NILU
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DISPERSION PARAMETERS DETERMINED FROM MEASUREMENTS OF WIND FLUCTUATIONS (σ_θ), TEMPERATURE AND WIND PROFILES

BJARNE SIVERTSEN

Prepared for the NATO/CCMS 9th International Technical Meeting on Air Pollution Modeling and its Application, Toronto August 28-31, 1978.

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DISPERSION PARAMETERS DETERMINED FROM MEASUREMENTS OF WIND FLUCTUATIONS (σ_θ), TEMPERATURE AND WIND PROFILES

by

Bjarne Sivertsen
Norwegian Institute for Air Research
Lillestrøm, Norway

Abstract. The applicability of using wind, turbulence and temperature data from the NILU automatic weather station to estimate dispersion parameters σ_y and σ_z has been investigated. The standard deviations of the horizontal wind direction fluctuations were used to estimate σ_y. Vertical eddy diffusivities calculated from similarity theory using wind and temperature profiles, were used to estimate σ_z.

Calculated values of σ_y and σ_z were compared to measured values determined from SF_6-tracer concentration distributions obtained during diffusion experiments.

The horizontal spread was best simulated by $\sigma_y = \sigma_\theta \cdot f \cdot x$ where f is a function of transport time (t): $f = (1+0.055t^{0.5})^{-1}$ for a surface roughness (z_o) of about 5 cm, $f = 4.6 \cdot t^{-1/3}$ for $z_o \sim 0.5$m. For unstable conditions σ_z was best simulated by $\sigma_z = \kappa u_* x / \phi_h u$.

1 Introduction

When applying Gaussian type dispersion models, which for many purposes might represent a useful tool in estimating air pollution concentrations, the results are sensitive to the choice of dispersion parameters. The so called Pasquill-Gifford-Turner (PGT) curves for σ_y and σ_z [1] have been used, and misused, for about 17 years. It has been pointed out that the PGT curves apply to a sampling time of about 3 minutes, a surface roughness of a few centimeters and a latitude of about 50°.[2] The selection of a proper σ-curve has been based upon atmospheric stability classes determined from observations of cloud cover and wind speed or temperature change with height.[3] The dispersion class specifies both lateral and vertical spread. During the last few years several authors have emphasized the importance of estimating the lateral and vertical dispersion parameters separately.[4,5] The use of this "split sigma" method has been demonstrated to be most important during low wind speed inversion conditions.[6] To improve plume calculations, it has been recommended to estimate σ_y from measurements of lateral turbulent velocity fluctuations σ_v, or from the standard deviation of wind direction fluctuations σ_θ, and σ_z from estimates of the vertical heat flux rather than from PGT curves.[7]

2 Measurements

An electronic monitor for measuring meteorological parameters including wind statistics, developed and tested at the Norwegian Institute for Air Research (NILU)[8], was used to collect dispersion data. This automatic weather station is completely digitized and has a capacity of 2 months unattended operation. Output signals are logged every five minutes on magnetic tape. Five minute average standard deviation of horizontal wind direction fluctuations (σ_θ), wind speed, wind direction, and temperature at two levels have been recorded during the past two years at different sites in Norway. Data were taken at either 2 m and 10 m or at 36 m. Surface roughness at the different sites ranged from 5 cm to 60 cm.

Dispersion experiments were carried out in the atmospheric surface layer at 3 sites, using sulfur hexafluoride (SF_6) as a tracer. The tracer was usually released at 1 m above the ground. Sequential automatic air samplers permitted the collection of 15-minute average samples at 20 points downwind from the source. Instantaneous samples were also collected along traverses downwind.[9]

3 σ_θ-statistics

The cumulative frequency distribution of 5-minute average values of σ_θ at different sites is presented in Figure 1. The σ_θ-statistics vary from one site to another. Apart from being a function of sampling height above the ground, as demonstrated by Pendergast and Crawford[10], the frequency distribution of σ_θ is also dependent upon the surface roughness at the site. The median value of σ_θ varies from 5 deg for a smooth snow covered surface, to 12 deg for a rough inland site. Measurements of σ_θ in the atmospheric surface layer may only represent the local turbulence generated by the roughness of the upwind surfaces. These characteristics of σ_θ should be considered when σ_θ data are to be applied in dispersion calculations.

