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Diurnal and annual variation of the sensation distance of odour emitted by livestock buildings calculated by the Austrian odour dispersion model (AODM)

Günther Schauberger[a,*], Martin Piringer[b], Erwin Petz[b]

[a]*Institute of Medical Physics and Biostatistics, University of Veterinary Medicine, Veterinärplatz 1, A 1210 Vienna, Austria*
[b]*Central Institute for Meteorology and Geodynamics, Hohe Warte 38, A 1190 Vienna, Austria*

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Abstract

The diurnal and annual variation of distances for different odour thresholds is investigated by the dynamic Austrian odour dispersion model (AODM) consisting of an emission module, a dispersion module, and a module to calculate instantaneous odour concentrations. The effect of daily variations in odour production, ventilation rates and indoor air temperature are included in impact assessments. The ambient half-hour odour concentrations calculated by a regulatory Gaussian plume model are transformed to instantaneous values representative for the duration of a single breath by an attenuation function decreasing the peak-to-mean ratio with increasing wind velocity, stability, and distance from the source. The resultant distances for different odour thresholds and their dependence on meteorological parameters are investigated and discussed in detail, focussing on the distance for the detection limit, $1\,\mathrm{OU\,m^{-3}}$, the so-called sensation distance. The results suggest a stronger dependence of the sensation distance upon variation in meteorological conditions than diurnal and annual variations in odour emission rates. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Odour; Livestock building; Emission; Gauss model; Separation distance; Animal

1. Introduction

Livestock farming industry is increasingly confronted with questions of environmental protection because of different kinds of pollutants emitted into the atmosphere. One of them is odour which is a very important component because the acceptance of livestock farming in the vicinity can decrease due to an increase in odour sensation (Schiffman, 1998).

The concentration of odorants can be handled like other volatile pollutants and can be measured by an olfactometer in odour units per volume ($\mathrm{OU\,m^{-3}}$). One odour unit is the amount of odorants present in 1 $\mathrm{m^3}$ of odorous gas (under standard conditions) at the panel threshold (CIGR, 1994).

The odour sensation is triggered by the odour stimulus and characterised by intensity and frequency. To predict these parameters it is necessary to consider short-term fluctuations of odorant concentrations at the receptor point. Odour sensation can only be observed if the odorant concentration is higher than the odour threshold of the substances. Due to fluctuations an odour sensation can take place even if the mean odorant concentration is lower than the odour threshold.

Previous investigations of the present authors concentrated on a comparison of the shape of the different power functions used by various guidelines to calculate the separation distance between livestock farms and residential areas with that derived via a Gaussian plume model. In these studies, it was concluded that the latter shows a stronger dependence on the odour emission than suggested by the guidelines (Piringer and Schauberger, 1999) as well as on the development and test of a steady-state balance model to calculate the indoor climate of livestock buildings (Schauberger et al., 1999, 2000).

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* Corresponding author.

E-mail address: gunther.schauberger@vu-wien.ac.at (G. Schauberger).

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No diurnal variation of the odour emission was assumed in these publications. This paper investigates the diurnal and annual variations of the sensation distance of livestock farms depending on the appropriate variations of the odour emission as well as the ambient meteorological conditions. This will be achieved with a model based on three modules, the first calculating the odour emission of the livestock building, the second calculating ambient odour concentrations, and the third taking into account the conversion to instantaneous concentrations.

2. Materials and methods

2.1. Odour emission model

The emission model is based on a steady-state balance of sensible heat fluxes to calculate the indoor temperature and the related volume flow of the ventilation system. The corresponding odour flow is assessed by a simple model of the odour release. The model has been described extensively in Schauberger et al. (1999, 2000), and therefore only its main features are reported here.

The air temperature inside a mechanically ventilated livestock building is calculated using a balance equation of the sensible heat (Schauberger, 1988; CIGR, 1984, Albright, 1990, ASHRAE, 1972; Sallvik and Pedersen, 1999). The indoor air temperature (equal to the temperature of the outlet air) and the volume flow are calculated as a function of the outdoor temperature.

The balance equation (Eq. (1)) consists of three terms describing the sensible heat flux of the livestock building as

$$S_A + S_B + S_V = 0, \tag{1}$$

with the sensible heat release of one animal, S_A, the loss of sensible heat caused by the transmission through the building, S_B, and the sensible heat flow caused by the ventilation system, S_V.

The ventilation systems in livestock buildings are mainly designed as temperature-controlled variable-volume flow systems. The control unit uses the indoor air temperature as the control value. The output of the control unit is the supply voltage of the fans, which results in the volume flow of the ventilation system. Two parameters, the set point temperature, T_C and the proportional range, ΔT_C, describe the course of the volume flow depending on the indoor air temperature, T_i, as a control value (e.g. Bruce, 1999). For an indoor air temperature less than the set-point temperature, the volume flow of the ventilation system is a constant value according to the minimum design value, V_{min}. In the proportional range above the set-point temperature, the volume flow is increased until the maximum ventilation rate is reached. Above this range, the livestock building is supplied by the maximum ventilation flow, V_{max}. Eq. (2) gives the volume flow V as a function of the indoor air temperature, T_i:

$$V(T_i) = \begin{cases} V_{min} & \text{for} \quad T_i \leqslant T_C, \\ V_{min} + (T_i - T_C)\dfrac{V_{max} - V_{min}}{\Delta T_C} & \text{for} \quad T_C < T_i \leqslant T_C + \Delta T_C, \\ V_{max} & \text{for} \quad T_i > T_C + \Delta T_C. \end{cases} \tag{2}$$

The lower V_{min} and the upper V_{max} limit of the volume flow are design values according to the guidelines for the indoor climate for animals (CIGR, 1984; ASHRAE, 1972; Albright, 1990; Bruce, 1999) (Table 1).

The model calculations were done for a pig fattening unit of 1000 pigs with a forced ventilation system. The livestock building is moderately insulated, described by the U value (Table 1). The assumed space per animal is 0.75 m^2 according to the welfare guidelines. The chosen system parameters for a livestock building with these specifications, typical for middle Europe, are summarised in Table 1.

The odour release from the livestock building originates from the animals, polluted surfaces and the feed.

