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A PRACTICAL MODEL FOR THE CALCULATION OF σ_y AND σ_z FOR USE IN AN ON-LINE GAUSSIAN DISPERSION MODEL FOR TALL STACKS, BASED ON WIND FLUCTUATIONS

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Abstract—A practical model is proposed for estimating hourly dispersion parameters σ_y and σ_z directly from wind fluctuations for use in an on-line dispersion model for tall stacks. Taylor's formulation is used to calculate σ_y and σ_z, both σ_v, σ_w and the time scale of turbulence T_l are derived from simple lateral wind measurements. This is done by separating the fluctuations of the wind direction into a stability dependent and a non-stability dependent part. Stability classes or other stability parameters are not applied. In well defined conditions there is a good agreement with the Pasquill dispersion curves and using the Pasquill–Gifford–Turner (PGT) stability determination. In more complicated situations our model gives significant improvements.

During the daytime the PGT method estimates stability as neutral over many hours. This is also the case at night, when the atmosphere is more stable than is assumed by the PGT method and other methods using cloud cover.

Key word index: On line dispersion model, wind fluctuations, turbulence time scale, tall stack.

NOMENCLATURE

$A(f)$, $A_s(f)$	Amplitude of wind direction fluctuations and fast fluctuations, respectively, as a function of the frequency f (Hz)
f_c	Coriolis parameter (10^{-4})
H	effective stack height (m)
$H(f)$	amplitude amplification as a function of f
L	Obukhov length scale (m)
p	exponent in wind velocity power law
T_e	Eulerian time scale of turbulence (s)
T_l	Lagrangian time scale of turbulence (s)
t	(travel) time (s)
t_m	averaging time (s)
u	wind velocity (m s^{-1})
z	height (m)
z_i	mixing height (m)
z_0	terrain roughness length (m)
β	Lagrangian/Eulerian time scale ratio
$\rho(\tau)$	autocorrelation as a function of time step τ
σ_v, σ_{vs}, σ_{vl}	standard deviation of lateral wind velocity component, for the fast and slow component, respectively (m s^{-1})
σ_w	standard deviation of vertical wind velocity (m s^{-1})
σ_y, σ_{ys}, σ_{yl}	lateral dispersion parameter in Gaussian plume model for the total plume, stability dependent part and the stability independent part of the plume, respectively (m)
σ_z	vertical dispersion parameter in Gaussian plume model (m)
σ_θ, $\sigma_{\theta s}$, $\sigma_{\theta l}$	standard deviation of the wind direction, for the stability dependent and the stability independent part of the wind direction fluctuations, respectively.

INTRODUCTION

Several models are available to calculate short-term concentrations at ground level near a tall stack. In practice Gaussian models are used in which the values of the dispersion parameters σ_y and σ_z must be given, σ_z being the most important determining ground level concentrations. σ_y and σ_z depend on the degree of turbulence, which in its turn depends on the stability of the atmosphere. The stability class can be estimated in the following ways.

The use of synoptic data such as wind speed and cloud cover (for example the Pasquill–Gifford–Turner method). Advantages are the great availability of the input data and the wide applicability of these methods. A great disadvantage is the inaccuracy for short-term applications (Atwater and Londergan, 1984; Weil and Brower, 1982: DeMarrais, 1978; Draxler, 1987). On-line measurement of cloud cover is also a difficulty.

The application of more basic meteorological physics with typical parameters such as surface flux of heat and impulse, temperature gradient and inversion height (Weil and Brower, 1982; Golder, 1972; Sutherland *et al.*, 1986).

Estimation of σ values without the use of stability classes uses turbulence parameters such as σ_v, σ_w and T_{ly} and T_{lz}. Whether or not these parameters are a function of height, they are used as input data for models as proposed, for example, by Taylor (1921), Pasquill (1971) and Draxler (1976). The estimations of σ_y and σ_z appear to be more accurate in that σ_v and σ_w are actually measured, as opposed to the indirect methods using synoptic data (Irwin, 1982; Gryning and Lyck, 1984). However, in practice, measurements of σ_w are not available and the determination of σ_w from other boundary layer parameters appears to be inaccurate (Weber *et al.*, 1982; Wratt, 1987). Measuring time scales have seldom been applied in dispersion models because it is difficult to obtain consistent values (Moore *et al.*, 1985).

