. Based on derivation of equation 2.7, the following expression to be compared with equation 2.6 is found.

$$0.5 \frac{d\sigma_z^2}{dx} = \frac{\sigma_z^2}{u} \left[\frac{2T_L + 0.5\, t}{t\,(2T_L + t)}\right] \qquad (2.8)$$

At the point of transition equation 2.6 reads

$$0.5 \frac{d\sigma_z^2}{dx^2} = l(z_1)\, C_D^{0.5}\, (z_1) \qquad (2.9)$$

From equation 2.8 and 2.9 the ratio between the transport time and the Lagrangian time scale reads

$$t/T_L = 2(-1 + \sqrt{(1 + \frac{l(z_1)u_*}{\lambda_0 \sigma_w - \lambda(z_1)u_*})}) \qquad (2.10)$$

with the requirement for solution

$$\lambda(z_1) < \frac{\sigma_w}{u_*} \lambda_0$$

When a solution for t/T_L is not found, the surface layer turbulence lence structure determine dispersion. However, when $\lambda_0 >> \lambda(z_1)$ the σ_w -values become important for the determination of dispersion. The combination of 2.8 and 2.9 should be based upon the second order closure approximations in the surface layer. However, the author has rejected this part of the work. As the σ_w-value depend upon the structure of the surface as well as on the profiles of wind and temperature it is difficult to specify general rules for the mixing process near the ground. For the asymptotic behaviour of the combined equation the following variation in scale of turbulence with height is suggested.

$$\frac{1}{\lambda} = \frac{2h}{(z+h)\lambda_0} + \frac{z-h}{\lambda_s z} \qquad (2.11)$$

Referring to Garret (1980) correction methods may be used to define profiles for wind (u) and for the exchange coefficient (K) under influence of roughness elements. These corrected values may be used in equation 2.2 for estimating vertical diffusion as an alternative method that should be evaluated.

Additional complications are introduced by a rough surface with variable heat balance introducing vertical "motions" that are of particular importance for the dispersion. In some urban areas observations indicate that a horizontal convergence compensate for these vertical motions e.g. Grønskei (1973) and Eidsvik (1982) reported mean horizontal convergence for the Oslo area that may be of importance for the description of pollution dispersion.

The tendency for positive covariance between vertical velocity and temperature and the possibility of horizontal mass compensation was the main reason for planning dual tracer experiments over urban areas. The combination of equations 2.6, 2.7 and 2.11 do not cover this possibility for countergradient transfer of pollution. However, the σ_z-values determined by the equations take into consideration local σ_w -values and the general structure of the urban surface layer. The σ_z-values on distances over 1-2 km varies with the thermal stratification.

2.4 DIFFERENCE IN DISPERSION AS A FUNCTION OF EMISSION HEIGHT DESCRIBED BY THE GAUSSIAN FORMULA

To compare experimentally determined dispersion as a result of emission from different heights above the ground, scaled concentrations are defined in the following way:

$$S = \frac{c \cdot u}{Q} \tag{2.12}$$

S: Scaled concentration, unit: m^{-2}.
c: Tracer concentration.
u: Wind velocity, unit: m/s.
Q: Emission intensity, unit m^3/s.

According to the dispersion formulas maximum concentration as a result of tracer emission at ground level reads:

$$S_m\,(x,o,o) = \frac{1}{\pi\,\sigma_y(x)\,\sigma_z(x)} \tag{2.13}$$

$\left.\begin{matrix}\sigma_z(x)\\ \sigma_y(x)\end{matrix}\right]$: Standard deviation of vertical and horizontal concentration distribution.

A similar formula applies for the other tracer emitted at a different height.

$$S_m\,(X,O,H) = \frac{1}{\pi\,\sigma_y\,(x)\,.\,\sigma_z\,(x)}\,\exp\left(-0.5 \cdot \left(\frac{H}{\sigma_z}\right)^2\right) \tag{2.14}$$

H: effective height of emission.

To compare vertical dispersion from a furnace chimney with dispersion of emission from car traffic the crosswind integrated concentration (I) is considered.

$$I = \int_{-\infty}^{\infty} C(x,y,0,H)dy = \sqrt{\frac{2}{\pi}} \frac{Q}{\sigma_z u} \exp(-0.5 (\frac{H}{\sigma_z})^2) \qquad (2.15)$$

$$\bar{S}_p = \frac{I}{Q} u = \sqrt{\frac{2}{\pi}} \frac{I}{\sigma_z} \exp(-0.5 (\frac{H}{\sigma_z})^2) \qquad (2.16)$$

From a line source the following formula applies for gaussian dispersion

$$S_L = \frac{C_L(x,o)}{q} u = \sqrt{\frac{2}{\pi}} \cdot \frac{1}{\sigma_z} \qquad (2.17)$$

C_L (x,o): ground level concentration at the distance x from the line source.

q : line source emission intesity. Unit: m^3/ms.

The ratio (F) between the contribution from a line source and the crosswind integrated contribution from a point source reads:

$$F = \frac{\overline{S_p}}{S_L} = \exp (-0.5 (\frac{H}{\sigma_z})^2) \qquad (2.18)$$

By comparing the dispersion parameters in different experiments systematic deviation from the Gaussian formula is discussed in chapter 3.

3 RESULTS OF TRACER EXPERIMENTS IN THE SARPSBORG AREA

Dual tracer experiments were carried out to evaluate the contribution from different source groups to ground level concentration in episodes. The experiments were performed in Sarpsborg, a small urban area in southern Norway and accomplished in two test series, one in February and one in August 1983. A data report is written in Norwegian (Grønskei, 1984).

