ELSEVIER

Agriculture, Ecosystems and Environment 87 (2001) 13–28

Agriculture Ecosystems & Environment

www.elsevier.com/locate/agee

# Separation distance to avoid odour nuisance due to livestock calculated by the Austrian odour dispersion model (AODM)

G. Schauberger [a,*], M. Piringer [b], E. Petz [b]

[a] *Institute of Medical Physics and Biostatistics, University of Veterinary Medicine Vienna, Veterinärplatz 1, A 1210 Vienna, Austria*

[b] *Central Institute for Meteorology and Geodynamics, Vienna, Austria*

Received 21 March 2000; received in revised form 31 August 2000; accepted 28 September 2000

**Abstract**

Odour emission of livestock buildings is major burden for ambient residential areas. Using a dispersion model to calculate ambient odour concentrations, the separation distance between livestock buildings and residential areas was defined by a pre-selected odour threshold and an exceeding probability. The dynamic Austrian odour dispersion model (AODM) was 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 for a pig fattening unit of 1000 heads were compared with empirical guide lines used in some countries (Austria, Germany, Switzerland, The Netherlands, USA). For most guide lines, the separation distances were smaller compared to the model calculation, except for the German guide line applied for non-agricultural areas. Odour sensation occurred predominantly around sunset, with neutral or slightly stable atmospheric stability. The presented AODM is a useful tool for regulatory purpose. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* Odour; Livestock building; Emission; Separation distance; Swine; Guide line; Dispersion model; Austria

## 1. Introduction

Odour is one of the major nuisances in the environment mainly caused by livestock units and industry. In 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 Schwinkowski (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%).

* Corresponding author. Tel.: +43-1-250-77-4306; fax: +43-1-250-77-4390.
*E-mail address:* gunther.schauberger@vu-wien.ac.at (G. Schauberger).

0167-8809/01/$ – see front matter © 2001 Elsevier Science B.V.All rights reserved.
PII: S0167-8809(00)00299-1

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,b), The Netherlands (Ministrie van Landbouw, 1991), Germany (VDI 3471, 1986; VDI 3472, 1986; VDI 3473, 1994), USA (Heber, 1997, 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.

The objective of this study was the calculation of the ambient odour concentration by the AODM, for a pig fattening unit of 1000 heads. Subsequently, these model calculations were evaluated by odour impact criteria to determine the separation distances. The possibilities and restrictions of the AODM and the used odour impact criteria were discussed due to a comparison with national guide lines, using an empirical approach for the problem.

## 2. Material 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 air temperature inside a mechanically ventilated livestock building is calculated using a balance equation of the sensible heat (Schauberger et al., 1999, 2000a). 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

$$S_A + S_B + S_V = 0 \quad (1)$$

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, $\Delta T_c$, 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, $T_i$.

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

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 (Table 1).

The odour release from the livestock building originates from the animals, polluted surfaces and the feed. Outdoor odour sources such as slurry tanks or feed storage facilities are not taken into account. The concentration of odorants, $c_{OD}$, can be handled like other volatile pollutants and can be measured by an olfactometer in odour units per volume (OU/m$^3$). One odour unit is the amount of odorants present in 1 m$^3$ of odorous gas (under standard conditions) elicits a physiological response from a panel (detection threshold) equivalent to that elicited by 123 μg *n*-butanol dispersed in 1 m$^3$ of neutral gas at standard conditions (CEN, 1999).

The emission of the livestock building at the outlet air is quantified by the odour flow, $E = c_{OD}/V$, in OU/s and the specific odour flow, $e$, in OU/s 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 OU/s LU 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 Eq. (3).

$$E_m(T_o) = E_m(0.905 + 0.0095T_o) \quad (3)$$

Instead of a constant odour release in previous model calculations (Schauberger et al., 1999, 2000b), 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 $\tau$ 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

Table 1
System parameters of the livestock building typical for middle Europe[a]

| Parameters | |
|---|---|
| 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 m$^3$/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 m$^3$/h |
| Area of the building (ceiling, walls, windows, doors) per animal | 1.35 m$^2$ |
| 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 $\Delta T_c$ | 4 K |

[a] The parameters are representative for an unit of about 1000 fattening pigs.

to be the same, i.e. triggered by the animal activity. The minimum of the animal activity of fattening pigs occurs around 01.15 h local time at night (Pedersen, 1996; Pedersen and Takai, 1997).

$$E(t) = E_{\mathrm{m}}(T_{\mathrm{o}})\left[1 + 0.20\sin\left(\frac{2\pi}{\tau}(t - 7.25)\right)\right] \quad (4)$$

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 OU/s according to Eq. (4) divided by the volume flow, $V$, of the ventilation system in $m^3$/s. The model has been described extensively in Schauberger et al. (1999, 2000a).