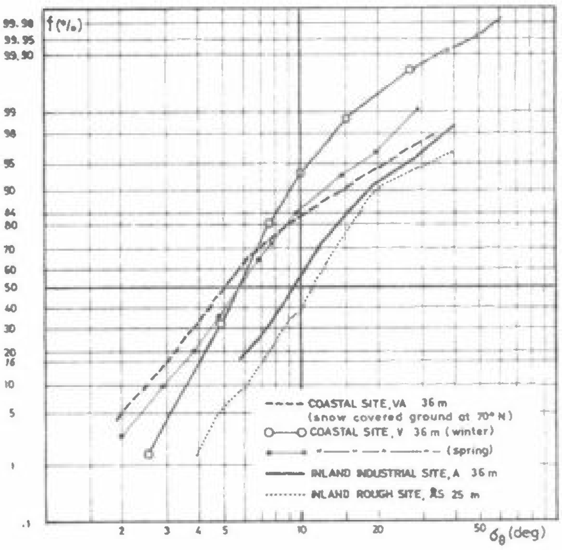

Figure 1: Cumulative frequency distribution of σ_θ at different sites.

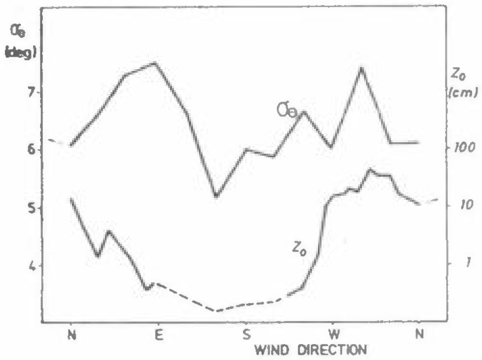

Figure 2: Average σ_θ and surface roughness values as a function of wind direction. (site V).

In Figure 2 the average σ_θ values from one site are presented together with calculated surface roughness length as a function of wind direction. The roughness lengths (z_0) were estimated from wind profile measurements during near neutral conditions assuming a logaritmic wind profile:

$$u_z = u_* \cdot \ln(z/z_0)/\kappa \qquad (1)$$

solving z_o from measurements of wind speed u_1 and u_2 at two levels z_1 and z_2:

$$z_o = \exp \frac{u_2 \ln z_1 - u_1 \ln z_2}{u_2 - u_1}$$

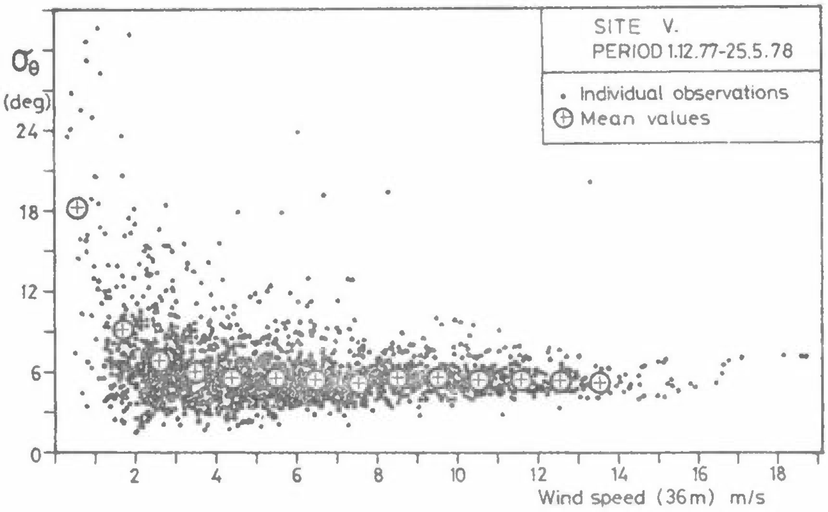

Figure 3: σ_θ versus wind speed measured at a 36 m tower, coastal site.