We therefore propose an easily applicable and low-cost method to derive σ_v, σ_w and T_l directly from wind measurements at ground level. We will show that consistent values of the (Eulerian) time scale T_e of turbulence can be derived from wind direction fluctuations. This method is applied to a time series of wind measurements. Calculated values of σ_y and σ_z are compared with the values given by Briggs (1973), Pasquill (Pasquill and Smith, 1983) and Draxler (1976).

THE WIND FLUCTUATION MODEL

Calculation of σ_y

For calculating σ_y and σ_z, the statistical model of Taylor (1921) is used. Application of Taylor's formula is attractive, because it gives a direct relationship between turbulence parameters and σ_y and σ_z:

$$\sigma_{y,z}^2 = 2\sigma_{v,w}^2 T_{ly,z}^2 (t/T_{ly,z} + \exp(-t/T_{ly,z}) - 1). \quad (1)$$

This formula is only true for homogeneous turbulence, i.e. the values of σ_v, σ_w and T_l are independent of place and time. In general, (1) will be applied with σ_v values in which both the turbulent and the nonturbulent components are included, regardless of the question as to whether or not the fluctuations are a result of stability dependent turbulence or originated from slow meandering fluctuations. Therefore we suggest a similar differentiation of σ_y into two terms, as proposed by Hanna (1983):

$$\sigma_y^2 = \sigma_{ys}^2 + \sigma_{yl}^2. \quad (2)$$

The first term σ_{ys} represents the contribution of the stability-dependent fluctuations and the second term σ_{yl} the contribution of the stability independent ones. σ_{ys} is calculated using the following formula:

$$\sigma_{ys}^2 = 2\sigma_{vs}^2 T_l^2 (t/T_l + \exp(-t/T_l) - 1). \quad (3)$$

σ_{yl} is calculated as follows:

$$\sigma_{yl} = \sigma_{vl} t. \quad (4)$$

In calculating σ_{yl} an infinite time scale is assumed; this implies that plume sections travel along straight lines. T_l is derived from T_e, using the following formula:

$$T_l = \beta T_e. \quad (5)$$

We have assumed $\beta = 3$, which fits in best with the results from dispersion experiments (Van Duuren and Erbrink, 1988). The values of σ_{vs} and T_e are determined after subtracting the moving average from the original data of the wind direction measurements. The σ values are calculated from $\sigma_{\theta s}$, $\sigma_{\theta l}$ and u using the small angle formula:

$$\sigma_{vs,l} = \sigma_{\theta s,l} u. \quad (6)$$

T_e is estimated by using Equation (9) and calculating the correlation $\rho(\tau)$ between two succeeding residual wind direction values with time step τ:

$$T_e = -\tau/\log(\rho(\tau)). \quad (7)$$

Calculation of σ_z

If we assume that the stability dependent part of the turbulence is isotropic above a height of $0.1z_i$, then the stability dependent term σ_{vs} can be given an equal value to σ_w:

$$\sigma_w = \sigma_{vs}.$$

Therefore, σ_z can be equated to σ_{ys}:

$$\sigma_z = \sigma_{ys}. \quad (8)$$

Due to our assumption of isotropy above $0.1z_i$, this formula for σ_z is only true for tall stacks with an effective stack height $H > 0.1z_i$.

Choice of averaging time t_m

To separate the fast fluctuations in the measured wind direction from the slow fluctuations, the method of the moving average is applied in an iterative procedure. An example of this processing of the wind direction measurements is given in Fig. 1. The averaging time should depend on the time scale of the fast

