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Calculating Direction-dependent Separation Distance by a Dispersion Model to avoid Livestock Odour Annoyance

G. Schauberger[1]; M. Piringer[2]; E. Petz[2]

[1] Institute of Medical Physics and Biostatistics, University of Veterinary Medicine Vienna, Veterinärplatz 1, A 1210 Vienna, Austria; e-mail of corresponding author: gunther.schauberger@vu-wien.ac.at
[2] Central Institute for Meteorology and Geodynamics, Hohe Warte 38, A 1190 Vienna, Austria

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Using a dispersion model to calculate ambient odour concentrations, the separation distance between livestock buildings and residential areas is defined by the odour impact criteria incorporating the probability of exceeding a pre-selected odour threshold in odour units (OU) per cubic metre. The dynamic Austrian odour dispersion model (AODM), a Gaussian model, is used to calculate the direction-dependent separation distances for several combinations of these two values, which represent the protection level of various land use categories. The calculated direction-dependent separation distances are a function of the prevailing wind velocity and atmospheric stability conditions. At a site in the Austrian North-alpine foreland, the direction-dependent separation distance for a 1000-head pig unit (calculated on the basis of a 2-year time series of meteorological data) for pure residential areas (3% probability of threshold exceedance over the year for an odour threshold of 1 OU m^{-3}) lies between 99 m (for northerly winds with a probability of less than 3% per year) and 362 m (for westerly winds with a probability of 34%). For the main wind directions, West and East, odour sensation can be expected more often for higher wind velocities and a neutral or stable atmosphere around sunset. North and South winds show the typical diurnal variation of a local valley wind system with predominantly northerly daytime up-valley and southerly nighttime down-valley winds. Odour sensation is therefore most likely around noon for North winds and during nighttime for South winds.

1. Introduction

Odour is one of the major nuisances in the environment caused mainly by livestock production and industry, *e.g.* rendering plants (Schauberger *et al.*, 2001). One way to reduce odour nuisance is to use a separation distance between the odour source and residential areas.

Apart from empirical guidelines used to estimate the separation distance (Piringer & Schauberger, 1999), it can also be calculated by dispersion models. The following information is required: odour release (Martinec *et al.*, 1998; Schauberger *et al.*, 1999), a dispersion model (e.g. ÖNorm M 9440, 1992/96), instantaneous odour concentration (Schauberger *et al.*, 2000a), and the validation of the instantaneous odour concentration taking into account the Frequency, Intensity, Duration and Offensiveness of odour sensation (FIDO) and the 'reasonableness' of the situation for neighbours.

The AODM consists of three modules: the first calculates the odour emission of the livestock building, the second estimates mean ambient concentrations using the Austrian Gaussian regulatory dispersion model, and the last transforms the mean odour concentration of the dispersion model to instantaneous values that depend on wind velocity and atmospheric stability. The direction-dependent separation distance is defined as the distance from the source where a sensation level dependent on a pre-selected odour impact criterion occurs. The odour impact criteria used in this study are a combination of odour threshold and probability of threshold exceedance.

Odour concentrations calculated by dispersion models have to be evaluated against the odour impact criteria. Watts and Sweeten (1995) suggest that the FIDO factors can be used to assess odour nuisance. Besides these FIDO factors, the concept of reasonableness should be considered (*e.g.* land use category).

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Notation

- a exponent of the power function of Eqn (1)
- C_m mean concentration calculated for an integration time t_m, OU m^{-3}
- C_p peak concentration for an integration time t_p, OU m^{-3}
- P_i probability of the ith wind direction class, %
- p_T probability of threshold exceedance of the odour impact criterion, %
- $p_{T,i}$ direction-dependent probability of threshold exceedance for an odour threshold T and a certain wind direction i, %
- S separation distance, m
- T odour threshold of the odour impact criterion, OU m^{-3}
- t_L Lagrangian time scale, s
- t_m integration time of the mean concentration, s
- u mean wind velocity, m s^{-1}
- x distance, m
- τ time of travel, s
- Ψ peak-to-mean factor in the distance x
- Ψ_0 peak-to-mean factor close to the odour source
- i classes of wind direction (0 North, 1 Northeast, 2, East ...)

Miner (1995) defines reasonableness of odour sensation as odour causing fewer objections within a community where odour is traditionally part of the environment. Lohr (1996) found that personal knowledge of the operator of the livestock unit, long-term residency, economic dependence on farming, familiarity with livestock farming and awareness of the agricultural–residential context are related to a reduced incidence of formal complaints. Only one paper was found which presents the result of a dispersion model and a sociological survey assessing the percentage of 'annoyed' and 'very annoyed' people in the vicinity of an odour source (Miedema & Ham, 1988). Winneke *et al.* (1990) give a probability of threshold exceedance of 3–5% per year for a person of average sensitivity not to feel annoyed by odour from livestock. An overview of the odour impact criteria used in several countries can be found by Schauberger *et al.* (2001).

In this paper, the Austrian odour dispersion model (AODM) is used to calculate direction-dependent separation distances for a typical agricultural site in the Austrian flatlands north of the Alps based on a 2-year time series of meteorological data (Section 2.3). In Section 2, the method to calculate the separation distance in the AODM and the meteorological conditions are outlined. The resulting separation distances are presented in Section 3, as well as a statistical analysis based on meteorological parameters. A discussion highlighting the achievements and shortcomings of the method used is given in Section 4, followed by brief conclusions in Section 5.

In many cases the dispersion models used for odour are not adapted to the special needs to describe the human odour sensation. The model presented tries to mimic the human perception by the assessment of the ambient instantaneous odour concentration.

2. Materials and methods

2.1. *Description of the Austrian odour dispersion model*

The dynamic Austrian odour dispersion model (AODM) consists of three modules: (1) calculation of the odour emission of the livestock building; (2) estimation of the mean ambient concentrations using the Austrian Gaussian regulatory dispersion model; and (3) transformation of the mean odour concentration of the dispersion model to instantaneous values depending on wind velocity and atmospheric stability.

The odour release from a livestock building originates from the animals, manure-polluted surfaces inside the building and the feed. Outdoor odour sources such as slurry tanks or feed storage facilities are not considered. The concentration of odorants can be handled like other volatile compounds and can be measured by an olfactometer in odour units per cubic metre (OU m^{-3}). One odour unit is defined as the amount of odorants present in one cubic metre of odorous gas (under standard conditions) which elicits a physiological response from a panel (detection threshold) equivalent to that elicited by 123 μg n-butanol dispersed in one cubic metre of odourless gas at standard conditions (CEN, 1999).