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 $0.75\,m^2$ according to welfare guide lines.

The odour concentration of the centre line of the plume is calculated by the Austrian regulatory dispersion model (ÖNorm M 9440, 1992/1996; 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).

### *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, personal communication), 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 and 2000 m from the source. The distances up to which the odour thresholds of 1, 3, and $5\,OU/m^3$, 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. For example, the 97%-percentile (corresponding an exceeding probability of 3%) of the $1\,OU/m^3$ threshold gives the separation distance for pure residential areas and general residential areas according to the limits used in Germany (G-PURE, Table 2).

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

Table 2
Odour impact criteria: 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, personal communication), Australia (Jiang and Sands, 1998), The Netherlands (Hagen and van Belois, 1998), Denmark, New Zealand and Massachusetts (USA) (after Jiang and Sands, 1998)

| Odour impact criteria[a] | Land use category[b] | Comment | Label[c] |
|---|---|---|---|
| Germany | | | |
| 1 OU/m$^3$/3% | Pure residential areas and residential areas | | G-PURE |
| 1 OU/m$^3$/5% | Residential and structured areas | | G-MIX1 |
| 1 OU/m$^3$/8% and 3 OU/m$^3$/3% | Restricted business-areas and village-area with mixed utilisation | | G-MIX2 |
| 1 OU/m$^3$/10% and 3 OU/m$^3$/5% | Village-areas with predominantly agricultural utilisation | | G-AGR |
| Germany, Thüringen | | | |
| 1 OU/m$^3$/7% | Pure residential areas and residential areas (WR) | Only valid in Thüringen | GT-PURE |
| 1 OU/m$^3$/10% | General residential areas and mixed utilisation (WS, WA, WB, MI, MK) | Only valid in Thüringen | GT-MIX1 |
| 1 OU/m$^3$/12% | Villages (MD) | Only valid in Thüringen | GT-VIL1 |
| 1 OU/m$^3$/15% | Villages with existing livestock units above a certain limit (MD) | Only valid in Thüringen | GT-VIL2 |
| 1 OU/m$^3$/15% | Business areas (GE) | Only valid in Thüringen | GT-BUS |
| 1 OU/m$^3$/15% | Industry (GI) | Only valid in Thüringen | GT-IND |
| UK | | | |
| 10 OU/m$^3$/2% | | Serious annoyance expected with near certainty | UK1 |
| 5 OU/m$^3$/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 OU/m$^3$/2% | | No serious annoyance expected in the large majority of cases | UK3 |
| 1 OU/m$^3$/0.5% | | Safe target value for new sources | UK4 |
| 10 OU/m$^3$/0.01% | | Safe target value for new sources applicable to highly intermittent sources | UK5 |
| Austria | | | |
| 1 OU/m$^3$/8% and 3 OU/m$^3$/3% | | Threshold for reasonable odour sensation for medical purpose | AUT |
| Australia | | | |
| 5 OU/m$^3$/0.5% | Rural and urban area | | AUS1 |
| 2 OU/m$^3$/0.5% | Residential area | New South Wales | AUS2 |
| 10 OU/m$^3$/0.5% | Residential areas | Victoria | AUS3 |
| The Netherlands | | | |
| 1 OU/m$^3$/2% | Residential areas | Existing units | NL |
| 1 OU/m$^3$/0.5% | Residential areas | New installations | NL |
| 1 OU/m$^3$/5% | Residential areas outside of villages and business areas | | NL |
| Denmark | | | |
| 5–10 OU/m$^3$/0.1% | | Plants | DEN1 |
| 0.6–20 OU/m$^3$/1% | | Surrounding | DEN2 |
| New Zealand | | | |
| 2 OU/m$^3$/0.5% | | Property boundary | NZ |
| MA, USA | | | |
| 5 OU/m$^3$/0.5% | | Plant boundary | USA |

[a] Odour concentration threshold percentile compliance: exceeding probability for the odour concentration threshold $p$ (%).
[b] The lend use category varies the accepted protection level.
[c] The labels are used in the following tables and figures.

distances, so that the separation distance of the guide line is given by an interval. 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 min for a 2-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 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 (2-year period) is from 14.9 to 35.3°C. The annual precipitation amounts to 838 mm (mean over the period 1961–1990).