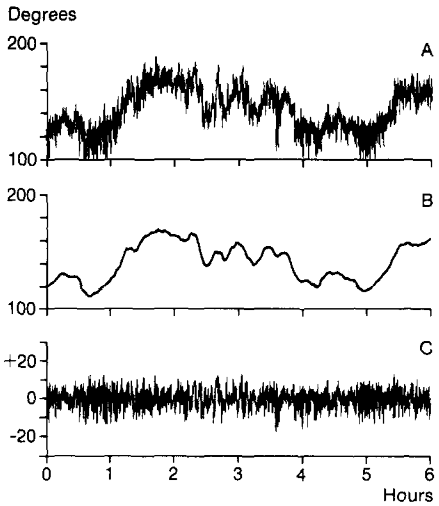

Fig. 1. Example of wind direction measurements over a period of 6 h and a sampling frequency of 0.2 Hz. A is the measured signal. B is the smoothed signal after the calculation of the moving average with an averaging time of 10 min. C is residual fast fluctuations after substracting B from A.

fluctuations, because then the stability independent changes in wind direction can be filtered out most effectively. The aim is to optimize the averaging time in such a way that most of the turbulent fluctuations are incorporated in σ_{vs}, while the stability independent changes are filtered out. The power spectra of σ_{vs} and σ_{vl} will be partly overlapping, so that neither aim will be achieved for 100%, and an optimum choice of t_m should be made for each hour of measuring. We will approach this problem with theoretical arguments.

Assuming an autocorrelation function of the stability dependent cross-wind fluctuations of the form:

$$\rho(\tau) = e^{-\tau/T_e}, \tag{9}$$

then the matching power spectrum is of the form (Bendat and Piersol, 1971):

$$A(f) = 4T_e/(1 + 4(\pi f T_e)^2). \tag{10}$$

The filter characteristics of the moving averaging filter, with an averaging time t_m, has the following form (Pasquill and Smith, 1983):

$$H(f) = (1 - \sin^2 \pi f t_m)/(\pi f t_m)^2. \tag{11}$$

The spectrum of the residual turbulent fluctuations after averaging becomes:

$$A_s(f) = A(f)H(f). \tag{12}$$

In order to find a relationship between t_m and T_e, the integral of each theoretical power spectrum ($fA_s(f)$ vs log (f)) is determined for many combinations of t_m and T_e. The area under the spectrum curve represents the fraction of the total variance included in the value of σ_{vs}. Integration of this curve with log(f) gives a measure for the value of σ_{vs} (Pasquill and Smith, 1983, pp. 54). These integral values are plotted against t_m; see Fig. 2. This figure makes clear how much variance is included in the value of σ_{vs} with increasing t_m. Figure 2 also shows that there exists a linear relationship between the integral value of $fA_s(f)$ and the value of t_m. A clear separation between the two terms cannot be made: any choice will be more or less arbitrary. Our choice is to set a value of t_m equal to 60 times the value of T_e; this is the broken line in Fig. 2.

Finally, a summary of the assumptions is given:

Taylor's formula is applicable to plume dispersion;

wind direction fluctuations can be separated in a stability dependent and non-stability dependent part;

the stability dependent term σ_{vs} is independent of height and equals σ_w for $z > 0.1z_i$;

the autocorrelation function of the stability dependent wind direction fluctuations is negative exponential with time scale T_e;

T_e is independent of height;

there is a constant ratio β between T_l and T_e;

the time scale of the non-stability dependent term σ_{yl} is infinite.

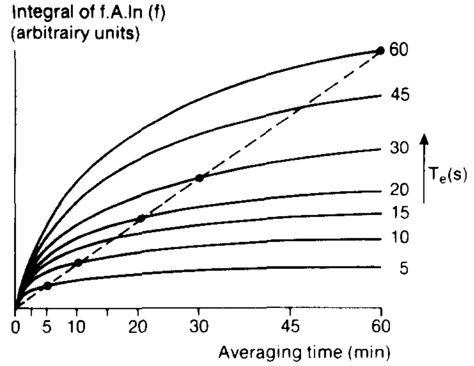

Fig. 2. Effect of a different averaging time t_m in the calculation of the moving average on the measured variance in the fast fluctuations as a function of the Eulerian time scale T_e of the wind direction fluctuations. A negative exponential autocorrelation function for this signal is assumed. See text for further explanation.

EXPERIMENTAL METHODS

To investigate the independence of σ_{vs} with respect to height, a dataset of The Royal Netherlands Meteorological Institute (KNMI) is used containing measured data over a period of a whole year (1973). Since these routine measurements (2-min averages) are not suitable for investigating time scales of turbulence, we built up a limited dataset at Deelen airport, where we carried out wind measurements with a sample time of 5 s.