Table 1
System parameters of the indoor climate (model calculation) per animal; the parameters are representative for an unit of about 1000 fattening pigs

Parameters	
Mean total energy release of an animal, Q_A (continuous fattening between 30 and 100 kg)	188 W
Minimum volume flow, V_{min}. Design value for the ventilation system taking into account the maximum accepted indoor CO_2 concentration of 3000 ppm, related to one animal	13.1 m^3 h^{-1}
Maximum volume flow, V_{max}. Design value for the ventilation system taking into account the maximum temperature difference between indoor and outdoor for summer ($T_i = 30°C$) of 3 K, related to one animal	66.0 m^3 h^{-1}
Area of the building (ceiling, walls, windows, doors) per animal	1.35 m^2
Mean thermal transmission coefficient, U	2.0 W m^{-2} K
Set point temperature of the control unit, T_C	18°C
Bandwidth of the control unit, ΔT_C	4 K

Outdoor odour sources such as slurry tanks or feed storage facilities are not taken into account. The emission of the livestock building at the outlet air is quantified by the odour flow, E, in $\mathrm{OU\,s^{-1}}$ and the specific odour flow, e, in $\mathrm{OU\,s^{-1}}$ LU related to the livestock (livestock unit (LU) equivalent to 500 kg live mass of the animals). The specific odour flow depends on the kind of animals and how they are kept. Available data are summarised by a literature review of Martinec et al. (1998). For the model calculation presented here, a mean specific odour flow, e_m, of $100\,\mathrm{OU\,s^{-1}\,LU^{-1}}$ and a mean live mass of 60 kg per fattening pig ($M = 0.12$ LU) were used.

As odour production is a biochemical process, the temperature has an important influence. Most authors select outdoor air temperature, T_o, to describe this relationship (Oldenburg, 1989; Kowalewsky, 1981). The linear regression of Oldenburg (1989) was adapted to assess the influence of the temperature T_o on odour flow E_m by

$$E_m(T_o) = E_m(0.905 + 0.0095T_o). \tag{3}$$

Instead of a constant odour release in previous model calculations (Schauberger et al., 1999, 2000), the diurnal variation of the odour release was assessed by the measurements of Rieß et al. (1999) of the odour concentration inside a pig fattening unit by an electronic nose. The diurnal variation of the odour release, $E(t)$, is taken into account by a sinusoidal function with the period τ of 24 h, proposed by Pedersen and Takai (1997) on the basis of the variation of the animal activity over the time of the day, t. The odour release was calculated by Eq. (4) with the relative amplitude of 20% related to the daily mean of $E_m(T_o)$ according to Eq. (3). The phase of the time course of the energy release and the odour release was assumed to be the same, i.e. triggered by the animal activity. The minimum of the animal activity of fattening pigs occurs around 01:15 local time at night (Pedersen, 1996; Pedersen and Takai, 1997).

$$E(t) = E_m(T_o)\left[1 + 0.20\sin\left(\frac{2\pi}{\tau}(t - 7.25)\right)\right]. \tag{4}$$

The odour flow of the livestock building depends on the odour release and the volume flow of the ventilation system. As a result of the model calculation, the odour concentration, C, of the outlet air is taken as the parameter to describe the odour release. The concentration is calculated by the odour flow, E, in $\mathrm{OU\,s^{-1}}$ according to Eq. (4) divided by the volume flow, V, of the ventilation system in $\mathrm{m^3\,s^{-1}}$:

$$C = \frac{E}{V}. \tag{5}$$

2.2. Dispersion model and meteorological conditions

The concentration of odorants can be handled like other volatile pollutants by well-known dispersion models such as those based on a Gaussian distribution (e.g. Kolb, 1981; ÖNorm M 9440, 1992/96). Then the concentration at a receptor point is calculated as a mean value of the concentration of odorants for a defined period (e.g. 0.5-h, 3-h mean value, etc.). To apply a dispersion model to odour emissions, the odour concentration and the volume flow of the outlet air have to be known. In many cases, these two parameters are assumed to be constant over time, although it is well known that the ventilation system of animal houses is designed to vary the air exchange in a range of 1:5–1:10 between the minimum and the maximum volume flow (Table 1, $V_{\min} : V_{\max} = 1:5$). In this study, appropriate variations of these parameters are taken into account (Section 2.1).

The odour concentration of the centreline of the plume is calculated by the Austrian regulatory dispersion model (ÖNorm M 9440, 1992/96; Kolb, 1981). The model has been validated internationally with generally good results (e.g. Pechinger and Petz, 1997).

The regulatory model is a Gaussian plume model applied for single-stack emissions and distances up to 15 km. Plume rise formulae used in the model are a combination of formulae suggested by Carson and Moses (1969) and Briggs (1975). The model uses a traditional discrete stability classification scheme with dispersion parameters developed by Reuter (1970).

The Austrian flatlands north of the Alps (200–400 m above sea level) are characterised by a moderate climate with both maritime and continental influences. The annual average temperature is 9–10°C. Precipitation occurs all the year round, culminating in summer storms, and yearly precipitation totals amount from 700 to 1000 mm from east to west. In general, there is a good ambient air movement, with mean wind velocities ranging from about $2–4\,\mathrm{m\,s^{-1}}$. Except for north–south-oriented valleys, main wind directions are west and east.

The meteorological data were collected at Wels, a site representative of the Austrian flatlands north of the Alps. The sample interval was 30 min for a two-year period between 30 January 1992 and 31 January 1994. The city of Wels in Upper Austria is a regional shopping and business centre of about 50,000 inhabitants. The surroundings are rather flat and consist mainly of farmland. The mean wind velocity in undisturbed environment is $2.2\,\mathrm{m\,s^{-1}}$, maximum velocities amounting to about $13\,\mathrm{m\,s^{-1}}$. The distribution of wind directions and wind velocities are shown in Fig. 1. The prevailing wind directions at Wels are W and WSW, as well as E and ENE. Calm conditions according to the Austrian regulatory dispersion model with wind velocity of less than $0.7\,\mathrm{m\,s^{-1}}$ amount to 18.2%; weak winds (wind velocities less than $1\,\mathrm{m\,s^{-1}}$) comprise 26.5% of all cases. Less than 10% of all wind velocities are larger than $5\,\mathrm{m\,s^{-1}}$. The annual mean temperature at Wels is 9.7°C, the temperature range (two-year period) is from −14.9 to 35.3°C. The