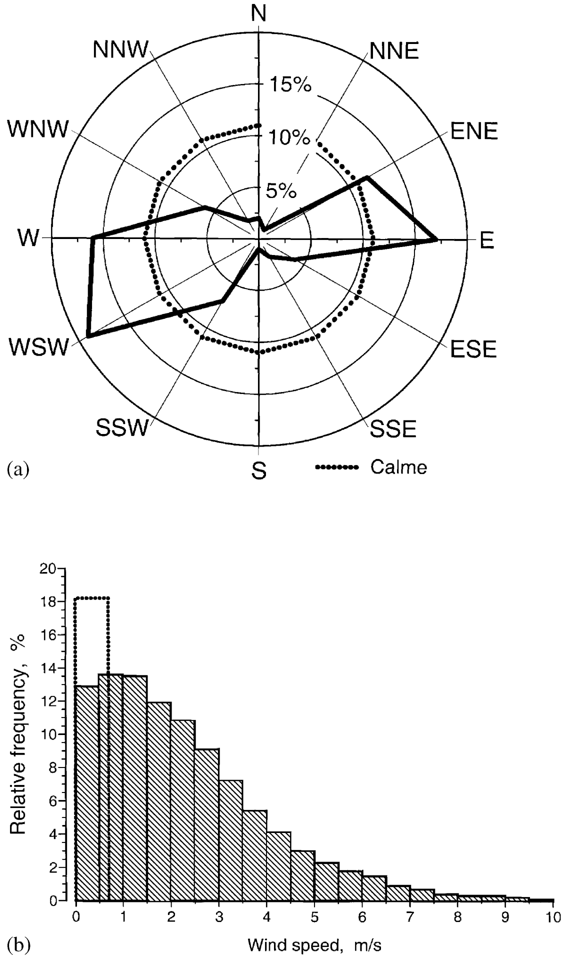


Fig. 1. Frequency distribution of (a) the wind direction and (b) wind velocity at Wels in Upper Austria; (- - - -) calm conditions according to the Austrian regulatory dispersion model with wind velocity less than 0.7 m/s (ÖNorm M 9440, 1992/1996).

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 2–7 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 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.

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

| Wind velocity (m/s) | Stability class (SC) | | | | | |
|---|---|---|---|---|---|---|
| | 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 | | | |
| Total | 102 | 161 | 431 | 59 | 110 | 137 |

## 3. Results

### 3.1. Odour separation distances

In Fig. 2, the separation distances calculated for a combination of odour thresholds of 1, 3, and 5 OU/m$^3$ 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 was more dependant on the odour threshold than on the exceeding probability. By increasing the exceeding probability from 0.5 to 10%, the separation distance was changed by less than 20%. On the other hand, the separation distance was changed between 55 and 52% due to a change of the odour threshold from 1 to 5 OU/m$^3$ (see also Fig. 2).

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

| Exceeding probability (%) | Odour sensation (OU/m$^3$) | | |
|---|---|---|---|
| | 1 OU/m$^3$ | 3 OU/m$^3$ | 5 OU/m$^3$ |
| 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) showed very little difference because only the exceeding probability changed from 3 to 5% (see also Table 4 and Fig. 2). For agricultural residential

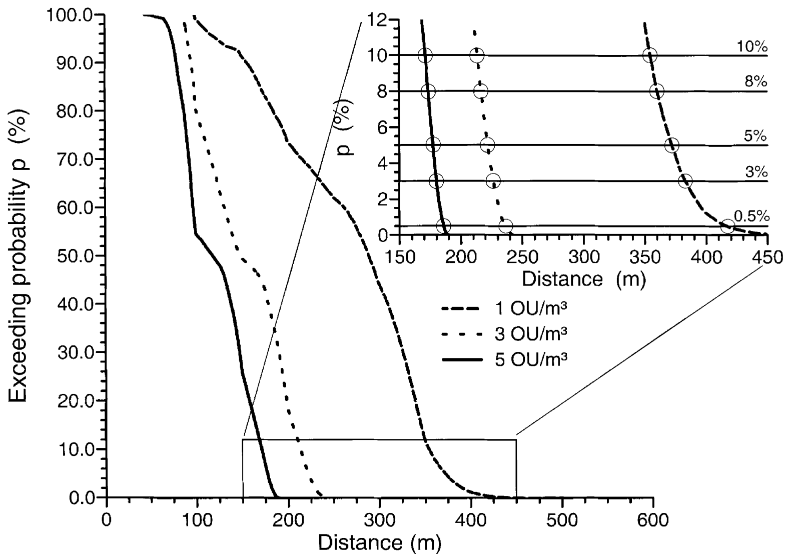


Fig. 2. Exceeding probability $p$ (%) for three odour thresholds (1, 3 and 5 OU/m$^3$) as a function of the distance (m) from the source. In the small panel the exceeding probability is zoomed, relevant to estimate the separation distance for odour impact criteria.