At Cabauw, in the centre of The Netherlands, KNMI has a meteorological mast in operation with a height of 213 m as described by Driedonks *et al.* (1978). At the tower wind speed, wind direction, temperature and r.h. are measured continuously at different levels. These data are averaged over periods of 2 min and stored on magnetic tape. The terrain consists mainly of grassland, low trees at the east side and occasionally dykes and houses at a distance of at least 500 m. The data are roughly equally divided among the seasons and between night- and daytime. Seven thousand six hundred hours of measurements are available—4000 in summertime and 3600 in wintertime.

In order to discriminate between the stability dependent fast fluctuations in the wind direction and the stability independent slower fluctuations, the original time series of 2-min averages is replaced by the differences between two succeeding wind direction values. In so doing, only the faster variations in wind direction will remain with periods of 2–20 min.

Hourly values of σ_{dv}, the standard deviation of these differences, are used to verify the assumption that σ_{vs} is independent of height. Although σ_{vs} and σ_{dv} do not embrace entirely the same frequency domain, both terms will be treated here as interchangeable.

The data set from Deelen consists of measurements of wind speed, wind direction, temperature and r.h. A Climatronics electronic weather station is used to measure wind speed and wind direction. For these measurements sensors are used which both have time constants of 2.4 μs; the cup anemometer has a threshold of 0.33 m s^{-1}. The electronic system in the weather station has a time constant of 5 s. A Kipp solarimeter CM-11 is used for estimating the global radiation. Additional meteorological information such as cloud cover and rainfall is available. The measuring site is flat and covered with agricultural fields and meadows over a distance of at least 1 km. Two measuring periods were chosen: one in the winter of 1984 without frost or snowfall, and one in the summer of 1985, according to Table 1.

The distribution of the PGT stability classes is presented in Table 2.

A number of hours (84) is not included in this data set because of variable wind direction, mostly due to low wind conditions. In these situations σ_v cannot be defined.

RESULTS AND ANALYSIS

Time scale T_e

Our method gives consistent values for T_e for specific atmospheric conditions. Typical measured values of T_e are as follows:

stable: $T_e = 5\text{–}10$ s;

neutral: $T_e = 10\text{–}30$ s;

unstable: $T_e = 30\text{–}100$ s.

Values of T_{1z} for vertical diffusion recommended by Gryning *et al.* (1987) also correspond with our values (if $\beta = 3$ is assumed): for stable conditions a value of 30 s is given and for unstable 300 s.

For vertical diffusion Draxler (1976) gives T_{1z} values of 100 s for stable and 500 s for unstable situations; for lateral diffusion a constant T_{1y} value of 1000 s is given. Gifford (1986) gives a summary of several applied time scales for lateral diffusion, which vary from 200 to 3000 s and Hanna (1986) concludes that T_{1y} should be 15,000 s applying Draxler's formula for σ_y. The explanation of the wide range of T_{1y} values is that they all contain a combination of the two time scales, depending on the sampling time and averaging time that is necessary for the estimation of plume dispersion.

Height dependency of σ_v *and* T_l

The wind data from Cabauw are used to investigate the question as to whether the fast fluctuations are a function of height.

Values of σ_{vs} are available for heights of 10 and 200 m. Initially, the logarithm is taken for each value, because values of σ_{vs} show a roughly lognormal distribution; applying statistics to this time-series is then more meaningful. σ_{vs} values at 10 m altitude are correlated with σ_{vs} values at 200 m altitude with a correlation coefficient of $r = 0.79$ and a slope of practically 1.0. This correlation is calculated over 7600 h, 87% of all the hours in 1973. This correlation coefficient remained the same when all stable situations were discarded (3500 h remaining). If the correlation between σ_{vs} at different altitudes becomes worse in stable situations, then the value of r should have increased. The atmosphere during 1 h is identified as stable when the difference between the wind direction at the heights of 10 and 200 m is more than 10 degrees. Other criteria for determining the stability (PGT stability class or $1/L$), appeared to be less useful. The average values of σ_{vs} are presented in Table 3.