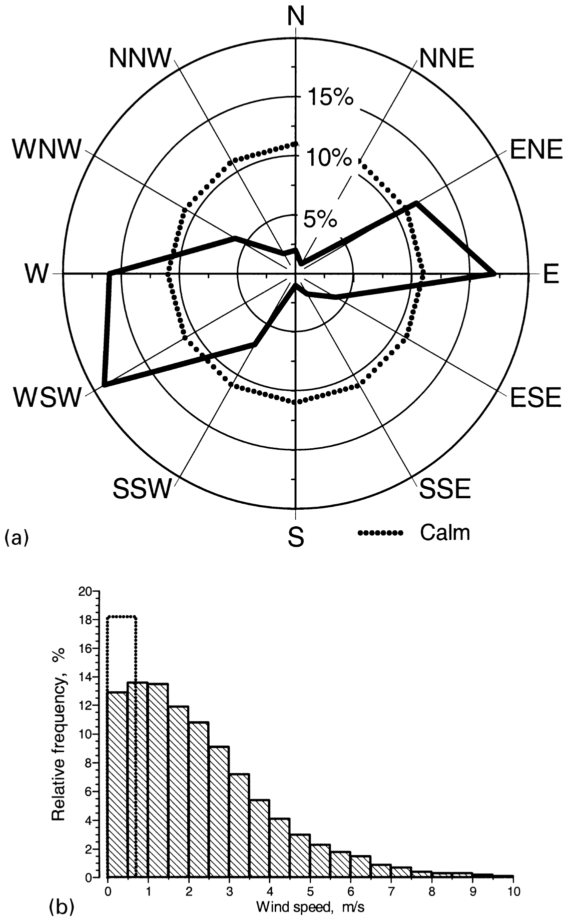


Fig. 1. Frequency distribution of (a) the wind direction and (b) wind velocity at Wels; (------), Calm conditions according to the Austrian regulatory dispersion model with wind velocity less than 0.7 $\mathrm{m\,s^{-1}}$ (ÖNorm, 1992/1996).

annual precipitation amounts to 838 mm (mean over the period 1961–1990).

Stability classes, SC, are determined as a function of half-hourly mean wind velocity and a combination of sun elevation angle and cloud cover (Table 2). The cloud cover was monitored by the meteorological station at the airport Linz-Hörsching, at a distance of about 13 km. As seen from Table 2, some combinations of stability class and wind velocity are not possible by definition (ÖNorm M 9440, 1992/1996). Stability class 4, representative of cloudy and/or windy conditions including precipitation or fog, is by far the most common dispersion category because it occurs day and night. Its occurrence peaks at wind velocities of 2 and 3 $\mathrm{m\,s^{-1}}$. Wind velocities larger than 6 $\mathrm{m\,s^{-1}}$ are almost entirely connected with class 4 (since a frequency of 1‰ is equal to about 17 half hours in the two-year statistics, smaller occurrences do not show up in Table 2). Stability classes 2 and 3 peak slightly below or around the average wind velocity, which by definition occur only during daytime in a well-mixed boundary layer. Class 3 allowing also for cases of high wind velocity and moderate cloud cover. They cover 26% of all cases. Class 5 occurs with higher wind velocities during nights with low cloud cover, a situation which is not observed frequently at Wels. Classes 6 and 7 are relevant for clear nights, when a surface inversion, caused by radiative cooling, traps pollutants near the ground. Such situations occur in 25% of all cases.

The average occurrence of stability classes for each month is given in Table 3.

Table 3 shows a lot of seasonal variation of the occurrence of stability classes. Especially the probability for stability class 2 is about 10 times higher during summer than during winter months. The effect of this variation on the distance, where sensation occurs, is discussed in Section 3. The occurrence frequencies for stability classes 3 and 4 vary by a factor of 3, those for classes 5–7 by a factor of about 2.

2.3. Assessment of the expected maximum concentration in an interval of a breath

The regulatory model calculates half-hour mean concentrations. The sensation of odour, however, depends on the momentary odour concentration and not on a mean value over a long time of integration. Smith (1973) gives the following relationship:

$$\frac{C_{\mathrm{p}}}{C_{\mathrm{m}}} = \left(\frac{t_{\mathrm{m}}}{t_{\mathrm{p}}}\right)^{u} \tag{6}$$

with the mean concentration, C_{m}, calculated for an integration time of t_{m} and the peak concentration, C_{p}, for an integration time of t_{p}. Smith (1973) suggests the following values of the exponent u depending on the stability of the atmosphere: 0.35 ($\mathrm{SC} = 4$), 0.52 ($\mathrm{SC} = 3$) and 0.65 ($\mathrm{SC} = 2$). Using $t_{\mathrm{m}} = 1800\,\mathrm{s}$ (calculated half-hour mean value) and $t_{\mathrm{p}} = 5\,\mathrm{s}$ (duration of a single breath), the following peak-to-mean factors, depending on atmospheric stability, are derived by a quadratic function based on the values of Smith (1973): 43.25 ($\mathrm{SC} = 2$), 20.12 ($\mathrm{SC} = 3$), 9.36 ($\mathrm{SC} = 4$), 4.36 ($\mathrm{SC} = 5$), 1.00 ($\mathrm{SC} = 6$) and 1.00 ($\mathrm{SC} = 7$). The use of Eq. (6) for periods that are as short as the period of a single breath are based on measurements of Mylne (1990).

These values are only valid close to the odour source. Due to turbulent mixing, the peak-to-mean ratio is reduced with increasing distance from the source. Mylne and Mason (1991) analysed the fluctuation of the plume concentration and developed the following relationship: The peak-to-mean ratio in Eq. (6) is modified by an exponential attenuation function of T/t_{L}, where $T = x/u$

Table 2
Two-dimensional frequency distribution in ‰ of stability classes SC (2–7) and wind velocity in $\mathrm{m\,s^{-1}}$ at Wels

	Stability class SC					
Wind velocity ($\mathrm{m\,s^{-1}}$)	2	3	4	5	6	7
< 1.0	13	35	42		41	71
1.0–1.9	44	55	79		35	59
2.0–2.9	30	39	91	30	22	7
3.0–3.9	10	19	91	25	12	
4.0–4.9	5	8	63	4		
5.0–5.9		5	31			
6.0–6.9			22			
⩾ 7			12			
Sum	102	161	431	59	110	137