The source groups included ground level and elevated sources in an industrial complex and in a small urban area, further emission from car traffic. The different test areas in Sarpsborg are shown in Figure 3.

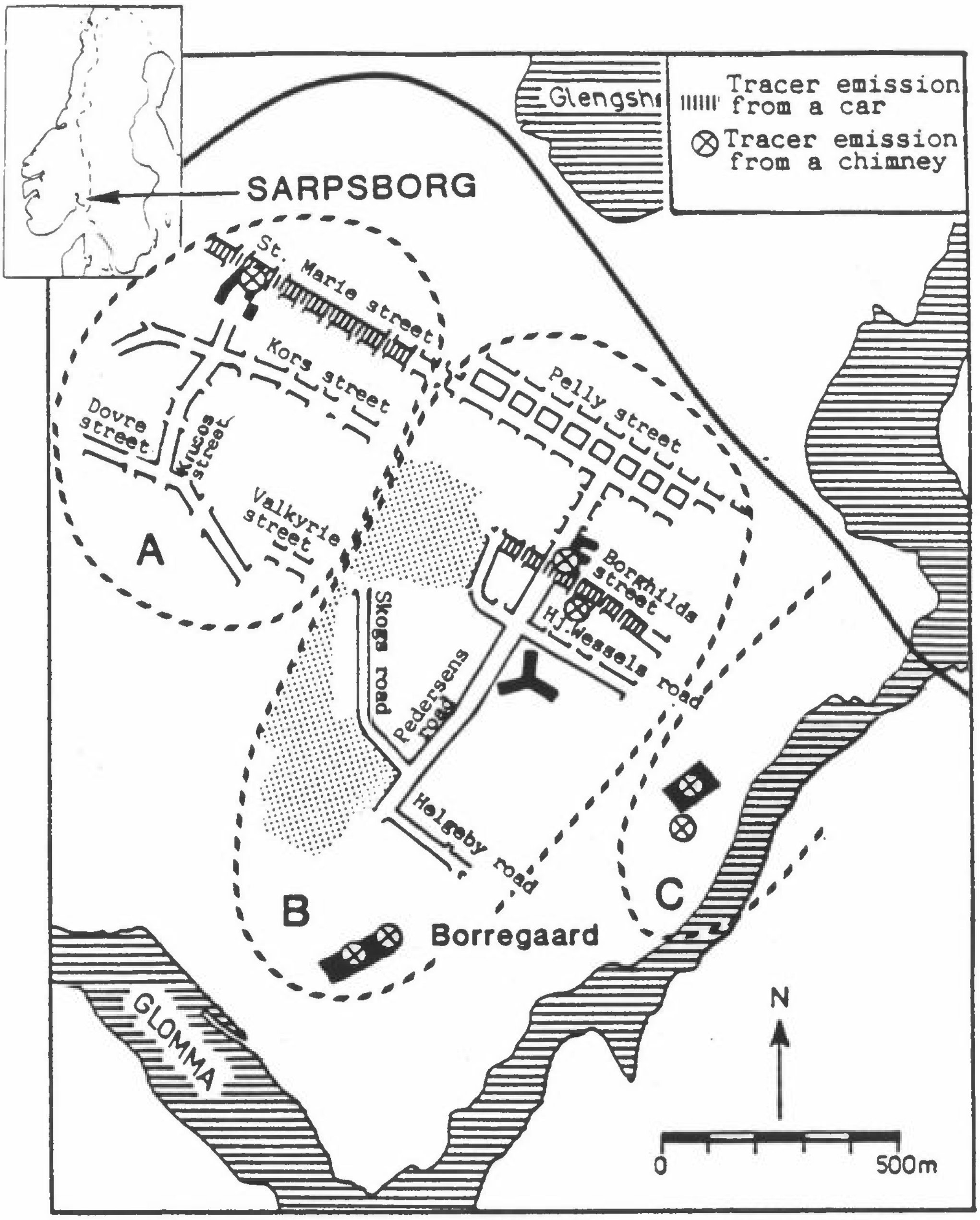

Figure 3: Areas for tracer experiments.
A: The area is used for experiments with wind from north-east.
SF_6 is emitted from a car driving in St. Marie street and $CBrF_3$ emitted from the chimney at Kruseløkka school marked ⊗ .
B: Wind from northeast:
SF_6 emission from a car in Borghilds street and $CBrF_3$ emission from the chimney at Borg school or at Borghilds street 10. The chimneys are marked by ⊗ .
Wind from southwest:
SF_6 emission from one of Borregaards chimneys. $CBrF_3$ emission at ground level adjacent to the chimney.
C: Wind from southwest:
SF_6 emission from one of Borregaards roof vents. $CBrF_3$ emission at ground level adjacent to the factory building. This area is characterized by about 20 m high roughness elements.

3.1 RESULTS OF TRACER EXPERIMENTS IN FEBRUARY

Seven dual tracer experiments were carried out in area B. Sulphur hexafluorid (SF_6) was emitted from a car driving back and forth in Borghilds street and $CBrF_3$ was emitted from an adjacent roof chimney (marked in Figure 3). Tracer samples were collected along cross-sections, Wessels road at a distance of 150 m, and Helgeby road at a distance of 720 m.

Two similar experiments were carried out in test area A recording concentrations at the distance of 200 m. The results describe the dispersion close to the ground in small towns under inversion conditions when the wind speed is low. The emission and dispersion conditions are shown in the Tables 1 and 2.

