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Omnidirectional separation distance due to odour emission of livestock buildings calculated by the Austrian odour dispersion model (AODM)

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Summary

Using a dispersion model to calculate ambient odour concentrations, the separation distance between livestock buildings and residential areas is defined by a preselected odour threshold and an exceeding probability. The dynamic Austrian Odour Dispersion Model (AODM) is used to calculate the separation distance for several combinations of these two values, which represent the protection level of various land use categories. The AODM consists of three modules: (1) odour release on the basis of a simulation model for the indoor climate of livestock buildings, (2) a regulatory dispersion model (Gauss) to calculate hourly or half-hourly ambient odour concentrations and (3) a fluctuation module, calculating the instantaneous odour concentration, depending on wind velocity and stability of the atmosphere. The calculated separation distances are compared with empirical guide lines used in some countries (Austria, Germany, The Netherlands, USA). For most guide lines, the separation distances are smaller compared to the model calculation, except for the German guide line applied for non-agricultural areas. Odour sensation occurs predominantly around sunset, with neutral or slightly stable atmospheric stability.

Keywords: Odour; livestock building, emission, separation distance, swine, guide line, dispersion model

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Omnidirectional separation distance due to odour emission of livestock buildings calculated by the Austrian odour dispersion model (AODM)

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Abstract

Using a dispersion model to calculate ambient odour concentrations, the separation distance between livestock buildings and residential areas is defined by a pre-selected odour threshold and an exceeding probability. The dynamic Austrian Odour Dispersion Model (AODM) is used to calculate the separation distance for several combinations of these two values, which represent the protection level of various land use categories. The AODM consists of three modules: (1) odour release on the basis of a simulation model for the indoor climate of livestock buildings, (2) a regulatory dispersion model (Gauss) to calculate hourly or half-hourly ambient odour concentrations and (3) a fluctuation module, calculating the instantaneous odour concentration, depending on wind velocity and stability of the atmosphere. The calculated separation distances are compared with empirical guide lines used in some countries (Austria, Germany, Switzerland, The Netherlands, USA). For most guide lines, the separation distances are smaller compared to the model calculation, except for the German guide line applied for non-agricultural areas. Odour sensation occurs predominantly around sunset, with neutral or slightly stable atmospheric stability.

Keywords: Odour; livestock building, emission, separation distance, swine, guide line, dispersion model

1. Introduction

Odour is one of the major nuisances in the environment mainly caused by livestock units and industry. In the USA, about 70% of all complaints on air quality concern odour (Watts and Sweeten, 1995). For the UK (Skinner et al., 1997), there were 3700 complaints about odour from farms in the years 1989 and 1990. This is about 25% of all complaints received by the Environmental Health Officers. More than half are caused by livestock buildings (building, slurry storage, feeding), the other half by slurry spreading. For Thüringen, Germany, Lotze and Schwinowski (1998) report that 16% of all complaints in the year 1996 were odour related, 34% of these stem from agricultural sources. The complaints due to farms dominated with 89% over slurry spreading (11%).

To overcome such problems, a separation distance between the odour source and residential areas is used to reduce the odour annoyance to a certain level. With livestock farming, two regulatory approaches are used. The first one is a guide line approach, the second one a modelling approach. In guide lines, the separation distance between residential houses and livestock buildings, which is a common objective of various guidelines of several countries, is empirically assessed (e.g. Austria (Schauberger et al., 1997; Schauberger and Piringer, 1997a and 1997b), The Netherlands (Ministrie van Landbouw, 1991), Germany (VDI 3471,1986; VDI 3472, 1986; VDI 3473, 1994), USA (Heber, 1997 and 1998), and Switzerland (Richner and Schmidlin, 1995)). In most cases the structure of the guide lines is very similar. First of all the odour source is assessed by the number of animals and additionally by some parameters which describe the odour release. On the basis of the odour source, the separation distance is calculated by using an empirical function, in many cases a power function (Piringer and Schauberger, 1999). In the last step this separation distance is modified by a reduction factor to adapt the separation distance to various land use categories, which are distinguished by different levels of claims for exemption from odour sensation.

The second regulatory approach are model calculations of the separation distance using dispersion models. The following information has to be available: odour release (Martinec et al., 1998; Schauberger et al., 1999), a dispersion model (e.g. the normative Gauss model used in Austria, Kolb, 1981), the calculation of the instantaneous odour concentration (Schauberger et al., 2000b), and the validation of the instantaneous odour concentration taking into account the FIDO factors (frequency, intensity, duration and offensiveness) of odour sensation and the reasonableness.

In this paper a first attempt is presented to calculate the separation distance by the Austrian Odour Dispersion Model (AODM) and to compare the results with various national guide lines using an empirical approach.

2. Materials and Methods

2.1. Austrian Odour Dispersion Model AODM

The dynamic Austrian odour dispersion model (AODM) consists of three modules: the first calculates the odour emission of the livestock building, the second estimates mean ambient concentrations by a regulatory dispersion model, and the last transforms the mean odour concentration of the dispersion model to instantaneous values depending on wind velocity and stability of the atmosphere.

The emission module is based on a steady-state balance of the sensible heat flux to calculate the indoor temperature and the related volume flow of the ventilation system (Schauberger et al., 2000a). The corresponding odour flow is assessed by a simple model of the odour release. 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. Outdoor odour sources such as slurry tanks or feed storage facilities are not taken into account. For the model calculation presented here, a mean specific odour flow of 100 OU/s LU (Martinec *et al.* 1998) and a mean live mass of 60 kg per fattening pig (M = 0.12 LU) are used. The model has been described extensively in Schauberger et al. (1999a and 1999b).