Table 3
Relative frequency (%) of the stability classes SC for each month

	Stability class SC						
Month	2	3	4	5	6	7	
1	3.5	13.0	42.1	8.6	14.8	18.0	100.0
2	5.3	10.7	53.1	6.6	8.6	15.6	100.0
3	7.8	12.5	48.2	6.9	11.0	13.6	100.0
4	11.9	18.1	38.8	7.4	10.0	13.8	100.0
5	20.9	22.4	23.9	4.1	12.2	16.5	100.0
6	16.0	22.6	34.2	5.0	10.6	11.7	100.0
7	16.7	23.8	31.8	6.0	7.9	13.8	100.0
8	25.3	19.6	19.8	3.9	11.2	20.2	100.0
9	12.8	17.3	32.4	6.0	10.0	21.5	100.0
10	1.9	15.9	51.5	6.0	13.6	11.0	100.0
11	0.5	9.0	64.9	5.8	13.8	6.0	100.0
12	1.0	7.8	66.8	6.1	11.7	6.5	100.0

is the time of travel with the distance, x, and the mean wind velocity , u, and t_L is a measure of the Lagrangian time scale (Mylne, 1992)

$$\Psi = 1 + (\Psi_0 - 1)\exp\left(-0.7317\frac{T}{t_\mathrm{L}}\right), \tag{7}$$

where Ψ_0 is the peak-to-mean factor calculated in Eq. (6).

The time scale, t_L, is taken to be equal to σ/ε where

$$\sigma = \tfrac{1}{3}(\sigma_u^2 + \sigma_v^2 + \sigma_w^2)$$

is the variance of the wind velocity as the mean of the three wind components u, v, and w, respectively, and ε is the rate of dissipation of turbulent energy using the following approximation:

$$\varepsilon = \frac{1}{kz}\left(\frac{\sigma_w}{1.3}\right)^3, \tag{8}$$

where $k = 0.4$ is the von Karman constant and $z = 2\,\mathrm{m}$ is the height of the receptor, the human nose. The ratio of the variances of the three components u, v and w to the horizontal wind velocity u depending on the stability of the atmosphere is given in Table 4. For stability classes 6 and 7 no change of the peak-to-mean ratio is assumed. For σ_u/u and σ_v/u, values are taken from Robins (1979), and no change with stability is assumed. σ_w/u is taken to be stability-dependent, using our long-term Sodar experience which suggests an increasing importance of σ_w compared to u in unstable conditions.

The peak concentration, C_p, is calculated by the following equation:

$$C_\mathrm{p} = C_\mathrm{m}\Psi. \tag{9}$$

The approach leading to Eq. (9) assures a gradual decrease of the peak-to-mean ratio with increasing distance,

Table 4
Variance of the three components of the wind *u, v* and *w* as a function of the stability of the atmosphere (for details, see text)

Class of stability	Variance of the wind velocity		
	σ_u/u	σ_v/u	σ_w/u
2	0.2	0.2	0.3
3	0.2	0.2	0.2
4	0.2	0.2	0.1
5	0.2	0.2	0.1

wind velocity and stability, as can be seen from Fig. 2. For classes 2 and 3, Ψ, starting at rather high values near the source and at low wind velocities, rapidly approaches 1 with increasing wind velocity and distance. This is in agreement with the premise that vertical turbulent mixing in weak winds can lead to short periods of local high-ground level concentrations, whereas the ambient mean concentrations are low. For class 4, the decrease of the peak-to-mean ratio is more gradual with increasing wind velocity and distance, because vertical mixing is reduced and horizontal diffusion is dominating the dispersion process. This is even more in the case for class 5, when the peak-to-mean ratio never exceeds 2. Compared to uncorrected peak-to-mean values reported at the beginning of Section 2.3, the damping is most effective for class 2 and decreases with increasing class number.

The problem of odour regulation is summarised by Nicell (1994) discussing the whole chain of odour sensation, discrimination, unmistakable perception (complaint level), and as a last step the degree of annoyance. Following this definition, three distances were calculated named sensation distance, discrimination distance, and complaint distance, by linear interpolation of the odour concentration calculated for discrete 41 distances between 50 and 2000 m. Following limits were used: for the detection of odour 1 OU M^{-3}, for the discrimination 3 OU m^{-3} (Schön and Hübner, 1996) and 5 OU m^{-3} to asses the annoying potential.

3. Results

The annual variation of the odour concentration, *C*, of the outlet air for the data set of the two years is shown in Fig. 3 (top panel). The line shows the moving average