Table 1: Emission data for the dispersion experiments in Sarpsborg, February 1983.

Test No.	Test Date	Time	Q_{CBrF_3}	Q_{SF_6}	X_1	Point source location
			l/min	l/min	km	
1	14	1120-1145	2.0	2	0.50	Borg school
2	14	1437-1502	4.1	2	0.50	Borg school
3	15	0900-0925	2.8	2	0.50	Borg school
4	15	1120-1145	2.8	2	0.50	Borghilds str. 10
5	15	1400-1425	2.4	2	0.50	Borghilds str. 10
6	16	0908-0933	2.4	2	0.50	Borghilds str. 10
7	16	1050-1115	2.4	2	0.50	Borghilds str. 10
8	16	1445-1510	2.4	2	0.50	Kruseløkka school
9	17	0945-1000	2.4	2	0.50	Kruseløkka school
10	18	0900-0945	2.5	5.9	1.80	Moum
11	18	1000-1045	2.5	5.9	1.80	Moum

Q_{CBrF_3} : Emission of $CBrF_3$-tracer.
Q_{SF_6} : Emission of SF_6-tracer.
X_1 : Length of line source.

Table 2: Dispersion parameters for the tracer experiments in February 1983.

Test	Day	Time	Z	U_z	z_o	θ_z	θ_o	u_*	θ_*	L	N	R	1/L
			m	m/s	m	^0K	^0K	m/s	^0K	m	Parts of 8	W/m^2	m^{-1}
1	14	1130-1145	10	1.6	0.4	276.8	276.7	0.13	0.029	48	8/8	20.5	0.02
2	14	1447-1502	10	0.9	0.4	276.6	276.5	0.004	0.014	.6	8/8	- 1.4	1.75
3	15	0910-0925	36	2.3	0.4	276.45	276.6	0.030	0.033	7.6	8/8	- 1.4	0.13
4	15	1130-1145	36	2.4	0.4	276.85	275.8	0.027	0.035	6.4	8/8- 4/8	20.6/ 1.96	0.16
5	15	-	-	-	-						-		
6	16	0918-0933	36	2.3	0.4	269.8	269.4	0.065	0.031	21	0/8	-24	0.05
7	16	1100-1115	36	2.2	0.4	271.6	270.2	0.015	0.027	3.6	0/8	20.6	0.28
8	16	1455-1510	36	1.9	0.4	274.7	273.3	0.009	0.020	2.6	0/8	-49	0.38
9	17	0945-1000	36	1.3	0.4	266.4	264.2	0.001	0.006	0.5	0/8	-13	2.
10	18	0930-0945	36	2.2	0.03	266.3	264.6	0.008	0.018	1.9	0/8	-25	0.52
11	18	1000-1015	36	1.8	0.03	267.7	266.2	0.005	0.012	1.4	0/8	-13	0.71

Test number :
Day : Date in February 1983.
Time : Sampling time for tracer material.
Z : Measuring height of wind and temperature.
Z_o : Roughness estimated for the area of tracer experiment.
U_z : Windspeed measured in a mast outside the area.
θ_z : Potential temperature.
θ_o : Potential temperature close to the ground.
u_* : Friction velocity based on surface layer similarity theory.
$u_*\theta_* = -\frac{H}{C_p \varrho}$: Vertical flux of sensible heat
L : Monin-Obukhov length.
N : Cloudcover in parts of 8.
R : Radiative flux of heat based on observations of cloud-cover, height of the sun and snow-cover according to Hanssen-Bauer (1983)

The surface layer characteristics based on Busingers evaluation of the surface similarity theory are estimated using

- observation of wind speed 36 m above ground level outside the urban area.
- observation of the temperature profile from an open area adjacent to the test ground.
- the roughness parameter was estimated assumed to be 0.4 m over the urban area.

The values determined for σ_z downwind of the line source are shown in Figure 4. All tracer experiments were carried out under stabel atmospheric conditions. The Gaussian dispersion model for urban areas underestimated the value for σ_z, and it was not able to differentiate between the observed concentrations in the tracer experiments. Local data on scale and intensity of turbulence is needed to clarify the differences.

A dispersion model based on surface layer similarity theory as suggested by Chaudhry and Merony (1972), underestimate the observed tracer concentrations.

The results of dispersion of emission from an adjacent chimney are shown in Table 3.

Table 3: Scaled crosswind integrated concentration ($\overline{S_p}$) measured as a result of $CBrF_3$-tracer emission with the flue gas from a furnace chimneys.

Test number	I_1	u	Q	$\overline{S}_p^{\,1}$	x_1	Location
	10^5 ppt m	m/s	l/min	10^{-3} m^{-1}	m	
1	-	1.6	2	-		Borg school
2	6.1	0.9	4.1	8.0	200	Borg school
3	3.2	1.3	2.8	8.9	200	Borg school
4	7.2	1.2	2.8	18.5	140	Borghilds str. 10
5	-	-	-	-	-	Borghilds str. 10
6	7.2	2.4	2.4	43.2	140	Borghilds str. 10
7	6.4	2.3	2.4	36.8	140	Borghilds str. 10
8	-	1.9	2.4	-	200	Kruseløkka school
9	9.3	1.3	2.4	30.2	200	Kruseløkka school

I_1: Crosswind integrated concentration.
X_1: Distance from point of emission to cross-section.