The chosen system parameters for a livestock building, typical for middle Europe, are summarised in Table 1. The model calculations were done for a pig fattening unit of 1000 pigs with a forced ventilation. The livestock building is moderately insulated, described by the thermal transmission coefficient U. The assumed space per animal is 0.75 m² according to welfare guide lines.

Table 1: System parameters of the indoor climate (model calculation). The parameters are representative for an unit of about 1000 fattening pigs.

Parameter	
Mean total energy release of an animal Q_A (continuous fattening between 30 and 100 kg) per pig	188 W
Minimum volume flow V_{min} per pig. Design value for the ventilation system taking into account the maximum accepted indoor CO_2 concentration of 3000 ppm	13.1 m³/h
Maximum volume flow V_{max} per pig. 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	66.0 m³/h
Area of the building (ceiling, walls, windows, doors) per animal	1.35 m²
Thermal transmission coefficient *U*	2.0 W/m² K
Set point temperature of the control unit T_C	18 °C
Bandwidth of the control unit DT_C	4 K

The odour concentration of the centre line of the plume is calculated by the Austrian regulatory dispersion model (ÖNorm M 9440, 1992/96; Kolb, 1981) by making use of a statistics of stability classes representative for the Austrian flatlands north of the Alps. The model has been validated internationally with generally good results (e.g. Pechinger and 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 Reuter (1970).

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. The peak value is derived from the half our mean value using the relationship of Smith (1973) depending on the stability of the atmosphere. These values 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 and Mason, 1991) using the time of travel with the distance, *x*, and the mean wind velocity, *u*, and the Lagrangian time scale as a measure of the stability of the atmosphere (Mylne, 1992). This approach is described by Schauberger et al. (2000b).

Table 2 Limits of odour concentration and exceeding probability used in Austria (Stangl et al., 1993), Germany (Knauer, 1994; Kypke, 1994), Thüringen, Germany (Lotze and Schwinkowski, 1998), UK (Hobson, 1997), Australia (Jiang and Sands, 1998), The Netherlands (Hagen and van Belois, 1998, Denmark, New Zealand and Massachusetts (USA) (after Jiang and Sands, 1998).

Odour concentration threshold (OU/m^3) @ Percentile compliance: Exceeding probability for the odour concentration threshold p (%)	Land use category	Comment	Label
Germany			
1 @ 3	pure residential areas and residential areas		**G-PURE**
1 @ 5	residential and structured areas		**G-MIX1**
1 @ 8 and 3 @ 3	restricted business-areas and village-area with mixed utilisation		G-MIX2
1 @ 10 and 3 @ 5	village-areas with predominantly agricultural utilisation		**G-AGR**
Germany, Thüringen			
1 @ 7	pure residential areas and residential areas (WR)	only valid in Thüringen	GT-PURE
1 @ 10	general residential areas and mixed utilisation /WS, WA/WB, MI,MK)	only valid in Thüringen	GT-MIX1
1 @ 12	villages (MD)	only valid in Thüringen	GT-VIL1
1 @ 15	villages with existing lievstock units above a certain limit (MD)	only valid in Thüringen	GT-VIL2
1 @ 15	busness areas (GE)	only valid in Thüringen	GT-BUS
1 @ 15	Industry (GI)	only valid in Thüringen	GT-IND
UK			
10 @ 2		Serious annoyance expected with near certainty	UK1
5 @ 2		Generally acceptable for existing installations. Emissions from stacks or large area sources may be acceptable at the relaxed end of the range	UK2
1 @ 2		No serious annoyance expected in the large majority of cases	UK3
1 @ .5		Safe target value for new sources	UK4
10 @ 0.01		Safe target value for new sources applicable to highly intermittent sources	UK5
Austria			
1 @ 8 and 3 @ 3		threshold for reasonable odour sensation for medical	**AUT**

			purpose	
Australia				
	5 @ 0.5	rural and urban area		**AUS1**
	2 @ 0.5	residential area	New South Wales	AUS2
	10 @ 0.5	residential areas	Victoria	AUS3
The Netherlands				
	1 @ 2	residential areas	existing units	NL
	1 @ 0.5	residential areas	new installations	NL
	1 @ 5	residential areas outside of villages and business areas		NL
Denmark				
	5 - 10 @.1		plants	DEN1
	0.6 – 20 @ 1		surrounding	DEN2
New Zealand				
	2 @.0.5		property boundary	NZ
Massachusetts, USA				
	5 @ .5		plant boundary	USA

2.2. Separation distance calculated by the AODM and national guide lines

With the AODM, the separation distance is calculated by using a threshold of the odour concentration and its exceeding probability. The odour impact criteria based on these two parameters are summarised in Table 2 for Austria (Stangl et al., 1993), Germany (Knauer, 1994; Kypke, 1994), Thüringen, Germany (Lotze and Schwinkowski, 1998), UK (Hobson, 1997), Australia (Jiang and Sands, 1999), The Netherlands (Hagen and van Belois, 1998, Denmark, New Zealand and Massachusetts (USA) (after Jiang and Sands, 1998).

For each half – hour of the meteorological data set (see section 2.3), momentary odour concentrations were calculated for discrete 41 distances between 50 m and 2000 m from the source. The distances up to which the odour thresholds of 1, 3, and 5 OU/m³, respectively, are exceeded were found by linear interpolation between the discrete data points. The final separation distance is defined according to the odour impact criteria defined in Table 2, i.e. for the combination of odour threshold and exceeding probability. E.g. the 97%-percentile (corresponding an exceeding probability of 3%) of the 1 OU/m³ threshold gives the separation distance for pure residential areas and general residential areas according to the limits used in Germany (G-PURE, Table 2).