The emission module of the AODM is based on a steady-state balance of the sensible heat flux, used to calculate the indoor temperature, and the ventilation rate of the livestock unit (Schauberger *et al.*, 2000b). The corresponding odour flow in OU m^{-3} is assessed by a simple model for odour release described by Schauberger *et al.* (1999, 2000b). The chosen system parameters typical for a livestock building in middle Europe (Schauberger *et al.*, 1995), are summarized in Table 1. The results were calculated for a mechanically ventilated pig fattening unit with 1000 pigs. The building is moderately insulated. The assumed space per animal is

Table 1
Typical system parameters for a 1000-pig fattening unit used to calculate the indoor climate and the related odour emission

Parameter	
Mean total energy release per pig continuous fattening between 30 and 100 kg	188 W
Minimum volume flow per pig design value for the ventilation system taking into account the maximum accepted indoor CO_2 concentration of 3000 ppm	13·1 m^3/h^{-1}
Maximum volume flow per pig design value for the ventilation system taking into account the maximum temperature difference between indoor and outdoor for summer of 3 K for a outdoor temperature of 30°C	66·0 m^3 h^{-1}
Area of the building (ceiling, walls, windows, doors) per animal	1·35 m^2
Thermal transmission coefficient	2·0 W m^{-2} K^{-1}
Set point temperature of the control unit	18°C
Bandwidth of the control unit	4 K

0·75 m^2 according to welfare guidelines. The height of the exhaust chimney was 7 m. The following parameters were calculated every half-hour over the 2-year period: outlet air temperature, outlet air velocity, volume flow of the ventilation system, odour concentration of the outlet air. The odour flow in OU s^{-1} is calculated by the product of the volume flow of the building in m^3 s^{-1} and odour concentration of the outlet air in OU m^{-3}.

The odour concentration at the centre line of the plume is calculated by the Austrian regulatory dispersion model (ÖNorm M 9440, 1992/96). The model has been validated internationally (*e.g.* Pechinger & Petz, 1999). 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 Turner (1964) and modified by Reuter (1970). Transformations of discrete stability classes to the Monin–Obukhov length scale are given by Golder (1972). Reuter stability classes are presented in Section 2.3.

The use of the Gaussian regulatory model ÖNorm M 9440 (1992/96) imposes some restrictions to the generalization of the results achieved (Schauberger *et al.*, 2001). 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.

The odour sensation is triggered by the odour stimulus and characterized 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. The regulatory model calculates half-hourly mean concentrations. The peak value as a measure of the short-term fluctuations is derived from the half-hourly mean value using Eqn (1) which depends on the stability of the atmosphere (Smith, 1973):

$$\frac{C_p}{C_m} = \left(\frac{t_m}{t_p}\right)^a \tag{1}$$

where C_m is the mean concentration in OU m^{-3} calculated for an integration time of t_m *in* s; C_p is the peak concentration in OU m^{-3} for an integration time of t_p *in* s; and a is the exponent of the power function, related to the stability of the atmosphere. Using a value for t_m of 1800 s (calculated half-hour mean value) and t_p of 5 s (duration of a single breath), the following peak-to-mean factors Ψ_0, depending on atmospheric stability, are derived by a quadratic function based on the values of Smith (1973) for stability classes 2 to 7: 43·25, 20·12, 9·36, 4·36, 1·00, and 1·00, respectively. These factors are only valid close to the odour source. Due to turbulent mixing, the peak-to-mean ratio is assumed to be reduced with increasing distance from the source using the wind velocity and the stability of the atmosphere. It is modified by an exponential attenuation function (Mylne & Mason, 1991) using the time of travel τ with the distance x and the mean wind velocity u and the Lagrangian time scale t_L as a measure of the stability of the atmosphere (Mylne, 1992):

$$\Psi = 1 + (\Psi_0 - 1)\exp\left(-0\cdot7317\frac{\tau}{t_L}\right) \tag{2}$$

where Ψ is the peak-to-mean factor at the distance x in m, depending on the mean wind velocity u in m s^{-1}, and the time of travel τ in s; Ψ_0 is the peak-to-mean factor, defined as the ratio of the mean concentration C_m, and the peak concentration C_p, calculated in Eqn (1), valid close to the odour source.

The meteorological background to calculate the instantaneous values using this peak-to-mean parameterization is described in detail by Schauberger *et al.* (2000a).

The direction-dependent probability threshold $p_{T,i}$ of exceeding an odour threshold T and a wind direction i is given by

$$p_{T,i} = \left| \begin{array}{ll} \dfrac{p_T}{p_i} & \text{for}\, p_T < p_i \\ 1 & \text{for}\, p_T \geqslant p_i \end{array} \right. \tag{3}$$

2.2. *Calculating sensation and separation distance*

For each half-hourly mean value, the separation distance is calculated. The separation distance is defined as the distance from the source where the odour concentration reaches the pre-selected odour concentration threshold of the impact criterion. For a North wind, this means a corresponding separation distance for a property to the South of the odour source. The separation distance is calculated in two steps. Firstly, sensation distances are calculated, defined as distances from the source where the momentary odour concentration is $1\,\mathrm{OU\,m^{-3}}$. For each half-hourly period of the meteorological two-year time series, momentary direction-dependent odour concentrations are calculated for 41 distances between 50 and 2000 m (in 50 m intervals) from the source. The sensation distances are found by linear interpolation between the discrete data points and classified into eight 45° wind direction sectors.

The second step is the calculation of the separation distance. Therefore, selected limits of the combination of odour concentration threshold T and probability of the threshold exceedance p_T are taken as defined in Table 2. A threshold of $1\,\mathrm{OU\,m^{-3}}$ and a probability of the threshold exceedance of 3% indicates that, during a typical year, there are 525 out of 17 520 half-hourly periods (3%) during which the ambient odour concentrations will be momentarily above $1\,\mathrm{OU\,m^{-3}}$. On the basis of the cumulative probability of the sensation distances for each of the eight wind direction sectors, the separation distances are calculated selecting the probability of threshold exceedance p_T for each of the selected odour impact criteria (Table 2, labelled with G-PURE, G-MIX, G-AGR, AUT, and AUS). For example, the 97percentile of the cumulative probability distribution $P_T = 97\%$ (corresponding to a probability of threshold exceedance p_T of 3%, according to $P_T = 1 - p_T$) of the $1\,\mathrm{OU\,m^{-3}}$ threshold gives the separation distance for pure residential areas and general residential areas according to the limits used in Germany (G-PURE, Table 2). For a selected wind direction sector, the distance at which this definition is fulfilled is called separation distance.