The concentration variation along Wessels street as a result of line source emission amounts to 25-40% of the average concentrations indicating that coherent vertical circulations exist along the line source mixing tracer material in the atmosphere.

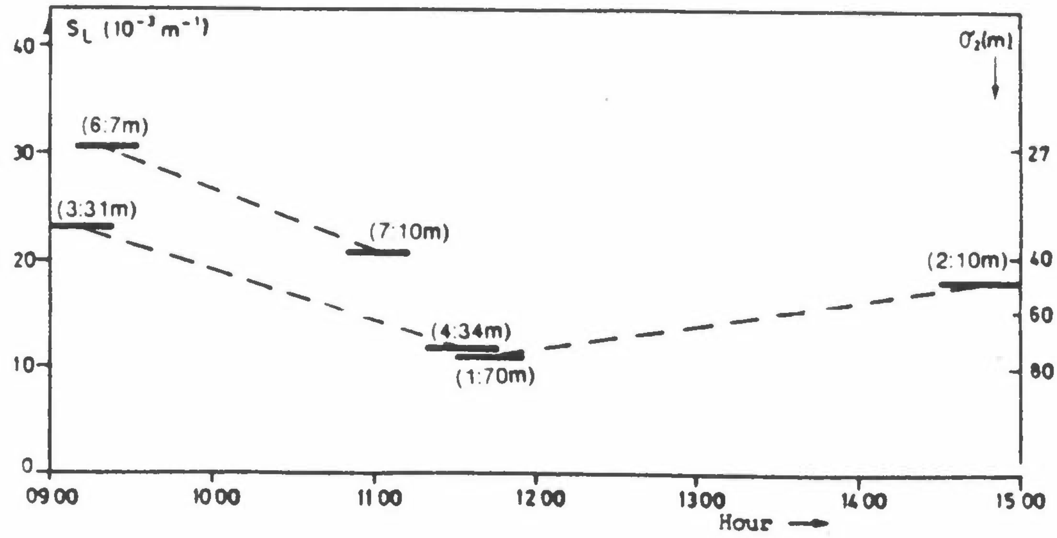

Figure 4: Scaled concentrations (S_L) in Wessels street, as a function of hour of the day. The tracer concentrations as a result of emission from a driving car in Borghilds street, are marked as horizontal lines during the hour of the experiment.
The test number and the calculated σ_z-value based on surface layer theory are given in paranthese for each experiment.

To further test the theory and the method of tracer experiments two tests were carried out adjacent to the mast outside the urban area. The vertical profile of tracer material was determined along the mast as a result of emission from two line sources.

The values of F determined for the different experiments is shown in Table 4.

Table 4: The ratio for scaled concentrations for emission from car traffic and emission from a furnace.

Test number	U	S_{L_1}	S_{L_2}	S_p	$F=\frac{\bar{S}_p}{S_{L_1}}$	Point source location
	m/s	$10^{-3}\ m^{-1}$	$10^{-3}\ m^{-1}$	$10^{-3}\ m^{-1}$		
1	1.6	11.4	-	-	-	Borg school
2	0.9	17.7	-	8.0	0.45	Borg school
3	1.3	23.1	-	8.9	0.38	Borg school
4	1.2	10.9	-	18.5	1.7	Borghilds str. 10
5	-	-	-	-	-	Borghilds str. 10
6	2.4	30.7	9.6	43.2	1.4	Borghilds str. 10
7	2.3	20.7	5.8	36.8	1.8	Borghilds str. 10
8	1.9	10.0	-	-	-	Kruseløkka school
9	1.3	21.2	-	30.2	1.5	Kruseløkka school

The results of dispersion of emission from an ajacent chimney are shown in Table 3 and simultaneous dispersion of emission from ground level and from roof level emission are compaired in Table 4 for the experiments in the urban area.

To explain the observations of F (see equation 2.18) both effective emission height and a large scale of turbulence have to be taken into account. The conditions close to the emission are of particular importance.

3.2 RESULTS OF TRACER EXPERIMENTS IN AUGUST

To examine the effect of the industrial complex on dispersion seven dual tracer experiments were performed in test area B with wind from southwest.

SF_6 was emitted from a chimney. As the chimney height was 50% higher than the building the dispersion was expected to be influenced by the building, but the tracer is not expected to be trapped in the wake of the building.

The second tracer ($CBrF_3$) was emitted from a ground level point source located at the downwind part of the building.

The emission data are given in Table 5 and the results of meteorological measurements are given in Table 6.

Table 5: Data for emission from a factory building. Experiments in August 1983.

Test	Date	Time	Q_{SF_6} (l/min)	Q_{CBrF_3} (l/min)
B1	9	1725-1740	3	4.1
B2	9	2005-2020	3	4.1
B3	10	1445-1500	3	4.1
B4	10	1715-1725	3	8.2
B5	11	0900-0915	3	8.2
B6	11	1045-1100	3	8.2
B7	11	1430-1445	3	8.2

Q_{SF_6} : Emission intensity for SF_6.
Q_{CBrF_3} : Emission intensity for $CBrF_3$.

Table 6: Data for dispersion parameters determined from meteorological measurements outside the test ground. Experiments in August 1983.