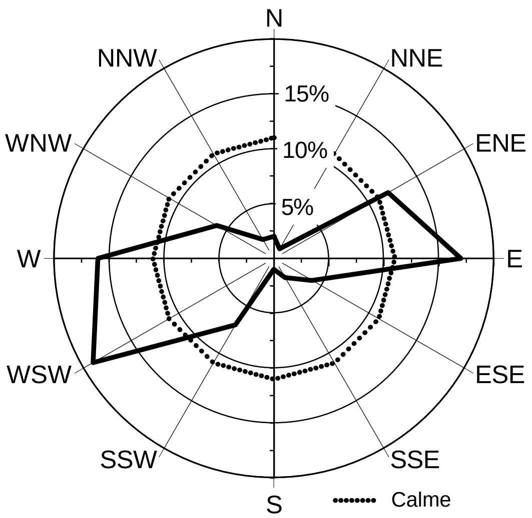
The model calculation was compared to the separation distances of the empirical guide lines of Germany, Austria, Switzerland, The Netherlands and the USA. To apply the guide lines, the necessary information about the livestock building and the agricultural equipment was assumed according to the description in Table 1. In some cases, use of the guide lines resulted in uncertainties e.g. due to missing or not precise specifications of the feeding factor or the geometry of the outlet air. This was overcome by calculating two distances, so that the separation distance of the guide line is given by an interval (Table 6). For the calculated difference between guide line and model calculation in percent, the centre of the interval was used. The impact criterion of a certain residential area was selected by the description of the level of protection necessary to fulfil the requirements for the land use category.

2.3. Meteorological conditions

The meteorological data were collected at Wels, a site representative of the Austrian flatlands north of the Alps. The sample interval was 30 minutes for a two-year period between January 30, 1992 and January 31, 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 the undisturbed environment is 2.2 m/s, maximum velocity amounting to about 13 m/s. The distributions of wind directions and wind velocity are shown in Fig. 1. The prevailing wind directions at Wels are west and WSW, as well as east and ENE. Calm conditions according to the Austrian regulatory dispersion model with wind velocity of less than 0.7 m/s amount to 18.2%; weak winds (wind velocity less than 1 m/s) comprise 26.5% of all cases. Less than 10% of all wind velocities are larger than 5 m/s. The annual mean temperature at Wels is 9.7 °C, the temperature range (two-year period) is from –14.9 °C to 35.3 °C. The annual precipitation amounts to 838 mm (mean over the period 1961 – 1990).

Table 3 Two-dimensional frequency distribution in ‰ of stability classes SC (2 to 7) and wind velocity in m/s at Wels

	Stability class SC					
Wind velocity, in m/s	*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



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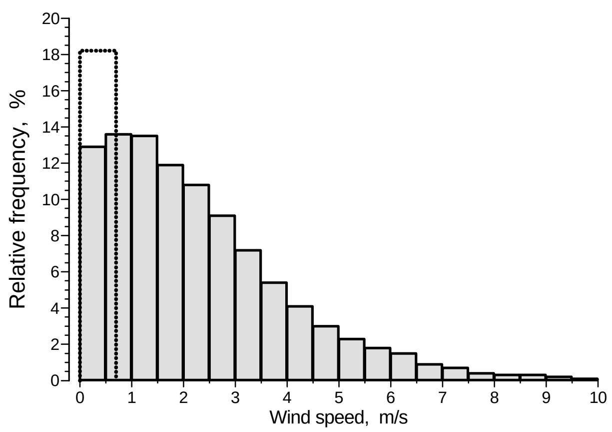

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Fig. 1. Frequency distribution of (a) the wind direction and (b) wind velocity at Wels; - - - - - -, Calm conditions according to the Austrian regulatory dispersion model with wind velocity less than 0.7 m/s (ÖNorm, 1992/1996).

Stability classes SC are determined as a function of half-hourly mean wind velocity and a combination of sun elevation angle and cloud cover. The cloud cover was monitored by the meteorological station at the airport Linz-Hörsching, in a distance of about 13 km. Within the Reuter (1970) scheme, classes 2 to 7 can occur in Austria. 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 velocity of 2 and 3 m/s. Wind velocity larger than 6 m/s are almost entirely connected with class 4. Stability classes SC=2 and SC=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, peak slightly below or around the average wind velocity. They cover 26% of all cases. Class 5 occurs with higher wind velocity 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. In Table 3, a two-dimensional frequency distribution between stability classes and wind velocity shows the relationship between these two parameters.

3. Results

In Figure 2, the separation distances calculated for a combination of odour thresholds of 1, 3, and 5 OU/m³ with selected exceeding probabilities are shown. In the small panel, the separation distances are highlighted with circles for the following exceeding probabilities: 0.5, 3, 5, 8, and 10%, respectively. Actual values of these separation distances are given in Table 4. The separation distance is more dependant on the odour threshold than on the exceeding probability. By increasing the exceeding probability from 0.5% to 10%, the separation distance is changing by less than 20%. On the other hand, the separation distance is changing between 55 and 52% due to a change of the odour threshold from 1 to 5 OU/m³ (see also Figure 2).