2.3. *Meteorological conditions*

The meteorological data for 30 January 1992 to 31 January 1994 were collected at Wels, a site representative of the Austrian flatlands north of the Alps. The sample interval was 30 min. The city of Wels in Upper Austria is a regional shopping and business centre with a population of about 50 000. The surrounding area is rather flat and consists mainly of farmland. The mean wind velocity 10 m above the mean rooftop level of 15 m is $2{\cdot}2\,\mathrm{m\,s^{-1}}$ with a maximum velocity of about $13\,\mathrm{m\,s^{-1}}$. The distribution of wind directions is shown in *Fig. 1*. The prevailing wind directions at Wels are west, as well as east. Calm conditions according to the Austrian ÖNorm M 9440 (1992/96) with wind velocities less than $0{\cdot}7\,\mathrm{m\,s^{-1}}$ occurred 11·2% of the time; light winds (wind velocity less than $1\,\mathrm{m\,s^{-1}}$) constituted 26·5% of all cases. Less than 10% of all wind velocities were higher 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 annual precipitation is 838 mm (mean over the period 1961–1990).

Discrete stability classes (Section 2.1) are still a widespread approach for considering ambient weather conditions in dispersion calculations. In Austria, the most widespread method to determine stability classes is based on sun elevation angle, cloud cover and low cloud base height, and wind speed (Reuter, 1970). From a combination of the first three parameters, a so-called radiation index is calculated. The index assumes negative values during nighttime and positive values during daytime; a zero value can occur during both day and night. The stability classification scheme based on the radiation index and the wind speed is shown in Table 3. The cloud data are measured at the Linz–Hörsching airport, about 13 km from Wels. Within the Reuter scheme, classes 2–7 can occur in Austria.

Stability classes 2 and 3, which by definition occur only during daylight hours in a well-mixed boundary layer, class 3 allowing also for cases of high wind velocity and moderate cloud cover, occur more frequently below or around the average wind velocity. They occur in 26% of all cases. Stability class 4, representing cloudy and/or windy conditions including precipitation or fog, is by far the most common

Table 2

Criteria to define the separation distance used in Germany (Knauer, 1994; Kypke, 1994), Austria (Stangl *et al.*, 1993), and Australia (Jiang & Sands, 1998); the criteria are given by the probability of threshold exceedance p_T of an odour concentration threshold T; criteria used to calculate the separation distance for this paper are labelled

Country	*Odour concentration threshold (T), $OU\,m^{-3}$*	*Probability of threshold exceedance for the odour concentration threshold (p_T), %*	*Land use category*	*Comment*	*Label*
Germany					
	1	3	Pure residential areas and residential areas		G-PURE
	1	5	Residential and structured areas		G-MIX
	1 3	8 3	Restricted business-areas and village-area with mixed utilisation	The higher separation distance of the two criteria has to be used	
	1 3	10 5	Village-areas with predominantly agricultural utilisation	The higher separation distance of the two criteria has to be used	G-AGR
Austria					
	1 3	8 3		Threshold for reasonable odour sensation for medical purpose The higher separation distance of the two criteria has to be used	AUT
Australia					
	5	0·5	Rural and urban area		AUS
	2	0·5	Residential area	New South Wales	
	10	0·5	Residential areas	Victoria	

dispersion category because it occurs during both day and night (43%). Its occurrence peaks at a wind velocity of 2–3 $m\,s^{-1}$. Wind velocities greater than 6 $m\,s^{-1}$ are almost entirely connected with class 4. Class 5 occurs with higher wind velocity during nights with low cloud cover, a situation which is not observed frequently at Wels (6%). 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.

3. Results

The results for the method outlined in Section 2.2 are presented for a mechanically ventilated livestock unit of 1000 pigs being fattened. Direction-dependent separation distances are calculated and analysed meteorologically.

The influence of the wind direction on the cumulative probability of the sensation distances for the odour impact criterion G-PURE (Table 2) is presented in *Fig. 2*. The cumulative probability distributions for the four cardinal directions (N, E, S, W) differ according to the probability of the wind velocity and the atmospheric stability for these directions (Schauberger *et al.*, 2001). The direction-dependent probability of threshold exceedance $p_{T,i}$ is calculated by Eqn (3) and marked by symbols on the cumulative probability distributions.

The direction-dependent probabilities of threshold exceedance $p_{T,i}$ for all eight classes of the compass are calculated by Eqn (3) and summarized in Table 4 for an odour threshold T of 1 $OU\,m^{-3}$ and various odour probabilities of threshold exceedance p_T. For the G-PURE criterion (Table 2; *i.e.* $T = 1\,OU\,m^{-3}$ and $p_T = 3\%$), only one out of the eight directions shows a direction-dependent probability of the threshold exceedance of 100%. For a probability of threshold

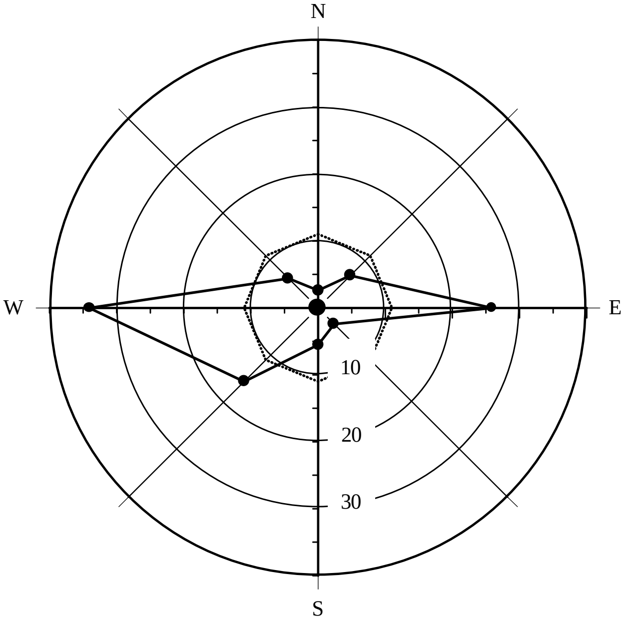

Fig. 1. Frequency distribution of the wind direction at Wels: ——, relative frequency for eight 45° sectors; •••••, calm conditions according to the ÖNorm M 9440 (1992/1996) with a wind velocity less than 0·7 m s^{-1} evenly distributed over all directions