Test number	Day	Time	Z	U_z	Z_o	Θ_z	Θ_o	u_*	Θ_*	L	1/L
			m	m/s	m	^0K	^0K	m/s	^0K	m	$10^{-2}\ m^{-1}$
B1	9	1725-1740	36	6.2	0.03	293.9	294.5	0.27	-0.13	-48.5	- 2
B2	9	2005-2020	36	3.6	0.03	290.9	290.2	0.02	0.01	2.5	40
B3	10	1445-1500	36	6.2	0.03	290.25	291.1	0.27	-0.19	-33.2	- 3
B4	10	1715-1725	36	6.4	0.03	289.35	289.7	0.27	-0.08	-73.5	- 1
B5	11	0900-0915	36	2.7	0.03	290.9	292.4	0.14	-0.36	- 4.8	-20
B6	11	1045-1100	36	3.7	0.03	292.55	294.4	0.19	-0.35	- 8.4	-12
B7	11	1430-1445	36	4.4	0.03	294.05	295.5	0.21	-0.32	-12.2	- 8

For symbol explanation: see legend to table 2.

Figure 5 shows scaled maximum concentrations at 800 m distance. The values are given as functions of the inverse Monin-Obukhov´s length. Results of the dual tracer observations in each experiment are connected by vertical lines.

Calculated values, using NILUs Gaussian dispersion model and urban σ-values, are presented as broken lines adjacent to the observed values in the figure. It is seen that the calculated maximum concentrations compare reasonably well with the observed tracer concentrations except for ground level emission in stable atmospheric conditions.

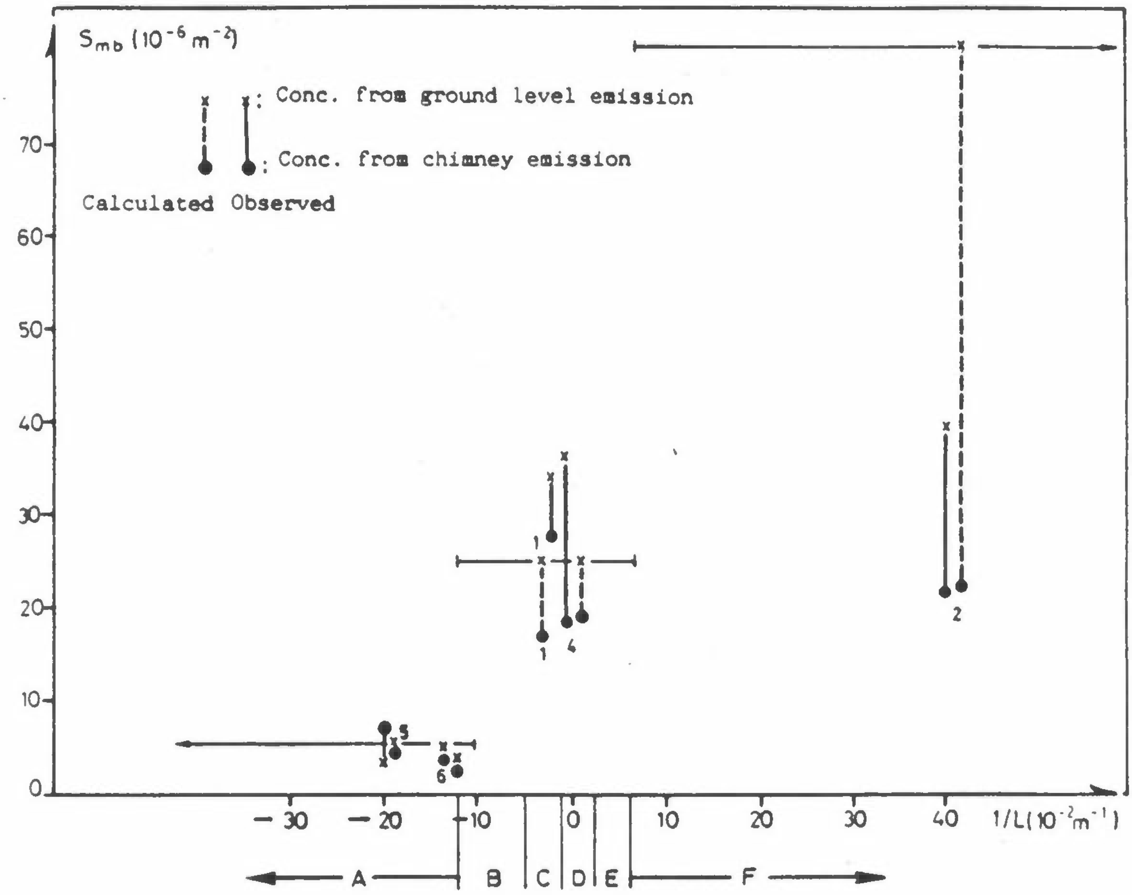

Figure 5: Calculated and observed maximum concentrations (800 m from the factory building) as a result of simultaneous emissions from a chimney (●) and from ground level (x). Calculated values for high and low level emissions are connected by a broken line. The observed values are connected by a full line. The scaled concentrations are given as a function of the inverse Monin-Obukhov´s length (1/L). The horizontal axis is further divided in dispersion classes (A-F).

Table 7 show observed and calculated values of horizontal and vertical σ-values. The observed σ_y-values for the two tracer components compare well. Both the values are smaller than the values to be expected in urban areas, larger than the values expected in the countryside.

Table 7: Calculated and observed σ-values (σ_y and σ_z). The calculated values are given for three stability classes (unstable-U, neutral-N and stable-S).