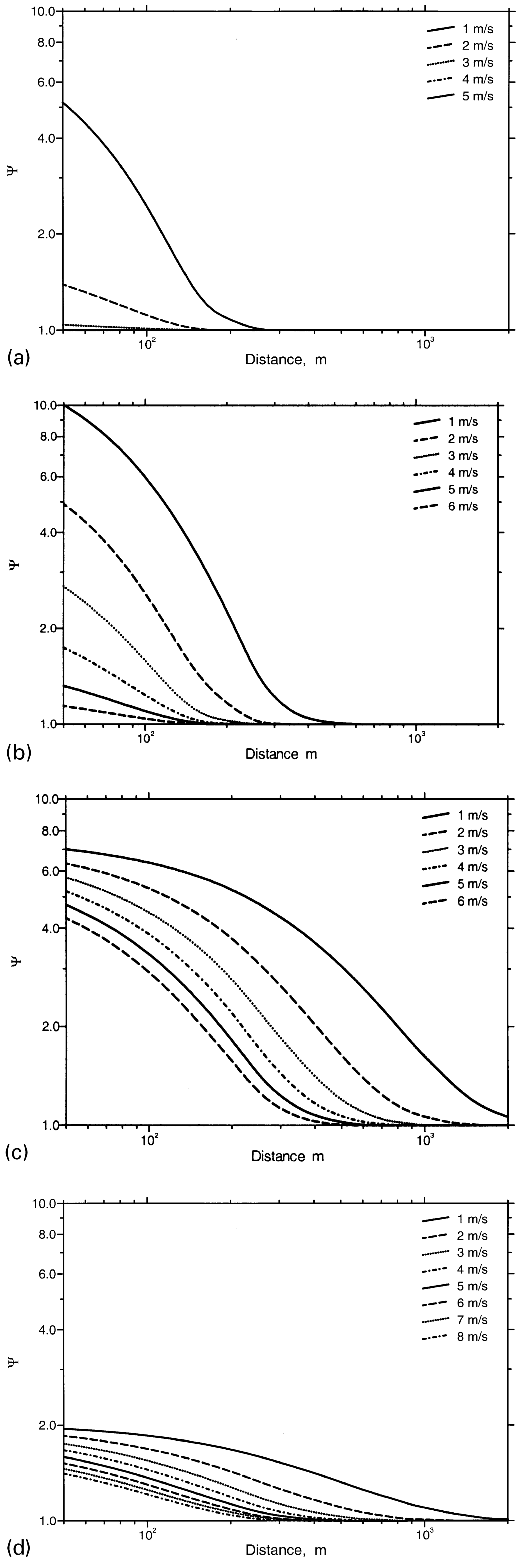


Fig. 2. Dependence of the attenuation function of the peak to mean ratio with distance for stability classes 2 (a), 3 (b), 4 (c) and 5 (d) for all classes of wind velocity which occur at Wels (see also Tables 2 and 3).

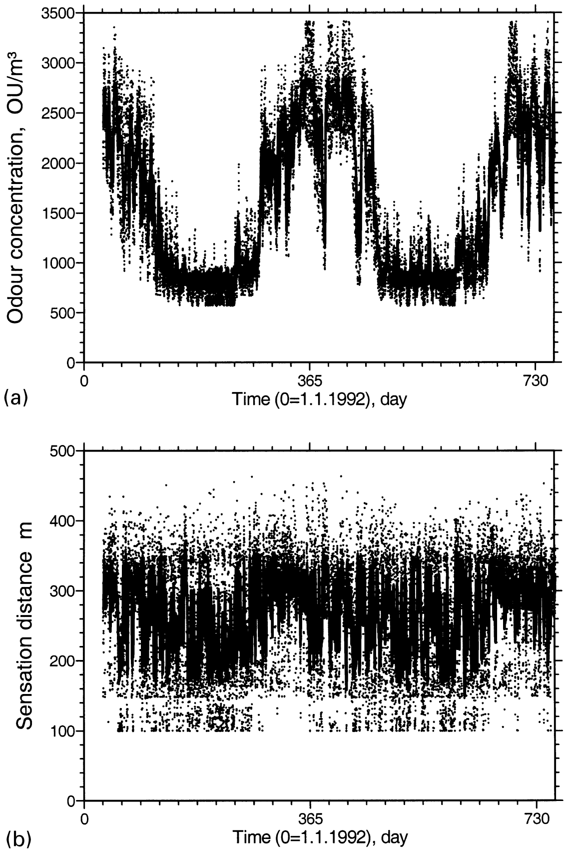


Fig. 3. Calculated odour concentration in OU m^{-3} of the outlet air (a) and sensation distance in m (odour threshold 1 OU m^{-3}) (b). Each point represents a half-hour mean value, calculated by the time series of meteorological elements at Wels.

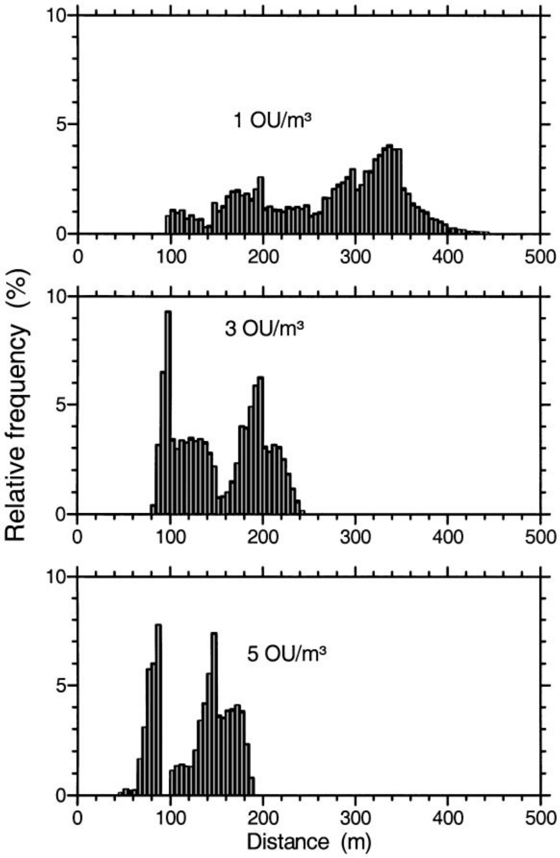


Fig. 4. Relative frequency distribution (%) of the distance in m for sensation (1 OU m^{-3}), discrimination (3 OU m^{-3}), and annoyance (5 OU m^{-3}).

(over 24 h) of the odour concentration to eliminate the diurnal variation. The odour concentration of the outlet air is characterised by a pronounced seasonal variation between low values in summer and about three times higher values in winter. The sensation distance (bottom panel) does not show this strong variation over the year. There is, however, a tendency for lower sensation distances in the summer months compared to the winter months. This is caused by generally lower wind velocities during summer and about ten times higher occurrence of stability class 2 (Table 3) which leads to high concentrations in the vicinity of the source.

The relative frequency distribution of the distances for sensation (1 OU m^{-3}), discrimination (3 OU m^{-3}), and annoyance (5 OU m^{-3}) are shown in Fig. 4. The sensation distance varies between about 90 and 450 m, the discrimination distance between about 80 and 250 m, and the distance of annoyance between 40 and almost 200 m for the livestock husbandry investigated. The higher the threshold, the smaller the range of distances, as expected. The distributions show several peaks, but none of the distance intervals occurs at frequencies above 10%. For the sensation distance, the main peak occurs at rather large distances, which is probably caused by cases of high wind velocities and stability class 4 which occur frequently, but do not show exceedance of the discrimination or the annoyance levels. The latter show two distinct peaks at low and middle distances. The peaks at low distances are probably caused by a combination of stability class 2 and weak winds, giving rise to the highest odour concentrations near the source. The peaks at greater distances are most probably caused by stable situations (SC = 6 and 7). The dependence of the threshold distance on the stability class can more clearly be seen from the example in Fig. 5, where odour concentration with distance is displayed for selected half-hours on 8 September 1992, with a large variety of stability conditions, ranging from SC = 2 (very unstable) to SC = 7 (very stable).