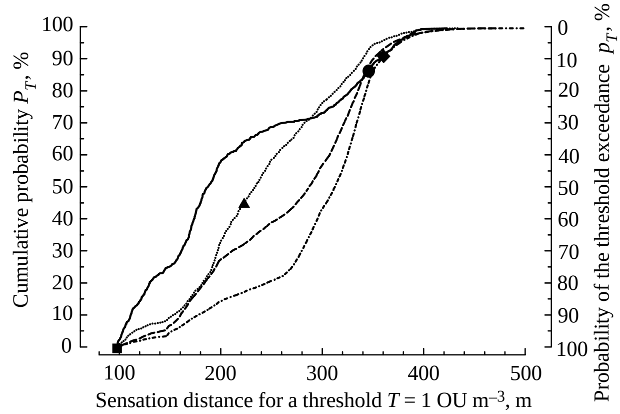

Fig. 2. Cumulative probability distribution P_T for the direction-dependent sensation distance for an odour threshold T of 1 OU m^{-3}) for North (——), East (– – –), South (•••••), West (–•–•) wind occurring 2·6, 25·9, 5·5, and 34·1% per year, respectively. The symbols mark the direction-dependent probability of threshold exceedance $p_{T,i}$ which results according to Eqn (3) in the separation distance for North (■), East (●), South (▲), West (◆) on the basis of the odour impact criterion G-PURE (Table 2; odour threshold T = 1 OU m^{-3} and a probability of exceeding this threshold p_T = 3% of the year). The differences in the cumulative probability distributions of the four wind directions are caused by varying meteorological conditions, especially wind velocity and stability of the atmosphere

Table 3
Stability classes, depending on radiation index and wind velocity in m s^{-1}

	Radiation index						
Wind velocity, m s^{-1}	*−2*	*−1*	*0*	*1*	*2*	*3*	*4*
< 1·8	7	6	4	3	2	2	2
1·8 to 3·3	6	5	4	4	3	2	2
3·4 to 3·8	5	4	4	4	3	2	2
3·9 to 4·8	5	4	4	4	3	3	2
4·9 to 5·3	5	4	4	4	4	3	3
5·4 to 5·8	4	4	4	4	4	3	3
> 5·8	4	4	4	4	4	4	3

exceedance p_T of 10%, five of eight direction-dependent probabilities of threshold exceedance $p_{T,i}$ reach 100%, *i.e.* all half-hourly values of this wind direction result in an odour sensation. The higher the probability of threshold exceedance of the odour impact criterion p_T, the higher the direction-dependent probability of threshold exceedance.

In Table 5 and Fig. 3, the calculated direction-dependent separation distances are shown for the five odour impact criteria labelled in Table 2. For northerly winds (for a southward separation distance), the separation distance is lowest, caused by the low probability for this wind direction of 2·6%. The maximum of the direction-dependent separation distances is found for westerly winds (eastward protection; *Fig. 7*).

Table 4
Relative frequency of the eight classes of wind directions p_i and the resulting direction-dependent probability of threshold exceedance $p_{T,i}$ on the basis of an odour threshold T of 1 OU m^{-3} and a probability of threshold exceedance p_T of 0·5, 3, 5, and 10% per year, respectively; direction-dependent probabilities of threshold exceedance of 100% (all half-hourly values of this wind direction result in an odour sensation) are marked in bold

Wind direction i	*Relative frequency (p_i), %*	*Direction-dependent probability of threshold exceedance ($p_{T,i}$), %*			
		Odour impact criteria (p_T), %			
		0·5	*3*	*5*	*10*
N	2·6	19·4	**100·0**	**100·0**	**100·0**
NE	6·8	7·4	44·2	73·7	**100·0**
E	25·9	1·9	11·6	19·3	38·7
SE	3·4	14·6	87·7	**100·0**	**100·0**
S	5·5	9·2	55·0	91·6	**100·0**
SW	15·6	3·2	19·2	32·0	64·0
W	34·1	1·5	8·8	14·7	29·3
NW	6·2	8·1	48·7	81·1	**100·0**

In *Figs 4–7,* the probability of odour sensation (sum of all classes is 100%) at the separation distance (Table 5, column 3) during the two-year period is compared against the probability of the entire data set (sum of all classes is 100%; grey bars in *Figs 4–7*) for the four cardinal wind direction classes. The comparison is undertaken for four selected parameters: time of the day (hours are in Central European Time (CET); in winter, CET is UTC (universal time co-ordinated) + 1 h, in summer, CET is UTC + 2 h), time of the year in month, wind velocity, and stability class. For North winds (*Fig. 4*), no comparison is possible: The probability for a North wind (2·6%) is less than the probability of threshold exceedance $p_T = 3\%$ of the selected odour impact criterion G-PURE. This means that all the time with North winds, odour sensation occurs, and the probability of the two-year period and the time of sensation are the same.

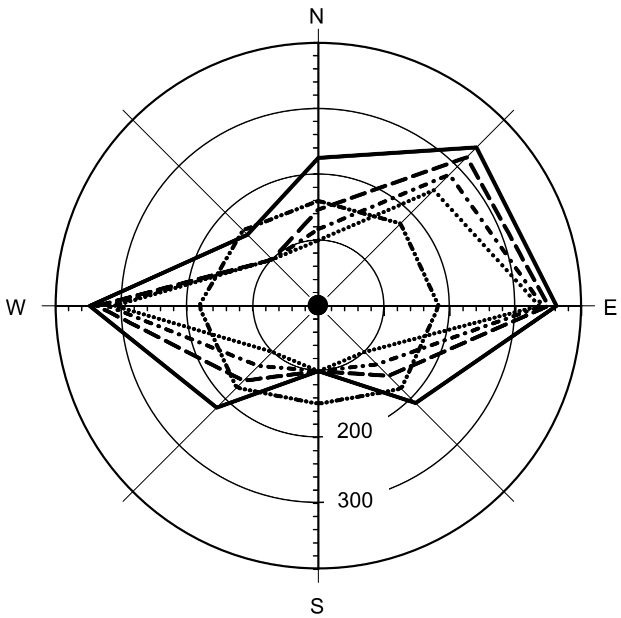

Fig. 3. Separation distances in m calculated by the model for eight wind directions based on an odour concentration threshold in $OU\,m^{-3}$ and the probability of the threshold exceedance in % of five odour impact criteria: ——, $1\,OU\,m^{-3}$ and 3% (G-PURE); – – –, $1\,OU\,m^{-3}$ and 5% (G-MIX); •••••, $1\,OU\,m^{-3}$ and 10% or $3\,OU\,m^{-3}$ and 5% (G-AGR); –•–•, $1\,OU\,m^{-3}$ and 8% or $3\,OU\,m^{-3}$ and 3% (AUT); -••-••-, $1\,OU\,m^{-3}$ and 0·5% (AUS)

The northerly and southerly winds (*Figs 4* and *6*) show a behaviour which suggests an influence of the North–South-oriented Alm river valley running into the Alpine foreland south of Wels. Northerly up-valley winds are more frequent during daytime, southerly down-valley winds more frequent during the night. Therefore northerly winds are frequently associated with stability classes 2–4, southerly winds with classes 4–7 (see Section 2.3 for an explanation of stability classes). For both wind directions, the wind velocity is rather small, with the 75 percentile at $1{\cdot}1\,m\,s^{-1}$ for North wind and at $1{\cdot}9\,m\,s^{-1}$ for South wind, respectively. In accordance with these findings, odour sensation at the separation distance for northerly winds (all half-hours) shows a maximum during daytime (between 7:00 and 20:00) and occurs frequently more often during the spring and summer months. For southerly winds, the odour sensation at the separation distance has its maximum in the evening (after 18:00), is large throughout the night, and shows a local maximum in the morning (before 6:00).