Test number	Stab.	X	σ_{yo}	σ_{yBB}	σ_{yBL}	σ_{zo}	σ_{zBB}	σ_{zBL}
		m	m	m	m	m	m	m
B1	N	850	74- 75	125	60	121	102	27
B1	N	1350	98-121	175	92	165	141	48
B2	S	850	62- 68	82	29	118	46	12
B4	N	850	76- 78	125	60	109	102	27
B5	U	1350	178-216	304	205	245	456	150
B6	U	850	77-122	219	135	726	262	90
B7	N-U	650	109-116	103-180	45-105	76	25-190	41

σ_{yo}, σ_{zo} : Dispersion parameters estimated from the observed distribution of tracer concentrations. Two numbers for σ_{yo} are determined for the $CBrF_3$-distribution and for the SF_6-distribution respectively.

σ_{yBB}, σ_{zBB} : Dispersion parameters based on MacElroy-Poolers formulaes for urban areas.

σ_{yBL}, σ_{zBL} : Dispersion parameters for areas with small roughness.

To determine the σ-values in the vertical direction the tracer distribution as a result of ground level emission is used. In some experiments the observed values compare well with values calculated for urban areas.

4 CONCLUDING REMARKS

To improve the description of low level dispersion a tentative method to include the effect of roughness elements is suggested.

Data on local eddy velocity components is of primary importance for the description close to the source. Available methods for calculating the eddy components may be used in well defined wind conditions. However, in weak, wind conditions the description becomes dependent on local measurements of the eddy velocity components (see Figure 1 and equation 2.7).

The dispersion effect of atmospheric surface layer structure is taken into account by considering horizontal variation in the moments of vertical concentration distribution. For this investigation a numerical solution of the vertical diffution equation is avoided by considering situations with simple profiles for wind and turbulent exchange. The horizontal variation of the vertical dispersion parameter depend on the vertical variation of the scale of turbulence. By referring to the literature it is assumed that the scale of turbulence approaches a constant value determined either by measurements of the vertical eddy velocity or by estimating the Monin-Obukov length.

To combine the description of phase one dispersion (dependent on local turbulence statistics) and the description of phase two dispersion (dependent on surface layer structure) a smoothed variation in the scale of turbulence with height is prescribed.

Results from studies on canopy flow were used to estimate the scale at the height of the roughness elements. The constant value estimated for the surface layer structure is used as an asymtotic value for increasing hight above the ground.

The results of tracer experiments in stable winter situations show variations of a factor two in observed values around the vertical dispersion calculated by the existing model. Data on local turbulence statistics are probably important for the description of the observed concentrations 150 m downwind of a line source in a small urban area. Calculated values based on surface layer theory underestimated the observed tracer concentrations. On the other hand results of tracer experiments outside the urban area indicated that the vertical dispersion could be described by the surface layer similarity theory.

Seven experiments accomplished in August described the influence of roughness elements downwind of an industrial area in different stability categories. The calculated and observed maximumconcentrations at the distance of 800-1400 m from the sources compaired fairly well exept for the dispersion in a stable atmospheric surface layer. The inverse value of Monin-Obukhov length was the best single meteorological parameter characterizing dispersion at the distance of 800-1400 m.

In stable atmospheric situations the standard deviation of vertical eddy velocity (σ_w) are influenced by local gravity waves that may not be important for the description of dispersion far from the source. It remains to be seen if these observations should enter the description of the surface layer structure.

The evaluation of the tentative model suggested in chapter two should include simultaneous measurements of local turbulence in the area of emission, and further development of the description on intermediate and long distances may be needed.

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APPENDIX A

CHANGE IN VERTICAL POLLUTION DISTRIBUTION

Any function of the vertical coordinate, z, may be averaged over the pollution distribution c(x,z):

$$\bar{f}(x) = \frac{\int_{z_1}^{z_2} f(z)c(x,z)dz}{\int_{z_1}^{z_2} c(x,z)dz} \tag{A1}$$

The horizontal variation in the f-function reads:

$$\frac{d\bar{f}(x)}{dx} = \frac{\int_{z_1}^{z_2} (f(z) - \bar{f}(x)) \frac{\partial c(x,z)}{\partial x} dz}{\int_{z_1}^{z_2} c(x,z)dz} \tag{A2}$$

Specifically, different moments of the c-distribution with respect to z may be calculated in this way. The horizontal variation in concentration is given by the diffusion equation simplified to describe the problem under consideration. As an example, the dispersion of pollution from a line source close to the ground is described by the equation:

$$u(x,z) \frac{\partial c(x,z)}{\partial x} = \frac{\partial}{\partial z} (K(x,z) \frac{\partial c(x,z)}{\partial z}) \tag{A3}$$

where: u(x,z) = horizontal wind speed
K(x,z) = coefficient of turbulent exchange

For simple vertical profiles of u and K (both constant with respect to x) the equation may be solved analytically given the boundary conditions. When the analytical procedure is not applicable, numerical methods require a high spatial resolution to give reasonable accuracy. An alternative way is to specify the variation in the moments of the vertical pollution distribution.