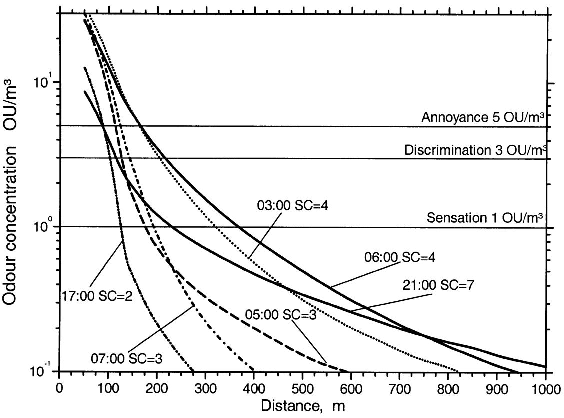


Fig. 5. Calculated odour concentration as a function of the distance for 8 September 1992. On this day, the stability of the atmosphere varied between class SC = 2 (very unstable) and class SC = 7 (very stable).

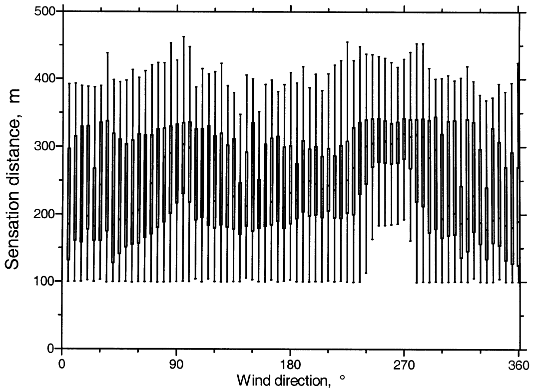


Fig. 6. Box plot (median, quartiles, the inner fences) for the sensation distance (1 $\mathrm{OU\,m^{-3}}$) as a function of wind direction.

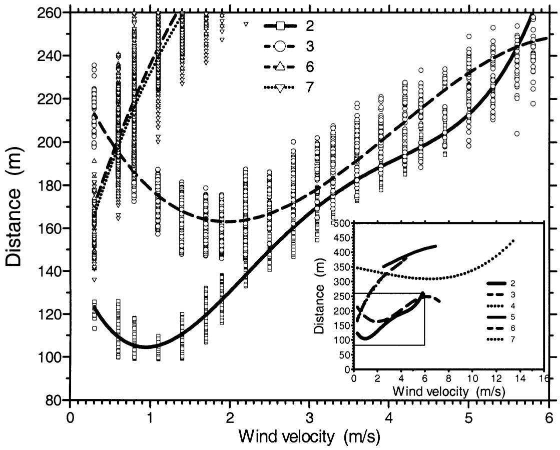
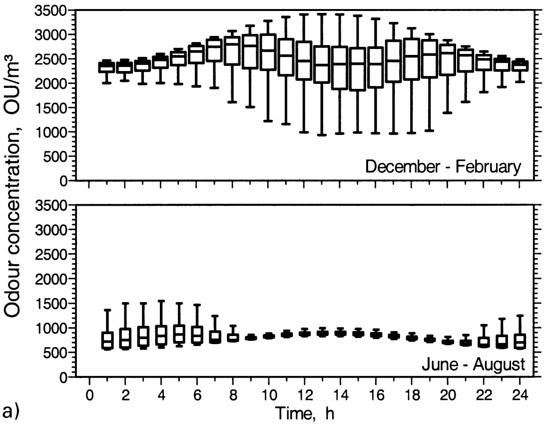


Fig. 7. Influence of wind velocity and stability of the atmosphere on the distance of sensation (1 $\mathrm{OU\,m^{-3}}$) The small panel shows the fit of a polynom of fourth order without the data points for all classes of stability which occur at Wels (see also Table 1).

In Figs. 6 and 7, the influence of the meteorological parameters of wind direction, wind velocity and stability of the atmosphere on the sensation distance are analysed and presented by boxplots. For the prevailing wind directions at Wels (W and WSW, as well as E and ENE), the median of the sensation distance is highest (around 300 m), between NW and NE, it is lowest (around 200 m; Fig. 6). The variance is smallest for westerly winds. Obviously, wind velocity and stability of the atmosphere are not homogeneously distributed over the wind directions. In Fig. 7, these two parameters are analysed. The dominant effect for low sensation distances to occur, which are most interesting for the environmental impact of the livestock building, is the stability. For unstable (SC = 2 and 3) and very stable conditions (SC = 6 and 7) combined with low wind velocity, the minimum sensation distances can be observed. From the occurrence frequencies of these classes, such minimum sensation distances can occur during daytime (high insulation) as well as during nocturnal radiative cooling situations.

The mean diurnal variation of the odour concentration of the outlet air and of the sensation distance (1 $\mathrm{OU\,m^{-3}}$) were calculated separately for winter (December–February) and summer (June–August). In Fig. 8, the median boxes for every hour of the day show the different patterns for these two periods. The day–night variation of the odour concentration of the outlet air is more pronounced during winter than during summer. In winter, the variability is larger during daytime when it covers the whole range of possible concentrations than during the night; in summer, the opposite is true. The median does not vary much throughout the day. In summer during daytime, the odour concentration of the outlet air is close to the minimum with a small variability (about 50% of the mean). In general, there is less variability in odour concentrations during summer than during winter. The larger odour concentrations during winter are a result of the smaller volume flow.

The median of the sensation distance (Fig. 8b) is around 300 m in winter, with only a small variation throughout the day. In summer, it varies between almost 300 m at night and less than 200 m during daytime. The variability of the sensation distance is always larger during daytime. The daytime variability of wind velocity and stability classes (from 2 to 4) obviously leads to a very different sensation distances, comprising the whole range of possible values (Fig. 4). Nighttime stability causes larger distances, and because of the generally lower wind velocities the variability is not as large as during daytime.