Table 4 Separation distance (m) for some odour thresholds and exceeding probabilities used for odour impact criteria

Exceeding probability (%)	Odour sensation OU/m³		
	1 OU/m³	3 OU/m³	5 OU/m³
0.5	417	237	186
3	383	227	180
5	372	222	177
8	360	217	173
10	355	214	171

For some of the selected odour impact criteria (Table 2), the separation distances are shown in Table 5. The separation distances for pure residential areas G-PURE (383 m) and mixed areas G-MIX1 (372 m) show very little difference because only the exceeding probability is changing from 3% to 5% (see also Table 4 and Figure 2). For agricultural residential areas G-AGR the distance is reduced to 227 m. For the Austrian impact criterion, the separation distance AUT is close to the German non non-agricultural residential area (G-PURE and G-MIX1) with 360 m. For Australia, the separation distance AUS is the lowest one with 186 m.

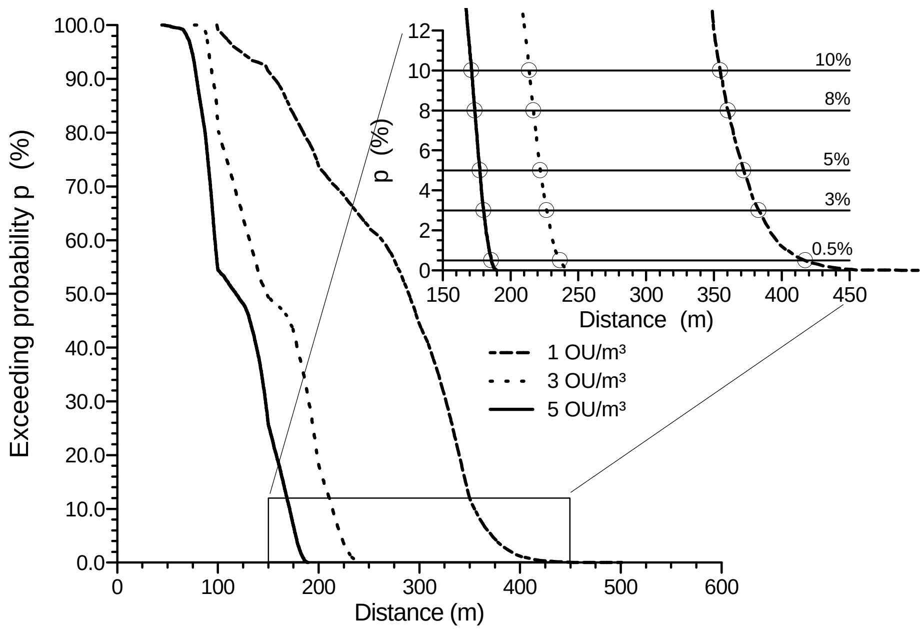


Fig. 2. Exceeding probability p (%) for three odour thresholds (1, 3 and 5 OU/m³) as a function of the distance (m) from the source. In the small panel the exceeding probability is zoomed, relevant to estimate the separation distance for odour impact criteria.

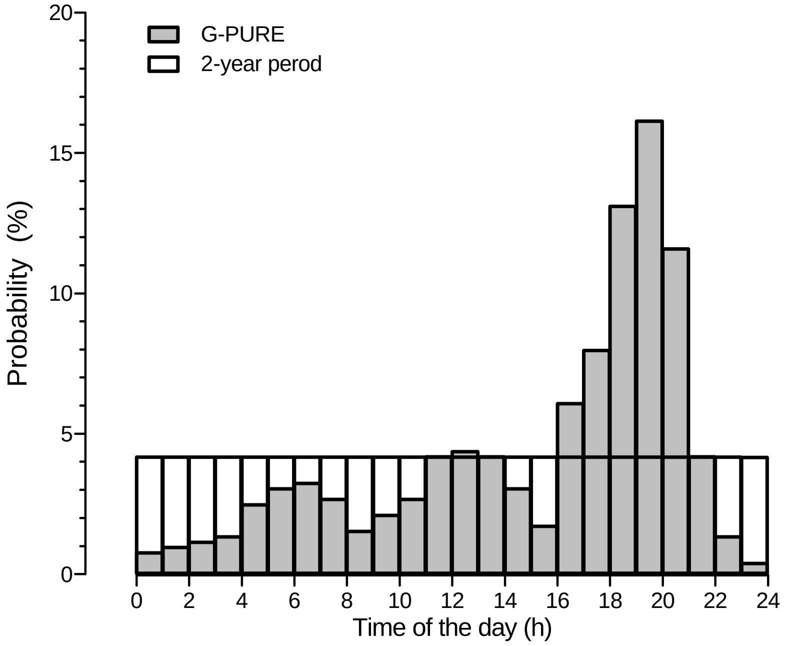
Table 5 Separation distance (m) for fife different combinations of odour threshold and exceeding probability used as odour impact criteria of Tab. 2

	Odour concentration threshold (OU/m³) and exceeding probability (%)	Separation distance (m)
G-PURE	1 @ 3	383
G-MIX1	1 @ 5	372
G-AGR	1 @ 10 and 3 @ 5	227
AUT	1 @ 8 and 3 @ 3	360
AUS	5 @ 0.5	186

The comparison of the model and the guide lines is summarised in Table 6. With the exception of Germany for the non-agricultural residential areas (G-PURE and G-MIX1), all guide lines show a shorter distance than the model calculation, in the range of 30 to 64%. The lower the protection level, the higher the differences.

Taking the separation distance defined for pure residential areas in Germany (G-PURE, odour threshold: 1 OU/m³ and exceeding probability 3% = 262 hours per year) as an example, the occurrence of odour sensation was analysed by comparing the frequency distribution of the entire data set (2-year period) with the sample of odour sensation (3% of the year). The following parameters were investigated: diurnal and annual variability (Figure 3), wind velocity and wind direction (Figure 4) and stability of the atmosphere (Figure 5).