Assuming $u(x,z) \neq 0$, Equation (A2) reads:

$$\frac{d\bar{f}}{dx} = \frac{\int_{z_1}^{z_2} (f(z) - \bar{f}) \frac{1}{u} \frac{\partial}{\partial z} (K \frac{\partial c}{\partial z}) \, dz}{\int_{z_1}^{z_2} c \, dz} \tag{A4}$$

Partial integration of Equation (A4) gives:

$$\frac{d\bar{f}}{dx} = \frac{1}{\int_{z_1}^{z_2} c \, dz} \left\{ \Big|_{z_1}^{z_2} [(f(z) - \bar{f}) \frac{K}{u} \frac{\partial c}{\partial z} - cK \frac{\partial}{\partial z} (\frac{f(z) - \bar{f}}{u})] + \int_{z_1}^{z_2} \frac{\partial}{\partial z} K \frac{\partial}{\partial z} (\frac{f(z) - \bar{f}}{u}) c \, dz \right\}$$

$$= \frac{1}{\int_{z_1}^{z_2} c \, dz} [\Big|_{z_1}^{z_2} [(f - \bar{f}) \frac{K}{u} \frac{\partial c}{\partial z} - c \frac{K}{u} (\frac{df}{dz} - \frac{\partial(\ln u)}{\partial z} (f - \bar{f})] +$$

$$+ \int_{z_1}^{z_2} (\frac{\partial}{\partial z} (\frac{K}{u}) [\frac{df}{dz} - \frac{\partial(\ln u)}{\partial z} (f - \bar{f})] + \frac{K}{u} [\frac{d^2 f}{dz^2} -$$

$$- \frac{\partial(\ln u)}{\partial z} \frac{df}{dz} - \frac{\partial^2 (\ln u)}{\partial z^2} (f - \bar{f})])c \, dz \tag{A5}$$

From Equation (A5) it is seen that $\frac{K}{u}$, $\frac{d}{dz}(\frac{K}{u})$, and the vertical distribution of ln u determines the atmospheric influence on all moments of the pollution distribution.

These parameters are then describing the growth of the pollution cloud in the atmospheric boundary layer.

Close to the ground:

$$u \frac{\partial c}{\partial x} \rightarrow 0,$$

and $z \rightarrow z_o$

where z_o = the roughness length.

The vertical flux of pollution close to the ground is described by deposition processes.

For dispersion calculations, empirically based formulae, considering horizontal variation in the second moment of vertical pollution distribution only (i.e. the Gaussian plume formula) are used. When the atmospheric dispersion conditions are horizontally homogeneous, the accuracy of the results is satisfactory. However, with horizontal change in roughness and/or heatflux from the ground, the vertical diffusivity change, and it is necessary to include this in specific dispersion calculations. Using the first and second moment for dispersion considerations, the following equations may be written.

The first moment:

$$f(z) = z \; ; \qquad \bar{f}(z) = \bar{z}(x),$$

The second central moment:

$$f(z) = (z-\bar{z})^2 \; ; \qquad f(x) = \overline{(z-\bar{z})^2} = \overline{z^2} - \bar{z}^2 .$$

Using Equation (A5) the horizontal derivations of these moments may be written:

$$\frac{d\bar{z}}{dx} = \frac{1}{\int_{z_1}^{z_2} c\, dz} \left[\Big[(z - \bar{z}) \frac{K}{u} \frac{\partial c}{\partial z} - c\, K \frac{\partial}{\partial z} \left(\frac{z - \bar{z}}{u}\right) \Big]_{z_1}^{z_2} + \right.$$

$$+ \int_{z_1}^{z_2} \frac{\partial}{\partial z} \left[K \frac{\partial}{\partial z} \left(\frac{z - \bar{z}}{u}\right)\right] c\, dz \qquad \text{(A6)}$$

$$\frac{d\overline{z^2}}{dx} = \frac{1}{\int_{z_1}^{z_2} c\, dz} \cdot \left[\Big[(z^2 - \overline{z^2}) \frac{K}{u} \frac{\partial c}{\partial z} - cK \frac{\partial}{\partial z} \left(\frac{z^2 - \overline{z^2}}{u}\right) \Big]_{z_1}^{z_2} + \right.$$

$$\left. + \int_{z_1}^{z_2} \frac{\partial}{\partial z} \left[K \frac{\partial}{\partial z} \left(\frac{z^2 - \overline{z^2}}{u}\right)\right] c\, dz \right] \qquad \text{(A7)}$$

DISPERSION OF POLLUTION FROM A LINE SOURCE CLOSE TO THE GROUND

Equation (A6) is integrated from the ground to a height z_2. Within the area of consideration:

$$c = 0, \text{ and } \frac{\partial c}{\partial z} = 0, \text{ for } z = z_2$$

When dry deposition is small:

$$K \frac{\partial c}{\partial z} = 0, \text{ for } z = z_1$$

According to Equation (A6):

$$\frac{d\bar{z}}{dx} = \frac{1}{\int_{z_1}^{z_2} c\, dz} \left[c(z_1) \left(K \left(\frac{\partial \left(\frac{z - \bar{z}}{u}\right)}{\partial z} \right)_{z=z_1} + \int_{z_1}^{z_2} \frac{\partial}{\partial z} \left(K \frac{\partial}{\partial z} \left(\frac{z - \bar{z}}{u}\right) c\, dz \right] \right. \right. \qquad \text{(A8)}$$

$$\frac{d\overline{z^2}}{dx} = \frac{1}{\int_{z_1}^{z_2} c\ dz}\left[c(z_1)K\frac{\partial}{\partial z}\left(\frac{z^2 - \overline{z^2}}{u}\right)_{z=z_1} = \int_{z_1}^{z_2} \frac{\partial}{\partial z}\ \left[K\frac{\partial}{\partial z}\left(\frac{z^2 - \overline{z^2}}{u}\right)\right]c\ dz\right] \tag{A9}$$

The horizontal derivatives of the vertical moment of the c-distribution may be calculated knowing the c-, the K-, and the u-profiles.