East and West winds are the dominant directions at Wels. Both directions (*Figs 5* and *7*) show no strong

Table 5

Direction-dependent separation distance calculated for five different odour impact criteria on the basis of an odour threshold T and a probability of threshold exceedance p_T (Table 2): $1\,OU\,m^{-3}$ and 3% (G-PURE); $1\,OU\,m^{-3}$ and 5% (G-MIX); $1\,OU\,m^{-3}$ and 10% or $3\,OU\,m^{-3}$ and 5% (G-AGR); $1\,OU\,m^{-3}$ and 8% or $3\,OU\,m^{-3}$ and 3% (AUT); $1\,OU\,m^{-3}$ and 0·5% (AUS). The direction for the separation distance is opposite to the wind direction. The maximum and minimum values are marked in bold

Wind direction	*Direction for the separation distance*	*Direction dependent separation distance (S_i), m*				
		Odour impact criteria				
		G-PURE	*G-MIX*	*G-AGR*	*AUT*	*AUS*
N	S	**99·4**	**99·4**	99·4	**99·4**	**148·9**
NE	SW	218·9	160·8	**99·1**	128·8	176·2
E	W	347·7	336·9	310·0	321·1	181·7
SE	NW	152·5	**99·4**	99·4	**99·4**	162·2
S	N	224·6	146·1	99·5	116·5	159·3
SW	NE	339·9	319·2	248·3	282·0	176·6
W	E	**362·1**	**349·7**	**335·7**	**341·0**	**183·0**
NW	SE	208·9	150·6	99·4	125·7	178·2

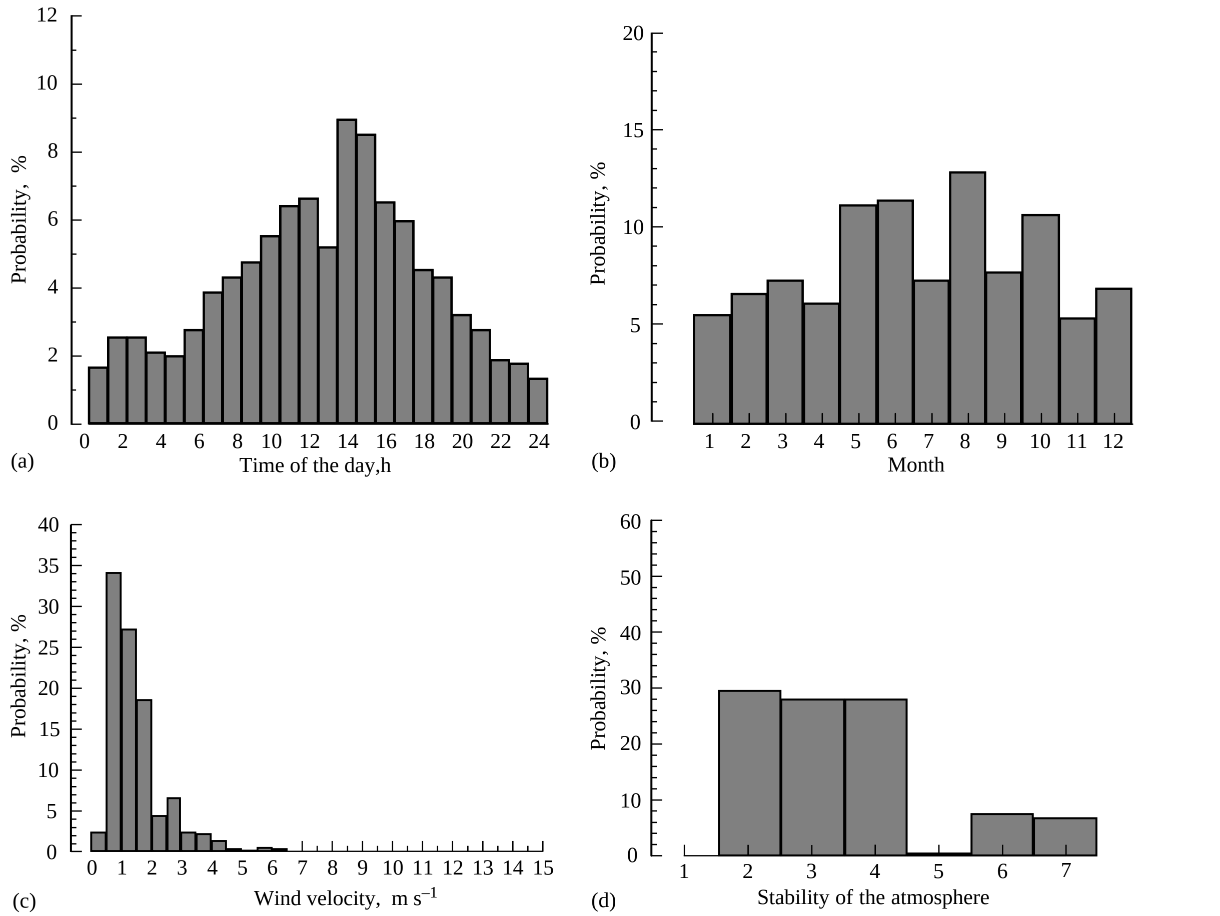

Fig. 4. Probability for North wind (separation distance South) for odour sensation at the separation distance calculated for the odour impact criterion G-PURE defined by an odour concentration threshold of 1 OU m^{-3} and the probability of the threshold exceedance of 3% for the hour of the day (a), for the months of the year (b), for wind velocity (c), and for the stability of the atmosphere (d). For North wind odour can be expected for all half-hourly intervals at the separation distance because the probability of North wind with 2·6% is lower than the probability of threshold exceedance of the odour impact criteria with 3%

variation over the day and some, but not systematic, variability across the year. Both directions are associated with much stronger wind velocities than North and South winds: the most frequent velocities for East wind are around 3 m s^{-1}, for West wind around 4 m s^{-1}. Maximum velocities are around 9 m s^{-1} for East wind and around 13 m s^{-1} for West wind. The distribution of stability classes with East and West winds is relatively similar to the overall distribution (Section 2.3), due to the large frequency of these directions. Stability class 4 dominates, especially for West wind frequently in conjunction with high wind velocities, cloudiness, and rain. Classes 2 and 3 as well as 6 and 7 are more common with East wind associated with anticyclonic conditions.