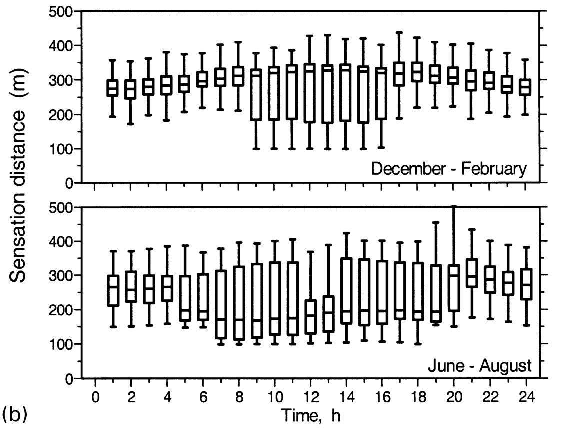


Fig. 8. Diurnal variation of (a) the odour concentration in OU m^{-3} and (b) the sensation distance in m (for 1 OU m^{-3}) during winter months (December–February) and summer months (June–August) as median boxes (median, upper and lower hinges, and the extremes).

The annual variation is shown in Fig. 9 as median box plots of the odour concentration of the outlet air and by monthly medians of the distances for sensation, distinction and annoyance. Odour concentration and these distances go in parallel, i.e. lower values are calculated for the summer months compared to the winter months. However, the reduction in the odour concentration amounts to a factor of almost 3, whereas the variability in all the distances is far less than 2. This again confirms that the influence of the meteorological conditions on the distances is larger than that of the odour emission.

The diurnal variation of the parameters of the ventilation system and the sensation distance as calculated by the model is shown for four exemplary days with special meteorological conditions (5–8 September 1992) in Fig. 10. In the lower panel of Fig. 10a the temporal course of the odour flow and the volume flow of the ventilation system is shown. The diurnal variation of the first is mainly caused by the animal activity (Eq. 4) and the temperature dependence (Eq. (3)). The volume flow is predominantly influenced by the characteristics of the control unit (Eq. (2)). The indoor temperature itself is calculated by the sensible energy balance. Eq. (5) gives the odour concentration of the outlet air (upper panel of Fig. 10a), showing a diurnal variation in the time pattern too.

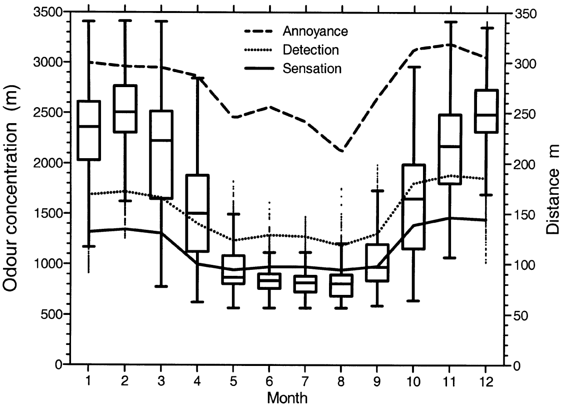


Fig. 9. Annual variation of the odour concentration as median boxes (median, upper and lower hinges, and the extremes) and the median of the distances for sensation, distinction and annoyance for all months.

Besides the variation of the parameters of the livestock building the meteorological situation is often changing from a stable situation during nighttime (stability class 6 (stable) or 7 (very stable)) to a well-mixed boundary layer during daytime (Fig. 10b). The first day, however, starts with above-average wind velocity and stability class 4. This is probably the reason why the volume flow does not reach a maximum value on 5 September. Meteorological conditions on 5 September lead to relatively large sensation distances, comparable to the nights from 7 to 8 September, when also stability class 4 prevails. 6 September shows a large amplitude of air temperature due to clear skies giving rise to nocturnal radiative cooling accompanied by a high stability (SC = 7) and to pronounced surface heating after sunrise (SC = 2 and 3). On this day, the volume flow (Fig. 10a, lower panel) of the ventilation system varies between the maximum V_{max} during daytime and the minimum V_{min} during night (Eq. (7) and Table 1). In parallel, the sensation distance also shows a large temporal variability. On the next two days, this effect was reduced due to cloudiness that decreased day–night temperature differences. Nevertheless, the diurnal variation of the air temperature causes a corresponding variation of the volume flow, and hence the contrary time course of the odour concentration of the outlet air. The sensation distance (odour threshold 1 OU m^{-3}) does not go parallel to the odour

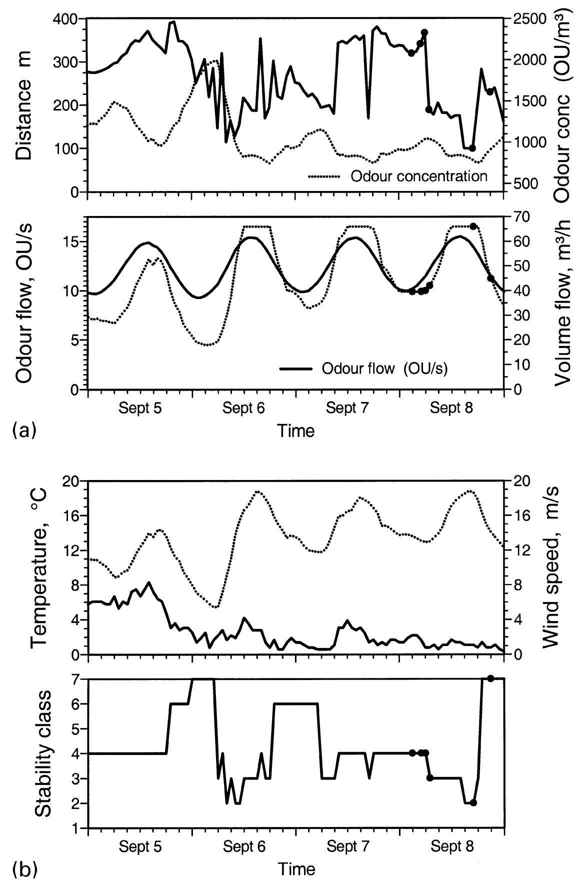


Fig. 10. Emission and meteorological situation between 5 and 8 September 1992. The points highlight the time of the day where the odour concentration as a function of distance is drawn in Fig. 7) (a) Calculated (————) sensation distance in m and (------) odour concentration in OU m^{-3} (upper panel); (————) odour flow in OU s^{-1} and (------) volume flow in m^3 h^{-1} per animal (lower panel). (b) Ambient conditions: (-----) outdoor air temperature in °C); (————) wind velocity in m s^{-1} (upper panel); stability class of the boundary layer (lower panel).

concentration of the outlet air or to any of the parameters displayed in Fig. 10. Its variability is caused in a complex way by the change of the meteorological parameters (Fig. 10b) and their influence on the dispersion. This example shows again that, compared to the variation of the emission (odour concentration and volume flow of the outlet air), the dispersion has a dominant influence on the variability of the sensation distance.