Investigating the diurnal variation of odour sensation (Figure 3a), a strong maximum between 16:00 and 21:00 is found. Two much smaller maxima occur in the morning and around noon. Meteorological reasons as well as the impact on the guide lines of the strong evening maximum will be discussed in section 4. The annual course (Figure 3b) shows an irregular pattern, but in general more frequent odour sensation during the winter months. In this case, the model calculations are not in agreement with expectations, as will be discussed also in section 4.



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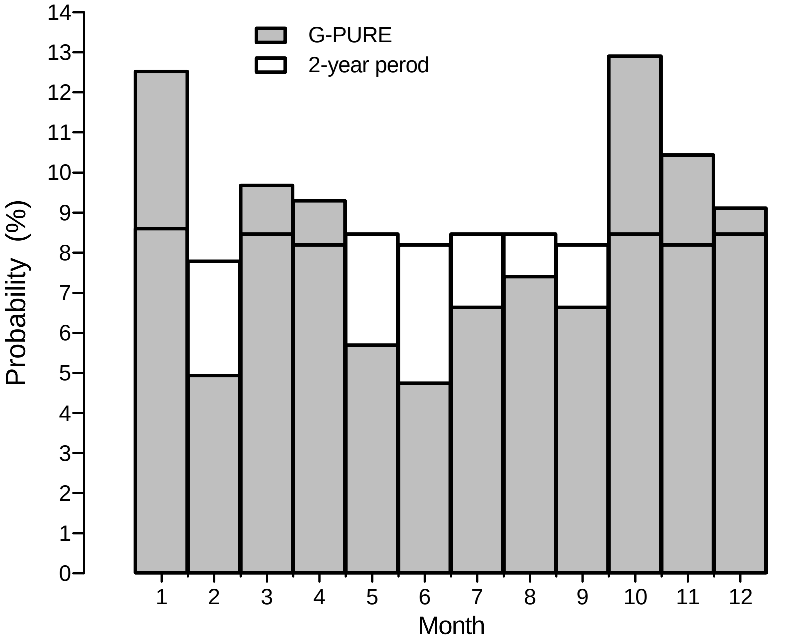

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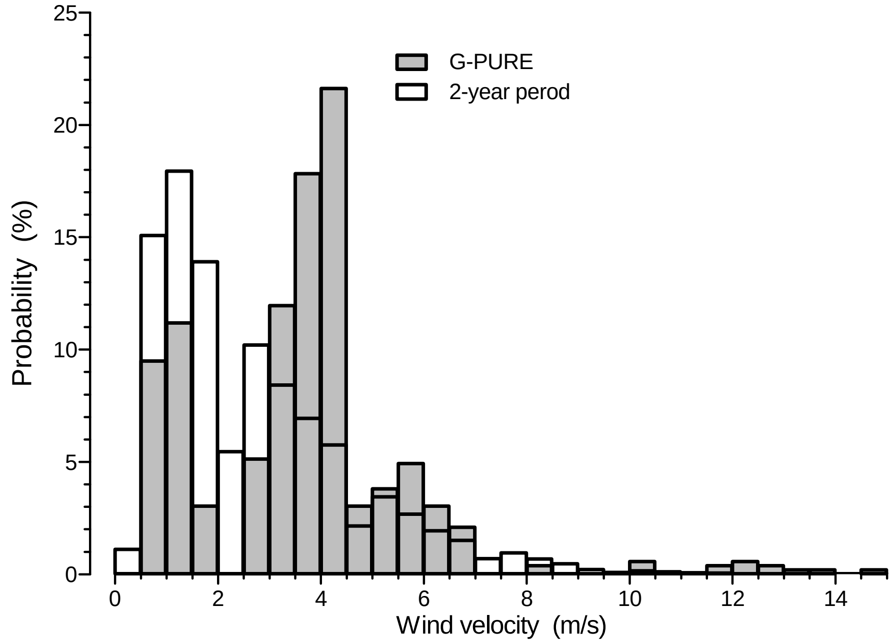
Fig. 3. Diurnal and annual variation: Comparison of the frequency distribution for the entire data (empty bars) set and the time of odour sensation (hatched bars; G-PURE) for the time of day (a) and for the months of the year (b).



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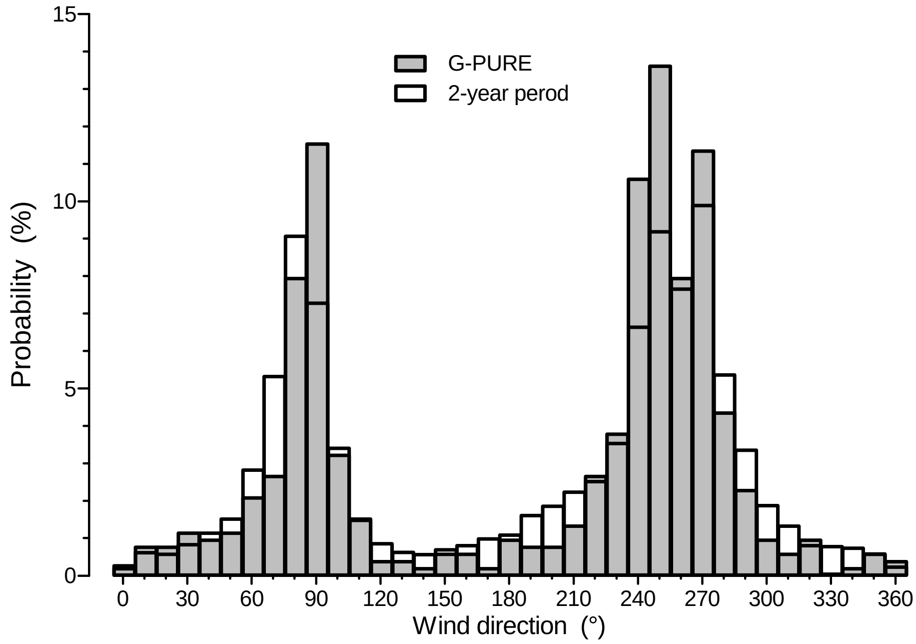

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Fig. 4. Wind velocity and wind direction: Comparison of the frequency distribution for the entire data (empty bars) set and the time of odour sensation (hatched bars; G-PURE) for wind velocity (a) and for wind direction (b).