Observations of σ_θ and wind speed at the 36 m level from a coastal site are presented in Figure 3. An inverse relation between σ_θ and wind speed is clearly evident, showing an enhanced wind direction variation for wind speeds less than ∿3 m/s. For wind speeds higher than 3 m/s σ_θ approaches 6 deg. To further demonstrate the diversity in σ_θ, average σ_θ values are presented as functions of wind direction at wind speed in Figure 4. For low wind speeds average σ_θ values varies considerably; from >10 deg for winds from N, E and SW to <5 deg for winds from S. For wind speeds above 4 m/s, the average σ_θ is between 5 and 6 deg, except for wind from N, where the up-wind surface roughness is large.

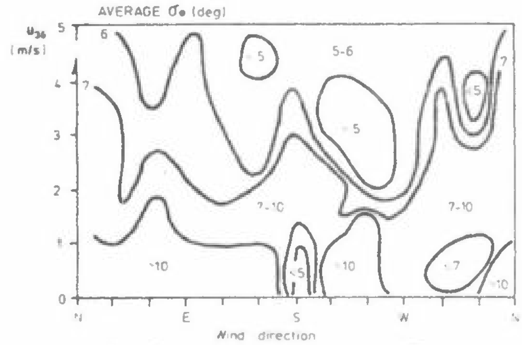

Figure 4: Average σ_θ values (in deg) as functions of wind direction and wind speeds at site V.

4 σ_θ versus stability classification parameters

The stability calssification from temperature lapse rate measurements as a method for determining dispersion parameters from PGT-curves, has been dmonstrated to greatly underpredict σ_y under very light wind speed, stable conditions.

The relationship between σ_θ and a bulk Richardson number $RB=dT_{36-10}/u^2$ and between σ_θ and dT_{36-10} is presented in Figure 5.

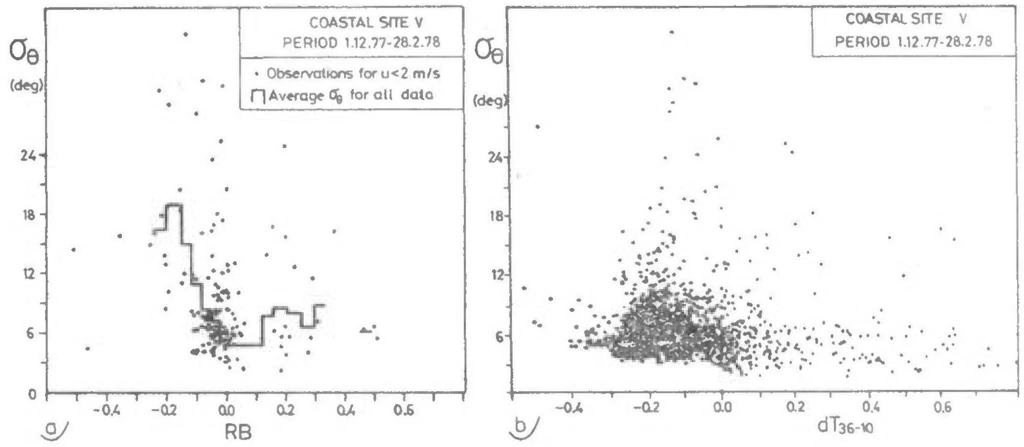

Figure 5: Observations of σ_θ versus:
a) Bulk Richardson number $RB=dT_{36-10}/u^2$
b) Temperaturedifference dT_{36-10} between two levels; 36 m and 10 m.

These data show the inadequacy of dT or RB to represent σ_θ. The spread of data points is considerable. In Figure 5a the largest average σ_θ value; 18 deg, occurs for RB ≃ -0.2. Values of σ_θ decrease to 5.6 deg for RB = 0 (neutral stability) and then increase again for positive values of RB (stable conditions).

The individual observations plotted as points in Figure 5, show that high values of σ_θ, i.e. large horizontal spread, might occur for all values of RB and dT. This emphasizes the importance of applying a "split sigma" method for estimating the dispersion of air pollutants. When applying the data from meteorological towers, horizontal and vertical dispersion should be estimated separately.

5 Dispersion data from SF_6 tracer experiments

To test different methods for estimating σ_y and σ_z based upon data from the NILU automatic weather station, diffusion experiments were carried out at 3 different sites during the last few months. Table 1 summarizes the data obtained during these studies.