For East and West winds, odour sensation at the separation distance takes place more often in the second half of the day, with peaks around 22 CET, and from October to January (*Figs 5* and 7). For both directions, the dependence of odour sensation on wind velocity shows several peaks, mostly at 1, 3 and 5 m s^{-1}. For East wind, odour sensation occurs only with stability classes 4–7; for West wind, it occurs with classes 4–6; classes 2 and 3 are free from odour sensation for the selected odour impact criterion G-PURE (Table 2), which is an effect of the large separation distances for these directions (Table 5).

4. Discussion

The Austrian Odour Dispersion Model was used to calculate direction-dependent separation distances for the city Wels, a typical agricultural site in the Austrian

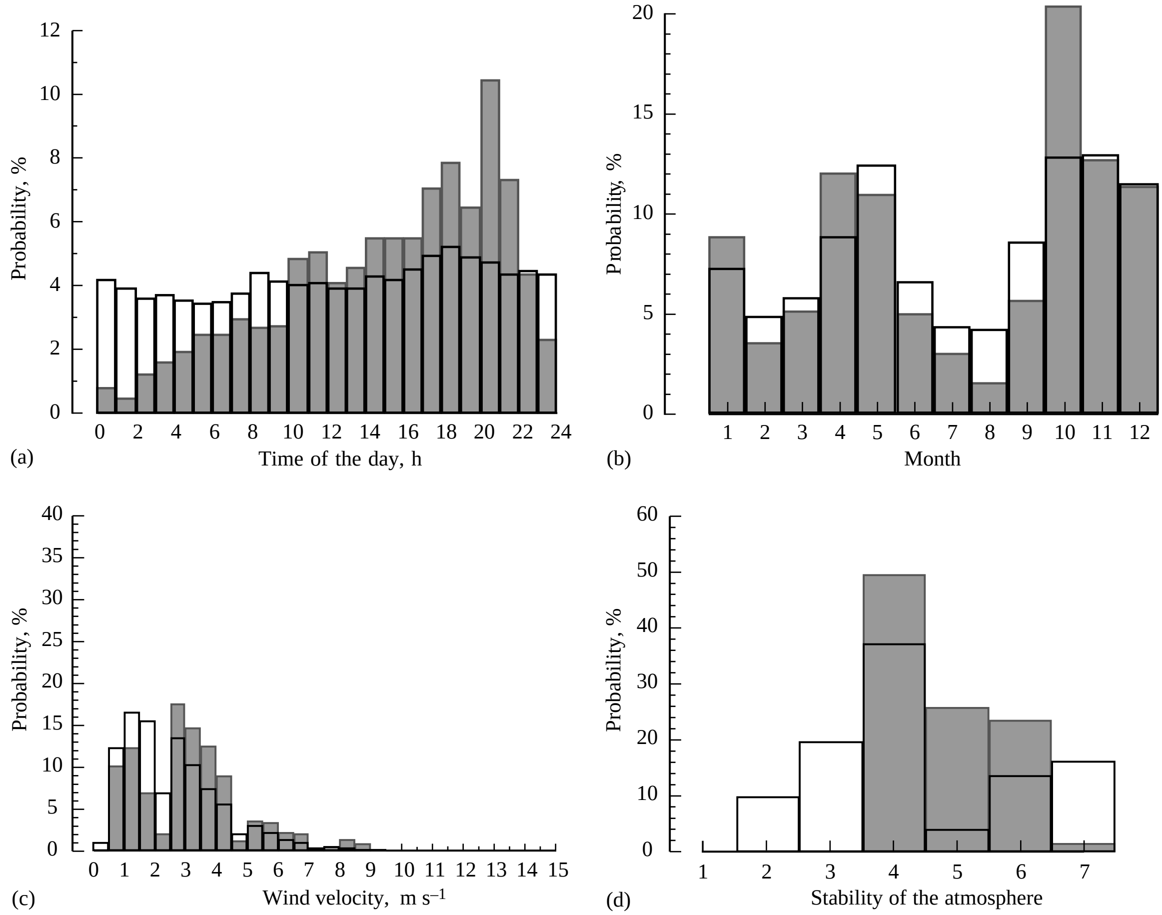

Fig. 5. Comparison of the probability for East wind (separation distance West) for the entire two-year period (□) and the probability of odour sensation (■) at the separation distance calculated for the odour impact criterion G-PURE defined by odour concentration threshold of 1 OU m^{-3} and the probability of the threshold exceedance of 3% for the hour of the day (a), for the months of the year (b), for wind velocity (c), and for the stability of the atmosphere (d)

flatlands north of the Alps, based on a two-year time series of meteorological data.

The direction-dependent distances up to which the odour thresholds—for the livestock unit under investigation—are exceeded are called sensation distances. The cumulative distribution of sensation distances (*Fig. 2*) shows differences according to wind direction, but the maximum sensation distances are relatively similar.

The resulting separation distances vary according to the probability of the wind direction p_i. The higher the probability of the wind direction p_i, the closer lies the separation distance to the maximum sensation distance. For example, the maximum sensation distances for East and West winds are 474 and 502 m, respectively. The separation distances for the odour impact criterion G-PURE for these two directions are 348 and 362 m, which gives 73 and 72% of the maximum of these directions. For North and South winds, the maximum sensation distances are 424 and 436 m, with separation distances of 99 and 245 m, respectively. This gives 33% of the maximum for North wind and 56% for South wind.

Whereas the maximum sensation distances do not depend much on the wind direction, the separation distances are influenced by the probability of the wind direction. The effect is weaker, the more frequent the wind direction. It means that for the main (frequent) wind directions the occurrence of odour sensation anywhere up to the maximum sensation distance is more certain than for less frequent wind directions where odour sensation might occur at large distances, but with a low probability.

Compared to the Austrian guideline (Schauberger *et al.*, 1997), the separation distance is reduced to 60% for frequencies of a wind direction lower than 10%.