The frequency distribution of the wind velocity of the entire data-set (Figure 4a) shows a maximum at 1.0 to 1.5 m/s. The distribution for odour sensation (impact criterion for G-PURE) shows two maxima, the absolute one around 4 m/s and a local maximum around 1 m/s. This result suggests of having one near – source maximum of odour sensation at low winds and another one for the most frequent combination of the dispersion parameters stability class, wind direction, and wind speed. The differences between the entire distribution of the wind direction and that for cases of odour sensation

(Figure 4b) are not large. For the main wind directions, slightly larger probabilities are calculated in case odour sensation occurs. The result of Figure 5 suggests that odour sensation only occurs for stability classes 4 to 6. More than 60 % of all odour sensation is associated with stability class 5, which itself is not frequent, compared to other classes. All three classes can occur around sunrise and sunset when odour sensation is frequent (Figure 3a).

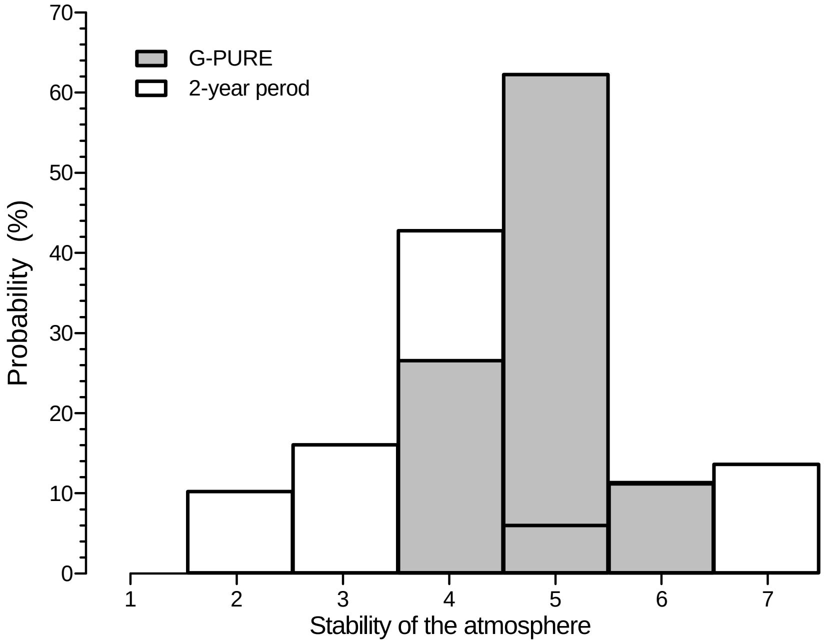

Fig. 5. Stability of the atmosphere: Comparison of the frequency distribution for the entire data (empty bars) set and the time of odour sensation (hatched bars; G-PURE) for the classes of stability (Reuter, 1970).

4. Discussion and Conclusions

For the calculation of the separation distance due to odour emissions of livestock buildings several dispersion models are in use. Most of them are based on regulatory Gauss models adapted for the requirements of odour.

The Austrian odour dispersion model AODM consists of an odour emission module based on a steady-state balance model including a simple odour release parameterisation (Schauberger et al., 1999 and 2000a). Other models use a constant emission scenario (Krause and Lund, 1993) or a simple parameterisation depending on the outdoor temperature (Jiang and Sands, 1998) which neglects the temporal variation of the emission parameters due to the variable volume flow of the ventilation system.

Table 6 Comparison of the calculated separation distance by the AODM with the separation distances assessed by national guide lines.

Country	Separation distance (m) Model and impact criterion	Guide line	Difference %
Germany			
Pure, general, special residential areas (categories W, WR, WA, WB)	383 G-PURE	245 - 387	17
Mixed residential areas MI	372 G-MIX1	245 - 387	15
Residential areas like agricultural villages (MD)	227 G-AGR	123 - 194	-30
Austria			
Pure residential areas with for recreation and tourist purpose	383 G-PURE	197 - 343	-30
General residential areas	383 G-PURE	138 - 240	-51
Residential areas with trade establishments	372 G-MIX1	99 - 172	-64
Switzerland			
Pure residential areas	383 G-PURE	169 - 271	-43
Mixed residential areas with trade establishments	372 G-MIX1	118 - 189	-59
The Netherlands			
Pure residential areas with high protection level (eg Hospitals) Category I	383 G-PURE	250	-35
Residential areas; Category II	383 G-PURE	195	-49
Isolated non-agricultural buildings; Category III	372 G-MIX1	135	-64
Agricultural residential areas; Category IV	227 G-AGR	84	-63
USA			
Pure residential areas with for recreation and tourist purpose	383 G-PURE	197 - 343	-30
General residential areas	383 G-PURE	138 - 240	-51
Residential areas with trade establishments	372 G-MIX1	99 - 172	-64

The use of the Gaussian regulatory model ÖNorm M 9440 (1992/96) 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 velocities equal to or above 1 m/s 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 a lot of large livestock farms in Austria are situated in rather flat terrain.