Table 1: Dispersion experiment data for surface releases.
Met. data taken at 10 m and 2 m.

Test no	Date	Hour	Site	$\bar{u}$ (m/s)	dT_{10-2} deg	σ_θ rad	Height for σ_θ-meas. (m)	distance, x (m)	σ_y (obs) (m)	σ_z (estim) (m)
1	1.3.78	11	K	2.2	-0.15	0.23	10	130	15	3
								850	110	25
2	30.3.78	10	K	4.1	-0.5	0.26	10	130	14	26
								850	93	108
4	6.6.78	17	K	4.0	-0.7	0.27	10	130	37	8
								850	155	57
		18	K	4.0	-0.5	0.34	10	850	187	48
5	7.5.78	14	K	3.7	-0.9	0.29	10	130	35	13
								850	108	34
		15	K	3.2	-1.4	0.4	10	850	151	13
6	29.5.78	13	V	4.2	-0.7	0.18*	36	100	29	4
								300	65	9
		14	V	3.7	-0.8	0.21*	36	100	34	4
							36	300	64	9
7	26.7.78	10	A	1.6	-0.7	0.26*	36	950	116	28
		13	A	2.0	-0.6	0.15*	36	950	124	23
		17	A	1.8	-0.7	0.16*	36	900	97	21

*) σ_θ measured at 36 m

The crosswind standard deviations σ_y were obtained from 15 minute average SF_6 concentrations taken along cross wind traverses. The values were calculated from the best fit gaussian curve to the concentration data. The vertical standard deviations σ_z were estimated from mass balance calculations. The tracer data were integrated to provide average flux of tracer passing through the traverse area assuming gaussian distribution in the vertical. It should be noticed that σ_θ data from site A and V were measured at 36 m: This might lead to reduced σ_θ values compared to the measured σ_y from ground level releases.

For comparison the observed values of σ_y and σ_z are presented on PGT curves in Figure 6.

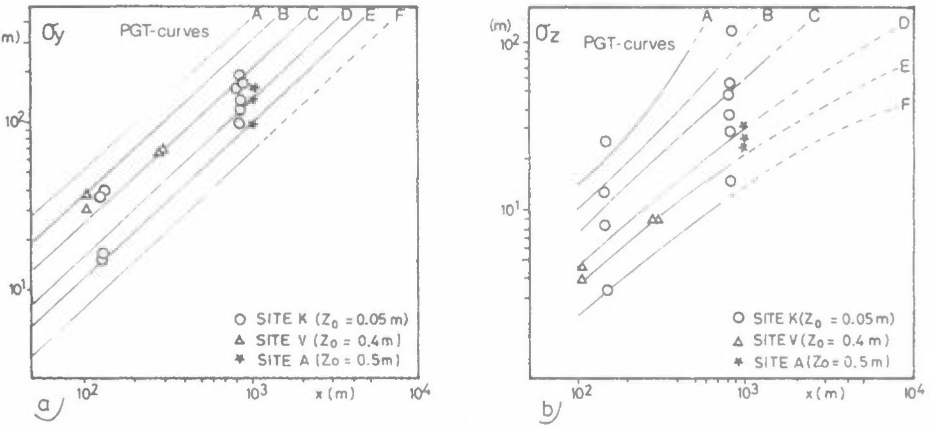

Figure 6: a) Crosswind standard deviation σ_y of tracer material
b) Vertical standard deviation σ_z of tracer material. Plotted on standard PGT curves as a function of down wind distance.

6 Estimates of the horizontal dispersion parameter, σ_y

Several methods for estimating σ_y from measurements of the horizontal wind direction fluctuations σ_θ (in radians) have been suggested. For example Cramer et al.[11] used a power law in x:

$$\sigma_y = \sigma_\theta \cdot x_r \; (x/x_r)^P \qquad (3)$$

where x_r is a reference length and x is the distance in metres.