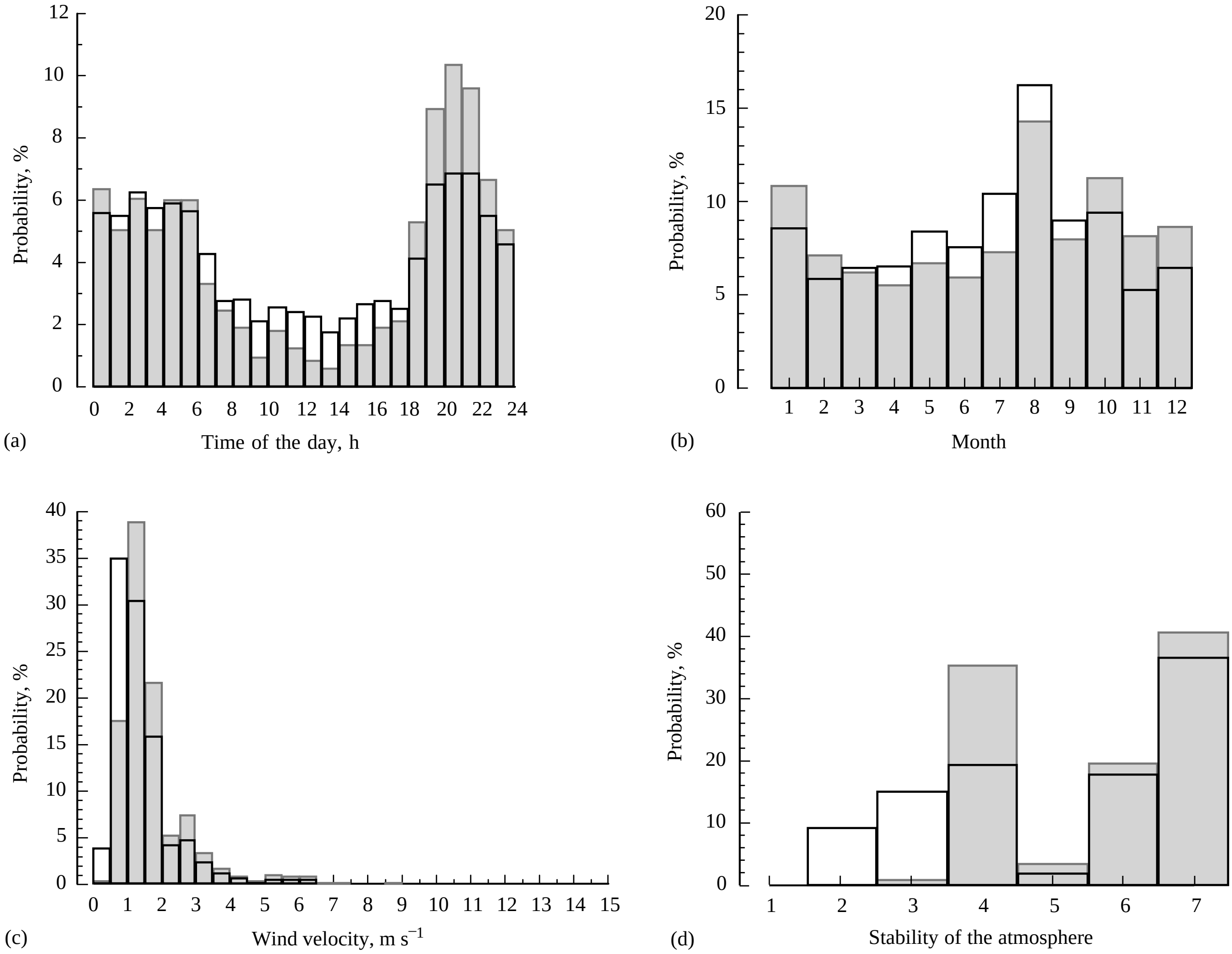

Fig. 6. Comparison of the probability for South wind (separation distance North) for the entire two-year period (□) and the probability of odour sensation (■) at the separation distance calculated for the odour impact criterion G-PURE defined by an odour concentration threshold of 1 OU m^{-3} and the probability of the threshold exceedance of 3% for the hour of the day (a), for the months of the year (b), for wind velocity (c), and for the stability of the atmosphere (d)

In the German guideline (VDI 4374, 2001) the separation distance is reduced to 25% for frequencies of a wind direction lower than 7·5%.

For pure residential areas (G-PURE) with the highest protection level, the ratio between maximum and minimum distance is 3·60, for the lowest protection level (AUS) the ratio is 1·23. From the calculated direction-dependent separation distances (*Fig. 3,* Table 5), for the five odour impact criteria labelled in Table 2, it is suggested that the more protective the odour impact criterion, the higher the direction-dependent variability of the separation distances. In the special case of Wels, the lowest separation distances are mostly found for North wind associated with low wind velocities and stability classes 2 and 3; the largest ones are found for West wind, caused by large mean wind velocities and frequent occurrence of stability class 4.

Odour sensation at separation distances depends on the time of the day, the month of the year, the wind velocity, and the stability of the atmosphere, for a selected wind direction (*Figs 4–7*). At the investigated site, the city of Wels, representative for the Austrian flatlands north of the Alps, two prevailing wind directions are observed with a probability of 26% for East wind and 34% for West wind. The less frequent North and South winds at this site are subject to the periodically changing wind system of the Alm river valley running from South to North and entering the flatlands south of Wels.