Our conclusion, based on these measurements, is that it is a reasonable assumption that σ_{vs}, at the altitudes where plume transport takes place, can be equated to σ_{vs} measured at 10 m, also in stable situations.

In our data sets no data for T_l or T_e are available at different altitudes. Weber *et al.* (1982) gives functions of height for T_l that show generally increasing values of T_l with z. In contrast with this, we take T_l to be constant with respect to height as a result of our assumption of isotropy. The height dependency of the slow fluctuations is not clear; in unstable conditions no serious problems are expected, but in stable conditions when σ_{vs} and T_e have small values, different atmospheric layers are uncoupled causing directional wind shear and horizontal movements that can have a completely different intensity. At the moment, carrying out measurements with sodar or lidar seems to be the only solution to obtain good estimations of these slow movements.

Comparison with other σ_y *and* σ_z *schemes*

Values of σ_{vs}, T_e, $\sigma_{\theta l}$ and σ_y and σ_z are computed for all 476 h of measurements at Deelen airport according to the described method for a hypothetical stack height of 100 m. σ_y and σ_z can be compared with σ values that are computed with the distance dependent curves of Pasquill and Briggs and with the time dependent curves of Draxler (1976). Since no measurements of wind profiles were in operation, the transport velocity at the height of 100 m had to be derived from measurements of wind speed at the height of 10 m. For simplicity we use the power law:

$$u(z) = u(10)(z/10)^p \qquad (13)$$

Table 1. Distribution of the measuring hours

Hours	Daytime	Night-time	Total
Summer	195	63	258
Winter	74	144	218
Total	269	207	476

Table 2. Frequency distribution of Pasquill stability classes during the wind measurements

Stability class	Hours
A	30
B	58
C	37
D	252
E	23
F	76

Table 3. Mean values of σ_{vs} at two levels

Height	10 m	200 m
Neutral and unstable	0.44	0.46
Stable	0.19	0.19

with values for the exponent p that depend on the stability class. The p-values are chosen according to the Dutch National Dispersion Model (TNO, 1976): $p=0.1$ for stability classes A and B; 0.16 for C and D and $p=0.3$ for E and F. For every hour, σ_y and σ_z curves are calculated as functions of distance. Time dependent curves are transformed into distance-dependent forms by taking $x=ut$. These curves are averaged for each stability class. In one stability class the Pasquill and Briggs curves each have a constant form from hour to hour of course, but the curves of Draxler and ours depend on actually measured values of turbulence parameters.

The results will be discussed for σ_y and σ_z separately.

Results for σ_y

In Fig. 3 the averaged σ_y curves are presented as functions of distance for each individual Pasquill–Gifford–Turner stability class. The stability dependent contribution σ_{ys} to the overall value of σ_y is also shown.

σ_y in stability class A is somewhat smaller than in class B, whereas one would expect the reverse. The reason for this difference is that stability class A mainly arose in the morning and evening hours, when the wind speed is lower than in the middle of the day in clear sky conditions. It is clear that the turbulence intensity is not large during those hours. This shows a disadvantage of the PGT method, for no impact of sun elevation is taken into account. As a result the PGT method gives an extreme change in stability from F to A at sunrise.

The absolute contribution of the slow fluctuations to σ_y is roughly the same in all stability classes; the term stability independent fluctuations appears to be justified. The relative contribution of σ_{yl} becomes greater in stable conditions: the ratio between σ_y and σ_z ($=\sigma_{ys}$) becomes greater. Our σ_y curves agree well with the curves of Draxler but are slightly greater, which may be a result of a different T_l value. The σ_y values according to Pasquill are greater. It is conceivable that these differences are a consequence of different site conditions (e.g. moisture and albedo of the terrain), or a consequence of the extrapolation of the curves beyond the distance at which they are fitted with measurements. The same can be said about the Briggs curves.