The third feature of the AODM is the calculation of the instantaneous concentration. Since the sensation of odour depends on the momentary concentration rather than on a mean value calculated by the Gauss 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 (1988) for a non-linear dose response relationship of Chlorine as a toxic substance. For odour a similar situation is given: First the odour threshold has to be succeeded to receive a sensation of odour, secondly odour intensity goes with the logarithm of the concentration (e. g Misselbrook et al., 1993). The fluctuation of the odour concentration at a certain receptor point is considered by using a fluctuation model. For the AODM this is realised by an attenuation function of the peak-to-mean ratio of the odour concentration which depends on the atmospheric stability (Schauberger et al., 2000b). This is a major improvement compared to a constant peak-to-mean ration of 10, according to the German regulatory TA Luft (1986) or a pure dispersion model for odour by Chen et al. (1998) using no correction for the instantaneous concentration. In Germany, the BAGEG model (Begehungskalibrierte Ausbreitungssimulation für Geruchsstoffe [Simulation of the dispersion of odouriphores calibrated by field mesurements]), developed by Krause and Lung (1993), uses a Gauss model and a fluctuation module which is used for a calibration against field measurements according to VDI 3940 (1993). Nevertheless this approach has no meteorological background.

From Table 2 it is apparent that odour thresholds in combination with their exceeding probabilities are explicitly related to land-use categories in Germany, the Netherlands, and Australia only. In all these countries, residential areas, in which, apart from existing installations, animal farming usually is not allowed, are best protected. However, the threshold systems are different. In Germany (including Thüringen) and the Netherlands, only the exceeding probability varies according to the land-use category. In Australia, the odour threshold varies, whereas the exceeding probability is fixed. In the UK, the odour thresholds are related to different levels of annoyance. Depending on the kind of odour threshold fulfilled for the investigated farm, the level of annoyance can be determined. Property domains are relevant for the validity of odour thresholds in Denmark, New Zealand, and Massachusetts, USA. Medical aspects led to the definition of the Austrian odour threshold.

Odour concentrations calculated by dispersion models at a certain point have to be evaluated against the odour impact criteria. Watts and Sweeten (1995) suggest the four factors frequency, intensity, duration and offensiveness (FIDO) of odour to assess the nuisance capacity. Besides these FIDO factors the concept of reasonableness has to be taken into account (e.g. land use category). Based on this concept, a definition is suggested based on the exceeding probability of a certain threshold and reasonableness for rural and urban sites. The odour threshold T (OU/m³) as a function of the exceeding probability p (h/a) is calculated by $T_{rural} = 800/p$ and $T_{urban} = 400/p$. According to Miner (1995), the reasonableness of odour sensation is 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 residence, economic dependence on farming, familiarity with livestock farming and awareness of agricultural-residential context are related with fewer reports of annoyance.

The odour thresholds for urban and rural impact as well as some odour impact criteria used in various countries for regulatory purposes are shown in Figure 6. The review of Watts and Sweeten (1995) shows that the presently used limits to assess odour nuisance are based on very little data. 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 and Ham, 1988). Winneke et al. (1990) give an exceeding probability of 3% to 5% of the year for an average sensitive person. The limits of odour impact criteria suggested by Watts and Sweeten show a similar behaviour. Especially if a pair of limit values is used for the definition (G-AGR, AUT and G-MIX2) of the impact criteria, the slope of these lines are almost the same, as shown in Figure 6. Besides the odour impact criteria, the separation distances for the exceeding probabilities and the corresponding odour thresholds (Table 4) are added to Figure 6 (filled circles labelled with the separation distance).