The following parameters are defined:

$$c = \bar{c} + \Delta c, \text{ when } z \leq \bar{z}, \text{ and } \int_{z_1}^{z_2} c dz = \bar{z}\bar{c}.$$

Equation (A8) may then be written:

$$\frac{d\bar{z}}{dx} = \left(\frac{K}{u}\right)_{z=\bar{z}} \frac{1}{z} + \frac{1}{\bar{c}\bar{z}}\left[\left(\Delta c K \frac{\partial\left(\frac{z - \bar{z}}{u}\right)}{\partial z}\right)_{z=z_1} + \right.$$

$$\left. + \int_{z_1}^{\bar{z}} \Delta c \frac{\partial}{\partial z}\left(K \frac{\partial}{\partial z}\left(\frac{z - \bar{z}}{u}\right)\right)dz + \int_{\bar{z}}^{z_2} c\ \frac{\partial}{\partial z}\left(K\ \frac{\partial\left(\frac{z - \bar{z}}{u}\right)}{\partial z}\right)dz\right] \tag{A10}$$

The following transformation of integration variable is made:

$$y = K\ \frac{\partial\left(\frac{z - \bar{z}}{u}\right)}{\partial z}$$

If it is further assumed that $\frac{dy}{dz} > 0$:

$$\frac{d\bar{z}}{dx} = \left(\frac{K}{u}\right)_{z=\bar{z}} \frac{1}{\bar{z}} + \frac{1}{\bar{c}\bar{z}}\left[\Delta C(z_1)y_1 + \int_{y_1}^{\left(\frac{K}{u}\right)_{z=\bar{z}}} \Delta C\ dy + \int_{\left(\frac{K}{u}\right)_{\bar{z}}}^{y_2} C dy\right] \tag{A11}$$

From the definition of $\bar{z}$ and ΔC it follows that:

$$\int_{z_1}^{\bar{z}} \Delta C\ dz = - \int_{\bar{z}}^{z_2} C dz + \bar{C}z_1 \tag{A12}$$

Numerical calculations show that avoiding extreme stable or unstable conditions in the surface boundary layer the integration variable y in equation (A10) may be approximated by a linear function of height z:

$$y = a(z - z_1) + y_1$$

Using this relation equation (A12) and (A11) reads:

$$\int_{y_1}^{K\left(\frac{K}{u}\right)_{z-\bar{z}}} \Delta C \, dy + \int_{\left(\frac{K}{u}\right)_{z-\bar{z}}}^{y_2} C \, dy = 0 \qquad \text{(A12b)}$$

$$\frac{d\bar{z}}{dx} = \left[\left(\frac{K}{u}\right)_{z=\bar{z}} - y_1\right] \frac{1}{\bar{z}} + \frac{C\,(z_1)}{\bar{C}\,\bar{z}}\, y_1 \qquad \text{(A11b)}$$

When K and u are constant with respect to z, the Gaussian plume formula is a solution of Equation (A3), and Equations (A8) and (A9) may be written as:

$$\frac{d\bar{z}}{dx} = \frac{K}{u\bar{z}} \cdot \frac{c\,(z_1)}{\bar{c}} \qquad \text{(A13)}$$

$$\frac{d\bar{z}^2}{dx} = \frac{2K}{u} \qquad \text{(A14)}$$

Considering a Gaussian plume with a standard deviation denoted by σ_z, the following interrelations are found:

$$\frac{c\,(z_1)}{\bar{c}} = \frac{2}{\pi}, \quad \bar{z} = \sqrt{\frac{2}{\pi}}\, \sigma_z, \quad \text{and} \quad \frac{d\sigma_z}{dx} = \frac{K}{u\sigma_z}$$

These expressions correspond well with the formula previously proposed (Pasquill, 1975):

$$\frac{d\bar{z}}{dx} = a \cdot \left(\frac{K}{uz}\right)^b_{z=\bar{z}} \qquad \text{(A15)}$$

According to Equation (A13) : $a = \frac{c(z_1)}{\bar{c}} = \frac{2}{\pi}$, $b = 1.0$. When using data on K and u profiles defined by similarity theory for the surface layer, it is found that the additional terms in Equation (A11) become small for a practical range of thermal stratification. Pasquill indicates that Equation (A15) may be used when the Monin-Obukhov length (L) is less than -7 m or larger than 4.

When an elevated source is considered, z_1 may be selected as the height of the maximum concentration in the plume, when there is no net flux of pollution across this level; the horizontal change in the vertical dispersion parameter may be considered in the same way.

In this way Pasquill´s proposal is not restricted to a ground level source.

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Grenselagsteori	Spredningsberegning	Ruhetselementer

REFERAT (maks. 300 anslag, 7 linjer)
Det beskrives en metode for å ta hensyn til ruhetselementer i beregning av vertikalspredning. Metoden bygger på data for turbulensintensitet og turbulensskala. Intensiteten kan eventuelt beregnes når vinden er veldefinert og over 1 m/s. Ved svak vind bør intensiteten måles. Turbulensskalaen er proporsjonal med ruhetselementene nær bakken og nærmer seg asymptotisk en verdi bestemt av atmosfærens grenselagsstruktur.

TITLE

ABSTRACT (max. 300 characters, 7 lines)
A tentative method to include the dispersion effect of roughness elements is suggested. The method is based on data for the intensity and scale of turbulence. The intensity may be calculated in well defined wind conditions. In weak or variable wind conditions the turbulence intensity should be measured. The scale of turbulence is assumed to be proportional to the height of the roughness elements close to the ground and approaches a constant value with increasing height. The asymtotic value is determined by the surface layer structure.

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