Pasquill [14] recommends, based upon Taylors statistical treatment of diffusion to estimate σ_y from:

$$\sigma_y = \sigma_\theta \cdot x \cdot f(t/t_L) \qquad (7)$$

where t is the travel time ($\simeq x/\bar{u}$) and t_L is the Lagrangian integral time scale. Draxler [15] analyzed experimental data, and found that the function f could be expressed by

$$f = \frac{1}{1 + a(t/T_i)^{\frac{1}{2}}} \qquad (8)$$

where T_i is the diffusion time required for f to become 0.5, and α is an empirical constant.

From the experimental data presented in Table 1 the σ_y/σ_θ ratio is plotted in Figure 7 as a function of distance, x (in metres). The range of data from various U.S. tests [12],[13] is also presented in Figure 7. The best fit curves to our diffusion data for site K ($z_o \simeq$ 5cm) yield:

$$\sigma_y = 2.2 \cdot \sigma_\theta \cdot x^{0.78} \qquad (5)$$

At site V and A, where the estimated roughness length is 0.4 m and 0.5 m respectively σ_y can be expressed by:

$$\sigma_y = 6.5 \cdot \sigma_\theta \cdot x^{0.69} \qquad (6)$$

The slope of this x-dependancy is in agreement to Mc-Elroy's data from St.Louis for urban dispersion[19].

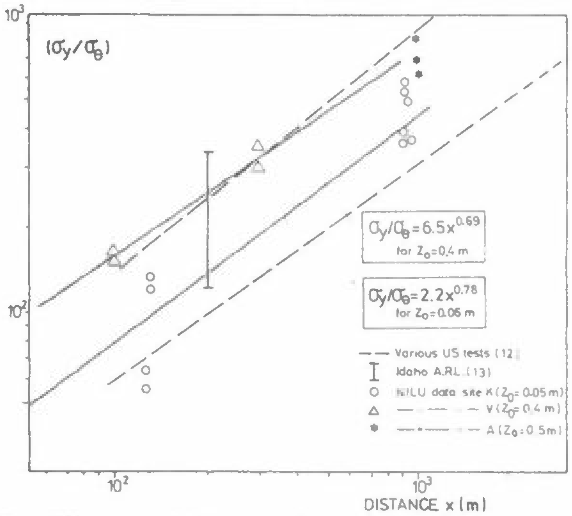

Figure 7: The ratio σ_y/σ_θ as a function of distance x (m).

The function f given in eq.7 is estimated from the diffusion data in Table 1, and presented as a function of the travel time t in Figure 8.

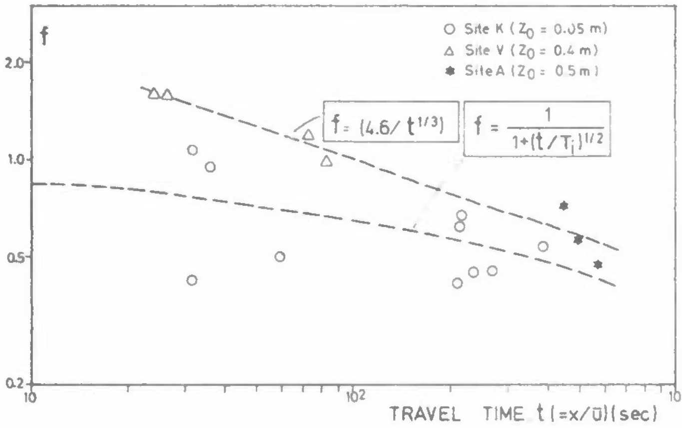

Figure 8: f as a function of travel time t for tracer releases within the atmospheric surface layer.

At site K, which is fairly smooth (roughness length $\simeq$ 5 cm), α = 1, and T_i = 330 S. The data agree with

$$f = \frac{1}{1 + 0.055 \cdot t^{\frac{1}{2}}} \qquad (9)$$

For the rougher sites V and A the function f can be approximated by

$$f = 4.6/t^{1/3} \qquad (10)$$

For travel times less than 97 sec the function f at these rough sites is greater than 1. This does not agree with Taylor's theoretical treatment of diffusion, which states that f shall approach 1 for short travel times. One reason for the discrepancy might be that σ_θ was measured at a level too high above the ground (36 m) compared to diffusion of SF_6 that took place within the surface layer; 0-25 m.