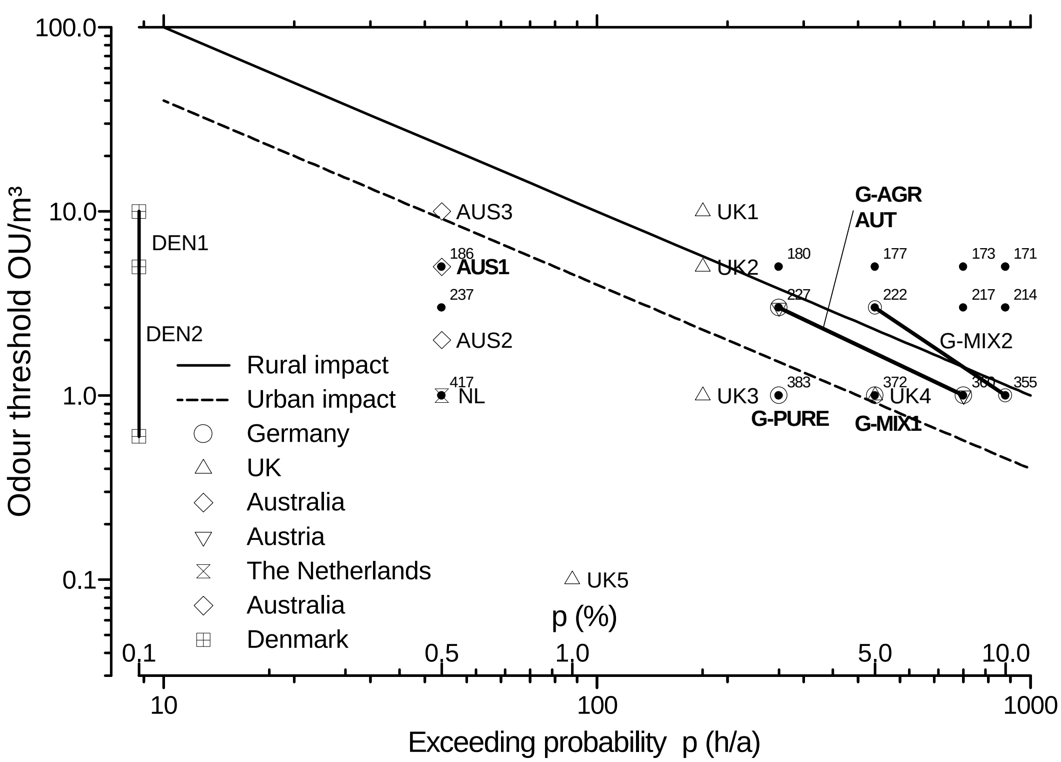

Fig. 6: Impact criteria of various countries defined by an odour threshold and its exceeding probability (Tab. 2) and the criteria for rural and urban impact, suggested by Watts and Sweeten (1995). The impact criteria discussed in this paper are highlighted in bold. The separation distances (m) calculated by the AODM are marked by filled circles, and labelled with the distance.

The problem of odour regulation is summarised by Nicell (1994) discussing the whole chain of odour sensation (unspecific detection 1 OU/m^3), discrimination (3 to 5 OU/m^3), unmistakable perception (5 OU/m^3, complaint level), and as a last step the degree of annoyance. The importance of hedonistic effects of odours is shown by comparing the assessment of odour intensity with the odour concentration: pleasant odours are more favourably assessed than unpleasant ones even if concentrations are equal (Hangartner, 1988 and 1990; Paduch, 1988). Bundy et al. (1997) showed that by selecting a power law the intensity of odour of pigs can be described by the odour concentration with an exponent in the range of 0.52 to 0.71. The relationship between odour concentration and the degree of annoyance seems to be weak in general because a covariance of only 10 to 20% is reported by Pulles and Cavalini (1990). On the other hand not only the odour concentration and the hedonic character of the odour is important but also the persistence of odour sensation.

The empirical approach to determine the separation distance between livestock units and residential areas is done by national guide lines. Most of them are used for regulatory purposes. The primary interest of all the guide lines is not the perception of odour but to avoid odour annoyance. The objective of the Austrian guideline (Schauberger et al., 1997) is to determine *"a separation distance to the neighbourhood which guarantees a far-reaching protection against odour annoyance"*. The German guidelines *"try to avoid considerable annoyance by odour"* (VDI 3471, 1986; VDI 3472, 1986; VDI 3473, 1994). The Swiss guideline was conceived as recommendation of minimum separation distances (Richner and Schmidlin, 1995) to fulfil the requests of the environmental protection act. Compared to the odour impact criteria based on the exceeding probability and the odour threshold used in the present investigation, the definitions in the guide lines are much weaker.

The discrepancy between separation distances calculated by the AODM and the guide lines (Table 6) can be explained by the uncertainties of the function describing the separation distance in relation to the odour emission (e.g. number of animals or livestock units), used in the guide lines. Piringer and Schauberger (1999) suggest an exponent of 0.7 for the power law compared to the exponent of the guide lines between 0.3 (Germany and Switzerland) and 0.5 (Austria and The Netherlands). This is in good agreement with calculations with a dispersion model developed by Krause and Lung (1993) using an exponent of 0.6 (Lung, 1999).

The diurnal variation of odour sensation at the calculated separation distance (data sample G-PURE, Figure 3a) is in accordance with the observed time of complaints. Schiffman (1994 cit. after Wilson 1996) found most complaints from swine odour to occur early in the morning or late at night, when the near-surface boundary layer is stably stratified. 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 interviewed persons feel constantly annoyed all over the year. Lohr (1996) investigated the odour perception for the four seasons by the frequency of odour exposure (number of odour sensation noticed per month) and found 3.24 for summer, 1.18 for spring, 0.71 for autumn, and 0.12 for winter, respectively. 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, respectively. The discrepancy between these results of the annual variability and the model calculation of the separation distance by the AODM (Fig. 3b) could be explained by a temperature effected sensation sensitivity (Strauss et al., 1986). 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 air temperature (18 – 28°C) and relative humidity (30 – 70%).

The dominant influence of the wind direction on the occurrence of odour is shown in Fig. 4b. For the dominant wind directions E and ENE as well as W and WSW (Fig. 1a) odour sensation occurs much more often than for the other directions. The Austrian guide line is the only one which considers the influence of the wind direction distribution on the separation distance. All other guide lines, except the Austrian one, use the concept of an omni-directional separation distance. The discrepancy between the overall wind speed distribution and the one related to odour sensation (Fig. 4a) can be explained by the sensitivity of the separation distance on wind velocity and stability of the atmosphere (Schauberger et al., 2000b). The dominant effect for low separation distances is the wind speed. For unstable (stability classes 2 and 3) and very stable conditions (stability classes 6 and 7) combined with low wind velocity, the lowest sensation distances are calculated. On the other hand, the highest sensation distances, relevant for the exceeding probability below 10% (Fig. 2), occur for higher wind velocities and stability classes 4, 5 and 6 according to the investigation of Schauberger et al. (2000b).

The discrepancies between the AODM and the cited investigations concerning the variation of odour sensation around the year need further study. The parameterisation of the peak-to-mean ratio used presently in the AODM has to be evaluated against measurements of the standard deviations of the three wind components done with ultrasonic anemometers to assess properly their relation to the horizontal wind speed, depending on discrete stability classes. These investigations will be undertaken in the near future.

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