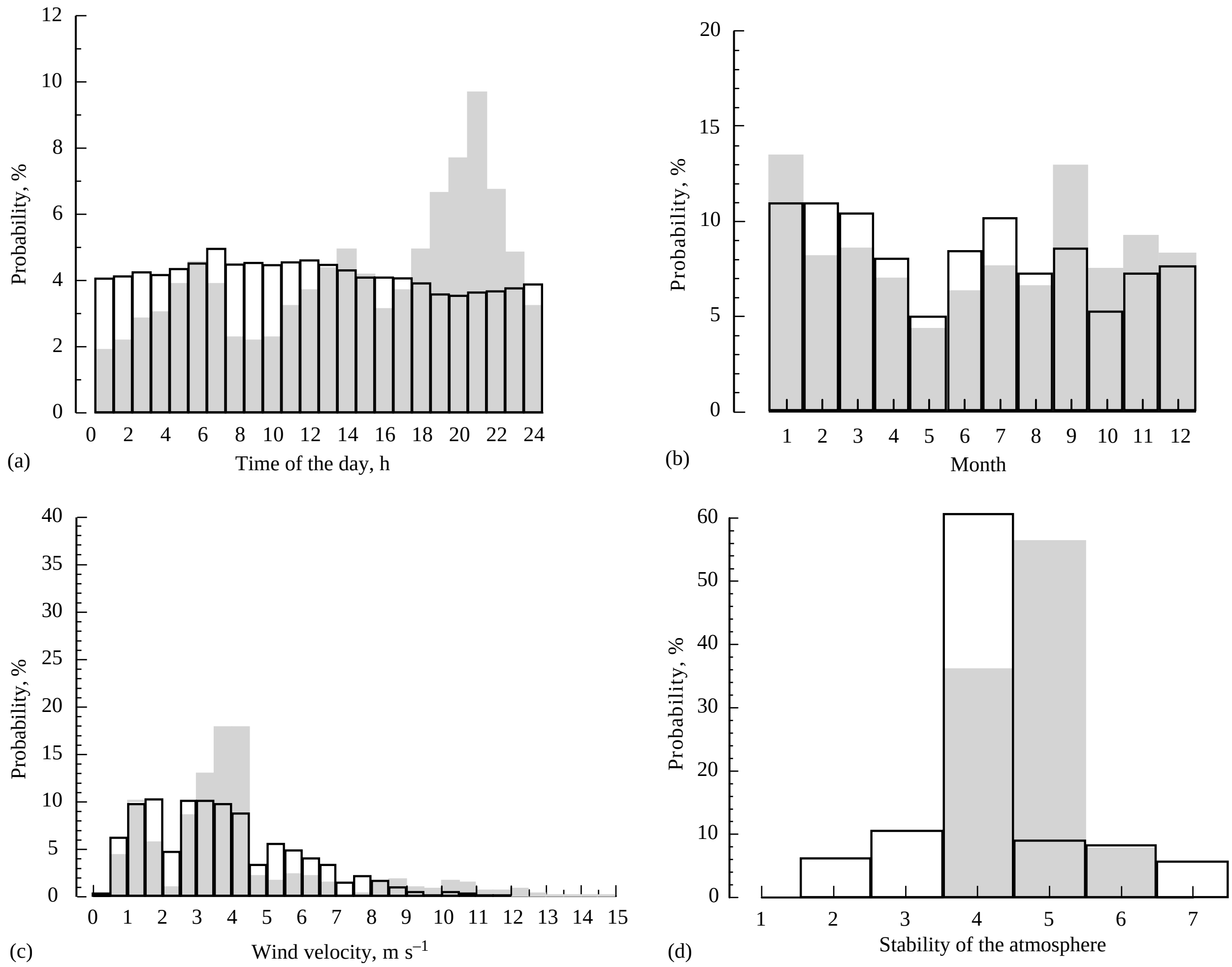

Fig. 7. Comparison of the probability for West wind (separation distance East) for the entire two-year period (□) and the probability of odour sensation (■) at the separation distance calculated for the odour impact criterion G-PURE defined by an odour concentration threshold of 1 OU m^{-3} and the probability of the threshold exceedance of 3% for the hour of the day (a), for the months of the year (b), for wind velocity (c), and for the stability of the atmosphere (d)

Based on the model calculations of the direction-dependent separation distance it has to be discussed if the odour impact criteria, defined solely by a probability of the threshold exceedance of a certain odour threshold (Table 2), are sufficient to guarantee protection with respect to the time of the day or the season of the year. It is obviously not the same with respect to odour reception if odour sensation of the same concentration occurs e.g. around sunset in summertime or during nighttime in winter. The situation is complicated because odour sensation is not equally distributed over the time of the day and the months of the year [diurnal variation: *Figs 4*(*a*), *5*(*a*), *6*(*a*) and *7*(*a*); annual variation: *Figs 4*(*b*), *5*(*b*), *6*(*b*) and *7*(*b*)]. In addition to the odour impact criteria, the local meteorological situation has a strong impact on possible odour nuisance from livestock farming.

Most complaints ('time of most complaint') from swine odour were recorded early in the morning or late at night under stable conditions (Schiffman, 1994). Another time of above-average complaints could well be the transition from day- to nighttime, when a stable stratification evolves in the near-surface boundary layer. The results presented in *Figs 4*(*a*), *5*(*a*), *6*(*a*) and *7*(*a*) show maximum odour probability to occur at different times of the day: afternoon hours for northerly winds [*Fig. 4*(*a*)], late evening hours for easterly winds [*Fig. 5*(*a*)], nighttime including evening and morning transition for southerly winds [*Fig. 6*(*a*)], and again late evening hours for westerly winds [*Fig. 7*(*a*)]. These results indicate that generalizations on maximum odour probability depending on the time of the day are difficult. It should be emphasized here that the model is designed to predict odour perception of the neighbours, but not the occurrence of neighbour complaints. Therefore the assessment of the perception by the AODM may not coincide with the real time of nuisance complaints because the behavioural response of the neighbours to the odours is not included in the model.

Strauss *et al.* (1986), in a survey about the complaints due to livestock units in Austria, found a higher probability during summer (50%) compared to spring (34%), autumn (25%), and winter (1%). Only 26% of the persons interviewed feel constantly annoyed all year. Lohr (1996) investigated the odour perception for the four seasons by the frequency of odour exposure (number of odour sensations noticed per month) and found 3·24 for summer, 1·18 for spring, 0·71 for autumn, and 0·12 for winter. The duration of exposure (hours per odour sensation) shows a similar pattern: 16·59 for summer, 12·00 for spring, 10·59 for autumn, and 2·47 for winter. The AODM calculation of the direction-dependent separation distance for Wels (*Figs 4–7*) does not show such a clear dependence of odour sensation on the season. The results, however, indicate high odour levels during daytime in summer for North wind as well as during nighttime for the other directions. The winter half-year is more affected by the predicted odour perception. The difference between this study and the results of Strauss *et al.* (1986) and Lohr (1996) can be explained first by a temperature-effected sensation sensitivity (Strauss *et al.*, 1986). The sensitivity of the neighbours increases with increasing outdoor temperature. This effect is not included in the AODM calculations. Fang *et al.* (1998) found a weak linear correlation between the acceptability of air quality and the enthalpy of the air with the restriction that the investigation was done for indoor air and a limited range of both air temperature (18–28°C) and relative humidity (30–70%). Secondly, the discrepancy can be explained by the variation of the odour annoying potential caused by the synchronized behaviour of neighbours (*e.g.* time to stay outdoors, open windows) which is also not reflected in the usual odour impact criteria.

5. Conclusions

The presented dispersion model for odour can be used to predict the occurrence of odour perception. The evaluation of these values by the odour impact criteria should not only be based on statistical limits as it is done today but also consider the annoying potential of odour due to the behaviour of neighbours. Therefore, the odour sensation should be weighted by the time of the day and the time of the year, as is done with the limit values for noise. This means that besides the suggested frequency, intensity, duration, and offensiveness (FIDO) factors, a diurnal and annual weighting should be introduced in the odour impact criteria which reflects the outdoor behaviour pattern of neighbours.

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