4. Discussion and conclusions

The dynamic Austrian odour dispersion model (AODM) consists of three modules: the first calculates the odour emission of the livestock building, the second estimates ambient concentrations, and the third takes into account the conversion to instantaneous values.

The odour emissions module is described in detail by Schauberger et al. (1999, 2000) and outlined in Section 2.1. The consideration of the diurnal variation of the odour emission is the most important feature of this module. Since odour is mainly released by the animals, by polluted surfaces and by the feed, the diurnal variation of the emission is assumed to be in phase with animal activity. Because the daily course of the animal activity and the volume flow of the ventilation system counteract each other, the daily ratio between maximum and minimum odour concentration of the outlet air is reduced – compared to the case when no diurnal variation is taken into account – according to Eq. (5).

The diurnal variation can be derived by various parameters inside the livestock building. Total energy and CO_2 release by animals show a typical diurnal variation (Pedersen and Takai, 1997; Schauberger and Pilati, 1998a, b; van Ouwerkerk and Pedersen, 1994), strongly correlated to the physical animal activity (Pedersen and Pedersen, 1995). The release of odour seems to be very similar to ammonia. However, a correlation between the two airborne pollutants is not very strong (Oldenburg, 1989). Therefore, ammonia cannot be used as a surrogate substance for odour. Nevertheless, the ammonia concentration shows a distinct day/night fluctuation. For eight different sow houses the ratio of the mean ammonia concentration between day and night is about 1.28 for the daily extremes, 2.10 (Phillips et al., 1998). As the ventilation flow counteracts this diurnal variation due to the animal activity (Eq. (9)), a weaker diurnal variation of the odour concentration of the outlet air appears (Schauberger et al., 1999). Dust, as an important carrier of odorants (Hoff et al., 1997), shows the same diurnal variation (Pedersen, 1993; CIGR, 1994). According to these findings, the diurnal variation of the odour release was assumed to vary in the same way as that of the total heat release.

The use of the Gaussian regulatory model (ÖNorm M 9440, 1992/1996) as the second module to calculate odour concentration imposes some restrictions to the generalisation of the results achieved. The model is applicable only in flat terrain. Building influence on the dispersion as well as the influence of low-level capping inversions on the concentrations are not considered. The model is reliable only for wind velocity equal to or above 1 m s^{-1} and is advised to be applied for distances equal to or larger than 100 m. Treating more complex meteorological or topographic conditions, more elaborate dispersion models have to be used. The restrictions are, however, not very severe because many large livestock farms in Austria are situated in rather flat terrain. Concentrations during calm wind conditions could be considered in a first step according to ÖNorm M 9440

(1992/1996) by multiplying the concentration calculated for the 1 $\mathrm{m\,s^{-1}}$ wind velocity and the appropriate stability class by a factor of 1.5.

The time series of meteorological parameters used for this study is representative for the Austrian flatlands and the North-Alpine foreland. These are regions where, apart from valleys with their specific flow regimes, good ambient air movement prevails throughout the year. Situations which can give rise to enhanced pollution concentrations, such as calm conditions, low-base temperature inversions or periodically changing wind regimes, are not as frequently observed in these areas as, for example, in inner-Alpine valleys or in the basins south of the Alps. The application of the Gauss model in the present investigation is therefore assumed to be justified (Pechinger and Petz, 1997).

Since the sensation of odour depends on the momentary concentration rather than on a mean value calculated by the Gaussian plume model over a longer period of integration, proper values of the peak-to-mean ratio have to be determined. The importance of the instantaneous concentration is discussed by Mylne (1990) for a nonlinear dose–response relationship of chlorine as a toxic substance. For odour a similar situation arises: Firstly the odour threshold has to be exceeded to receive a sensation of odour, secondly odour intensity goes with the logarithm of the concentration (e.g. Misselbrook et al., 1993). The procedure is outlined in Section 2.3. The use of Eq. (6) only takes into account the dependence on atmospheric stability, but not the damping of the peak-to-mean ratio with increasing distance and wind velocity. This is achieved by an attenuation function (Eq. (7)) which depends on travel time and a measure of the Lagrangian time scale (Mylne, 1992). The result is given in Fig. 2 which shows that, with increasing wind velocity and distance, a peak-to-mean ratio of 1 is more rapidly approached for stability classes 2 and 3 than for 4 and 5. This is in accordance with the premise of decreasing vertical turbulent mixing with increasing static stability of the atmosphere and increasing wind velocity. Uncertainties arise in the necessary determination of the variances of the three wind components depending on stability (Table 4). The values given there are seen as a first approximation, and more investigations will be necessary to properly assess a possible dependence on stability of the variances of the horizontal wind components as well as a final determination of the stability dependence of the variance of the vertical wind by measurements with ultrasonic anemometers.

The Gauss model, extended by the peak-to-mean module, has been used to calculate the sensation, discrimination and annoyance distances for the scenario outlined in Table 1, and the results are given in Section 3. Annual and diurnal variations as well as the influence of selected meteorological parameters have been investigated. For the configuration chosen, the distances for the three odour levels lie in a relatively narrow range (within 500 m; see Fig. 4). Qualitatively, this is in overall agreement with various national guidelines, discussed by Piringer and Schauberger (1999). The annual course of the distances (Figs. 3 and 9) shows a tendency to larger values in winter compared to summer. The detailed meteorological investigation of the sensation distance (Figs. 6–8 and 10) confirms a stronger dependence on meteorology than on the odour emission rate. Lower distances in summer are mainly caused by lower wind velocities and the more frequent occurrence of stability class 2 (Table 3) leading to maximum odour concentrations near the source. Higher wind velocities and the frequent occurrence of stability class 4 increase the distances during the winter months. The effect of air temperature, wind velocity and atmospheric stability on the sensation distance is most easily assessed from Fig. 10, which clearly shows the dominance of meteorological parameters compared to measures of the odour emission rate.

The approach chosen is judged to have given satisfactory results. The dependence on meteorological parameters shows the expected behaviour, i.e. lower distances occur during the summer months compared to the cold season due to lower wind velocities and far more frequent unstable situations. Overall, the results indicate a stronger dependence of the distances from meteorological conditions than from odour emission parameters.

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