Results for σ_z

In Fig. 4 the averaged σ_z curves are compared with the σ_z curves according to Pasquill, Briggs and Draxler. The agreement with Pasquill is quite good, though there are differences in class A which may be a result of a relatively low degree of turbulence in the morning hours, as discussed for σ_y. The differences from the Briggs curves are greater; his curves give more extreme values. The agreement with the Draxler

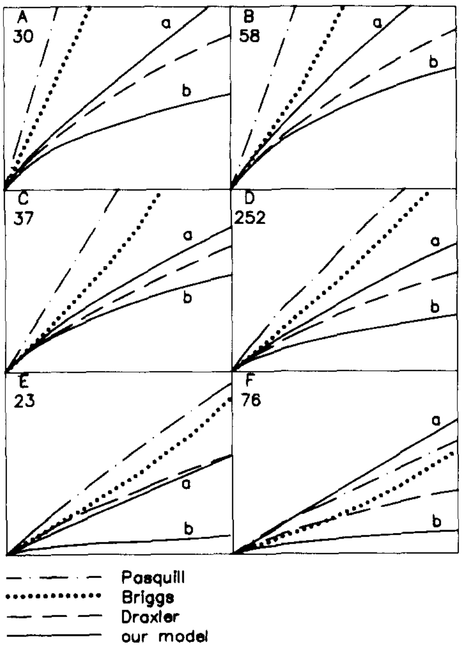

Fig. 3. Modelled values of σ_y when different methods are applied. x-axis: 0–15 km; y-axis 0–1 km. In the left-hand corner the PGT-stability class is denoted with the frequency of occurrence in hours. a Denotes total values of σ_y according to our model. b Denotes values of $\sigma_z=\sigma_{ys}$ according to our model.

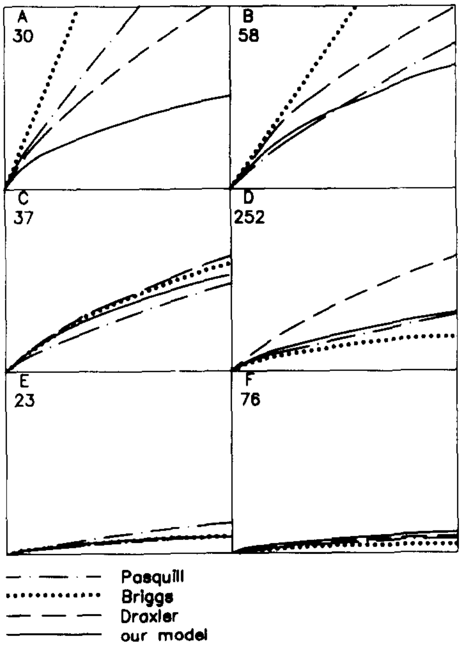

Fig. 4. Modelled values of σ_z when different methods are applied. x-axis: 0–15 km; y-axis: 0–1 km. In the left-hand corner the PGT-stability class is denoted with the frequency of occurrence in hours.

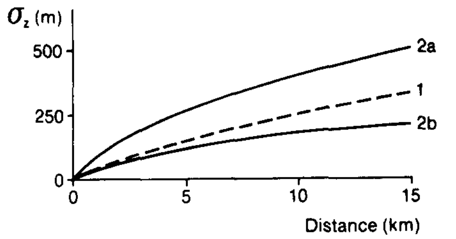

Fig. 5. Modelled values of σ_z according to our model in hours with PGT-stability class D (neutral case). Average curves are given for 144 daytime h (2a) and 108 night-time h (2b) separately. Curve 1 gives σ_z according to Pasquill.

curves is very good in stable conditions; in neutral and unstable conditions our method gives smaller values for σ_z. In calculating σ_z according to Draxler a value of σ_w is necessary; as an estimator for σ_w we used the value of σ_{vs}. An explanation for the differences between Draxler's values and our values can be found in the use of different T_l values. Our T_l values are derived from measurements; in neutral conditions a moderate T_l value will be found. A choice between stable or unstable conditions is not necessary as is the case with Draxler's method, which inevitably gives a discontinuity.

If we consider only the hours with Pasquill stability class D, and calculate averaged σ_z values separately for daytime and night-time hours, then a clear differentiation is shown by our method in Fig. 5. At night-time the atmosphere will be more stable than in the daytime with the same cloud cover, and as a result smaller σ_z values are given. On average the difference between night-time class D and daytime class D is about a factor of 2! The σ_z values of Draxler also express this difference, but this is less pronounced due to the constant value of T_l in his expression.