Based upon comparisons with several observations, Pasquill[4] has suggested values for f as a function of travel distance x. His values are given in Table 2 together with extrapolated values from our data.

Table 2: The function f for different travel distances as given by Pasquill[4], and evaluated from NILU data.

x (km)	0.1	0.2	0.4	1	2
f(x) Pasquill	0.8	0.7	0.65	0.6	0.5
site K(z_o=5cm)	0.78	0.68	0.63	0.52	
site V(z_o=40cm)	1.6	1.25	1.0		
site A(z_o=50cm)				0.65	

7 Estimates of the vertical dispersion parameter, σ_z

The vertical dispersion of air pollutants is described by the diffusion equation

$$\frac{dC}{dt} = \frac{\partial}{\partial z} \left(K_z \frac{\partial C}{\partial z}\right) \qquad (11)$$

where C is the concentration of material, K_z the eddy diffusivity and z is the vertical coordinate. For a simple diffusion process in a stationary situation with homogeneous wind and turbulence, the solution of equation (11) is of Gaussian form with variance

$$\sigma_z^2 = 2K_z t \quad \text{where } t=x/\bar{u} \qquad (12)$$

In the surface layer, the vertical eddy diffusivity K_z is strongly related to the eddy conductivity K_h:

$$K_z \simeq K_h = \kappa \cdot u_* \cdot z/\Phi_h(z/L) \qquad (13)$$

where κ is von Karman's constant, u_* is the friction velocity, L is the Monin-Obukhov length and Φ_h is a universal function of z/L. A model for the surface layer as proposed by Busch et al.[16], and based upon established similarity theory, was applied to estimate friction velocities, surface heat fluxes, H_o, and Monin-Obhukov lengths from measurements of wind and temperature profiles.

An iterative process was applied to estimate L from:

$$L = -c_p \rho T_o u_*^3/(\kappa \cdot g \cdot H_0) \qquad (14)$$

$$\text{with} \quad H_0 = -\rho c_p u_* \Theta_* \qquad (15)$$

where the wind and temperature profiles are given by:

$$u = \left[\ln(z/z_0) - \psi_m(z/L)\right] \cdot u_*/\kappa \qquad (16)$$

$$\Delta\theta = 0.74 \left[\ln(z/z_0) - \psi_h(z/L)\right] \cdot \theta_* \qquad (17)$$

The functions ψ_m and ψ_h are the integrals of the universal functions ϕ_m and ϕ_h given by Businger[17]:

$$\text{for } (z/L) < 0 : \phi_m = (1-15\ z/L)^{-1/4} \qquad (18)$$

$$\phi_h = 0.74(1-9\ z/L)^{-1/2} \qquad (19)$$

$$\text{for } (z/L) \quad 0 : \phi_m = 1 + 4.7\ z/L \qquad (20)$$

$$\phi_h = 0.74 + 4.7\ z/L \qquad (21)$$

Two approaches have been investigated for estimating K_z from eq. 13. In the first case K_z is estimated at a fixed reference height; z_{ref} equal to the anemometer height

$$K_z = \kappa\ u_*\ z_{ref}/\phi_h(z_{ref}/L) \qquad (22)$$

This formula was applied for all stabilities (all values of L). In the second approach, the plume height increase with downwind distance from the source has been taken into account. The height z at which K_z should be estimated in eq. 13, was assumed to vary with distance. In this case K_z was assumed to increase linearly with height in the surface layer of the atmosphere. The effective height, z_e, at which K_z is estimated, to simulate the vertical spread of the plume was assumed to be 0.5 σ_z.