The differences between the Pasquill method and the wind fluctuation method can be illustrated when the σ_z curves are plotted with the course of the time of the day. In Fig. 6 σ_z values are plotted as a function of distance at different hours on a typical day with a good deal of cloud cover and moderate wind speeds; almost all the hours were characterized as stability class D. According to Pasquill, σ_z has the same values in all these hours, but our method shows a remarkable difference in degree of turbulence, which can easily be explained by assuming that the clouds exist in a rather thin layer, that does not stop the incoming and outgoing radiation but only reduces it, leaving the atmosphere unstable during the daytime and fairly stable at night.

The estimation of stability by means of cloud cover and wind speed is strongly conservative—too many hours will be characterized as neutral.

CONCLUSIONS

An easily applicable method to calculate both σ_y and σ_z is presented. The input parameters σ_v and T_e are derived from continuous measurements; no additional information is needed. The same procedure is applied in all atmospheric conditions, so, no dis-

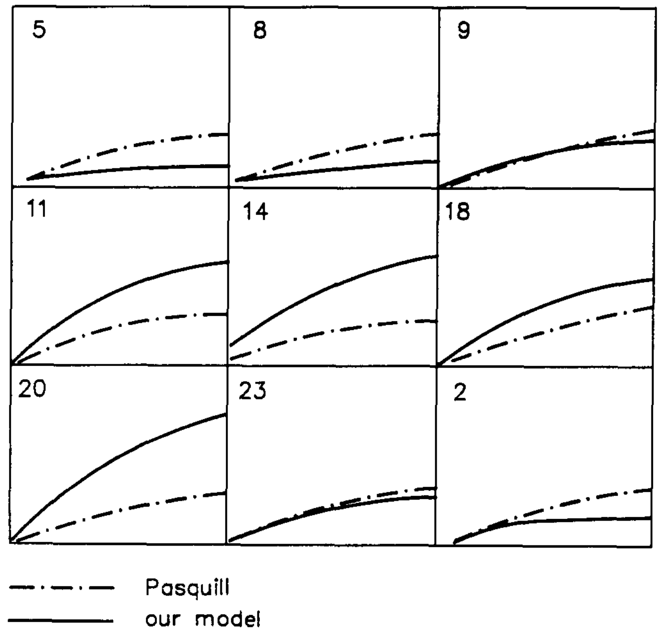

Fig. 6. Comparison of modelled values of σ_z according to our model and Pasquill during several hours on a cloudy summer day (16 July 1985). In the left-hand corner the hour of the day is given, all hours were classified as stability class D. x-axis: 0–15 km; y-axis: 0–1 km.

continuities will occur. Determination of the stability class is no longer necessary.

The measurements of parameters that reflect the degree of turbulence in the atmosphere in a direct way can be a great advantage in more complicated situations, because the effects on turbulence of cloud cover, sunshine in different seasons, low inversions, moisture or snow cover on the soil and other terrain effects are incorporated into the measured parameters.

The Pasquill–Gifford–Turner method for estimating the stability class results in too many hours with a neutral atmosphere; in reality there are more unstable hours in the daytime and more stable hours at night-time than the PGT method suggests. An analysis of several hundreds of hours with wind measurements shows a strong decrease of the number of hours with Pasquill D from 70% to only 20% when our model is applied (Erbrink, 1991).

The values of T_e, obtained from the fast fluctuations are consistent for a specific situation: small values for stable conditions (5–10 s) and larger values during unstable conditions (30–100 s). The constant value often assumed for T_l is a simplistic approach to reality.

For verification of the model, dispersion experiments were carried out using SF_6 and a mobile lidar system (Van Duuren and Erbrink, 1988). Comparing measured and calculated values of ground level concentrations, and of σ_y and σ_z values, our dispersion model for tall stacks is capable of giving better results than several other models. In this comparison the Dutch National Model is used, and also the PPSP model (Weil, 1982) and the RIVM Puff model (Van Egmond, 1983).

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