For unstable conditions ($L<0$) the function $\phi_h(z/L)$ varies little from the initial value:

$$\phi_h(z/L) \simeq \phi_h(z_{ref}/L) \simeq \text{const.}$$

The expression for K_z from (13) inserted in (12) with $z = 0.5\ \sigma_z$ gives:

$$\sigma_z = \frac{\kappa}{\phi_h}\ \frac{u_*}{\bar{u}} \cdot x \qquad (23)$$

Equation 23 states that σ_z increases linearly with travel distance x for unstable stratification ($\bar{u}$ is the average effective transport velocity). Deardorff and Willis [18] found from laboratory experiments that σ_z increased as $x^{3/2}$. In an unstable surface layer with an upper inversion at z_i a proposed formula for $\sigma_z < 0.5\ z_i$ was:

$$\sigma_z = 0.4 \left[(1 - \frac{13}{L}\ (\frac{u_*}{\bar{u}})\ x\right]^{\frac{1}{2}} (\frac{u_*}{\bar{u}}) \cdot x \qquad (24)$$

For <u>stable conditions</u> ($L>0$) the function ϕ_h (z/L) given in eq. 21 inserted in eq. 13 and 12 gives:

$$\sigma_z = 0.2\ L\left[\left(1 + \frac{9.4\,\kappa}{L}\ (\frac{u_*}{\bar{u}})\ x\right)^{\frac{1}{2}} - 1\right] \qquad (25)$$

8 Discussion

In Figure 9 the estimated values of σ_y and σ_z are plotted versus observed values.

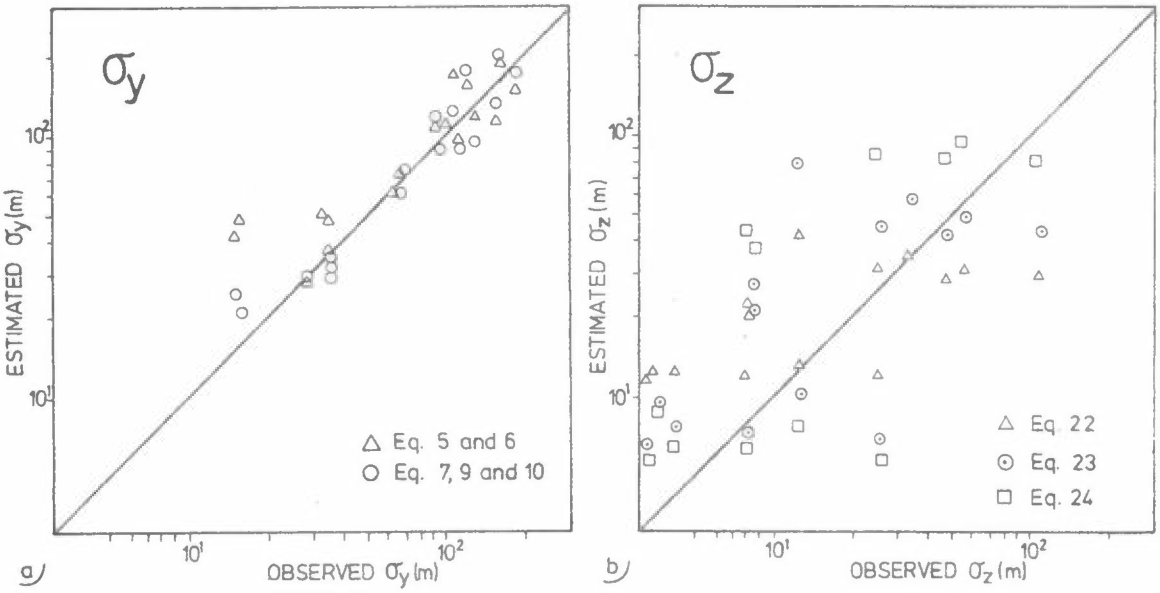

Figure 9: Estimated versus observed values of σ_y and σ_z.

All tracer experiments were carried out during unstable or near neutral situations. Equation 7; $\sigma_y=\sigma_\theta \cdot f(t/t_L)\ x$, appears to fit the σ_y data best. The function f seems to be dependent upon the surface roughness as given by eq. 9 and 10.

Equations 22, 23 and 24 were all tested against observed values of σ_z. The best fit is given by eq. 23 in which σ_z linearly grows with increasing distance from the source. Equation 22 overestimates σ_z close to the source while eq. 24 overestimates σ_z away from the source (at $x \geq 0.8$ km).

The main purpose of this study was to investigate the applicability of the NILU automatic weather station's wind statistics and temperature profiles in dispersion estimates. Future SF_6 tracer investigations will be conducted to study also cases with $L>0$, different release heights and the spread at larger downwind distances.

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