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

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

areas G-AGR the distance was reduced to 227 m. For the Austrian impact criterion, the separation distance AUT was close to the German non non-agricultural residential area (G-PURE and G-MIX1) with 360 m. For Australia, the separation distance AUS was the lowest one with 186 m.

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 showed a shorter distance than the model calculation, in the range of 30–64%. The lower the protection level, the higher the differences.

### 3.2. Occurrence of odour sensation

Taking the separation distance defined for pure residential areas in Germany (G-PURE, odour threshold: 1 $OU/m^3$ and exceeding probability 3% = 262 h per year) as an example, the occurrence of odour sensation was analysed for following parameters: diurnal and annual variability (Fig. 3), wind velocity and wind direction (Fig. 4) and stability of the atmosphere (Fig. 5). At a distance of the calculated sensation distance, the occurrence of sensation in conjunction with the above mentioned parameters was compared by the frequency distribution of the entire data set (all half-hour values of the 2-year period, empty bars) with the probability of odour sensation including all half-hour values when odour sensation takes place (3% of all half-hour values of the 2-year period; sum of all these classes is 100%, hatched bars).

Investigating the diurnal variation of odour sensation (Fig. 3a), a strong maximum between 16.00 and

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

| Country | Separation distance (m) | | Difference (%) |
|---|---|---|---|
| | Model and impact criterion | Guide line | |
| 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 (e.g. 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 |

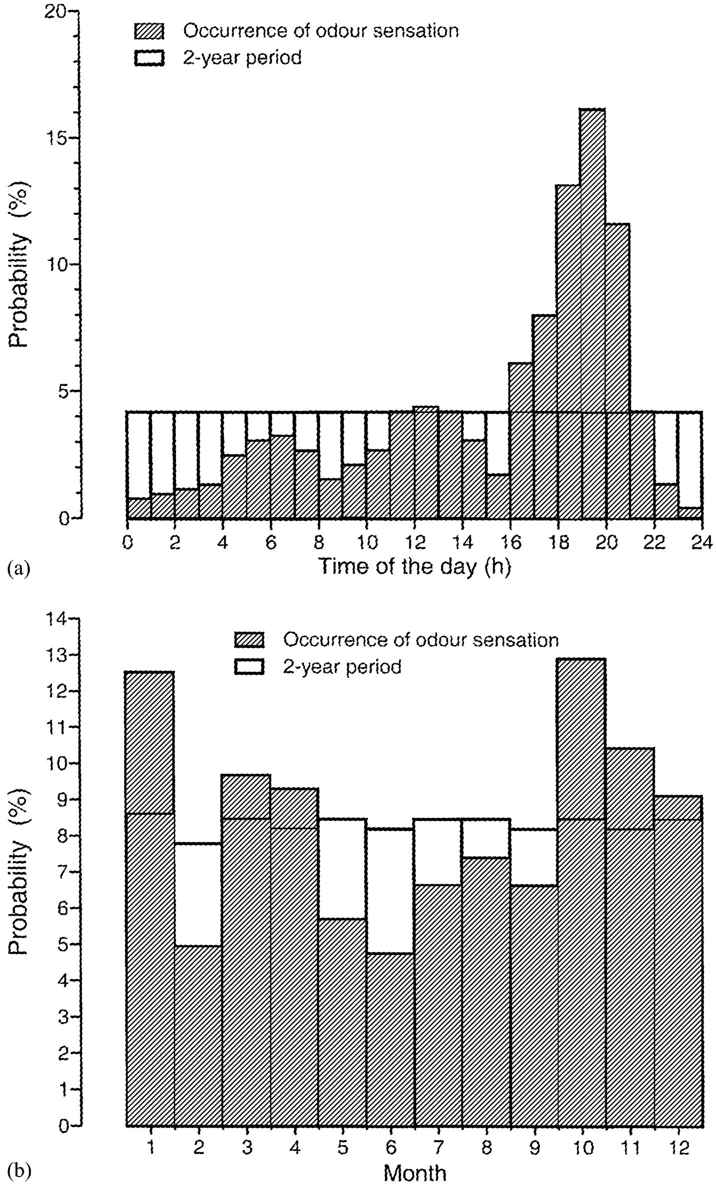


Fig. 3. Diurnal and annual variation: comparison of the frequency distribution for the entire data (empty bars) set and the occurrence of odour sensation (hatched bars; G-PURE) for the time of day (a) and for the months of the year (b).

21.00 h was 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 are discussed in Section 4. The annual course (Fig. 3b) showed an irregular pattern, but in general more frequent odour sensation occurred during the winter months. In this case, the model calculations were not in agreement with expectations (see discussion in Section 4).

The frequency distribution of the wind velocity of the entire data-set (Fig. 4a) showed a maximum at 1.0–1.5 m/s. The distribution for odour sensation

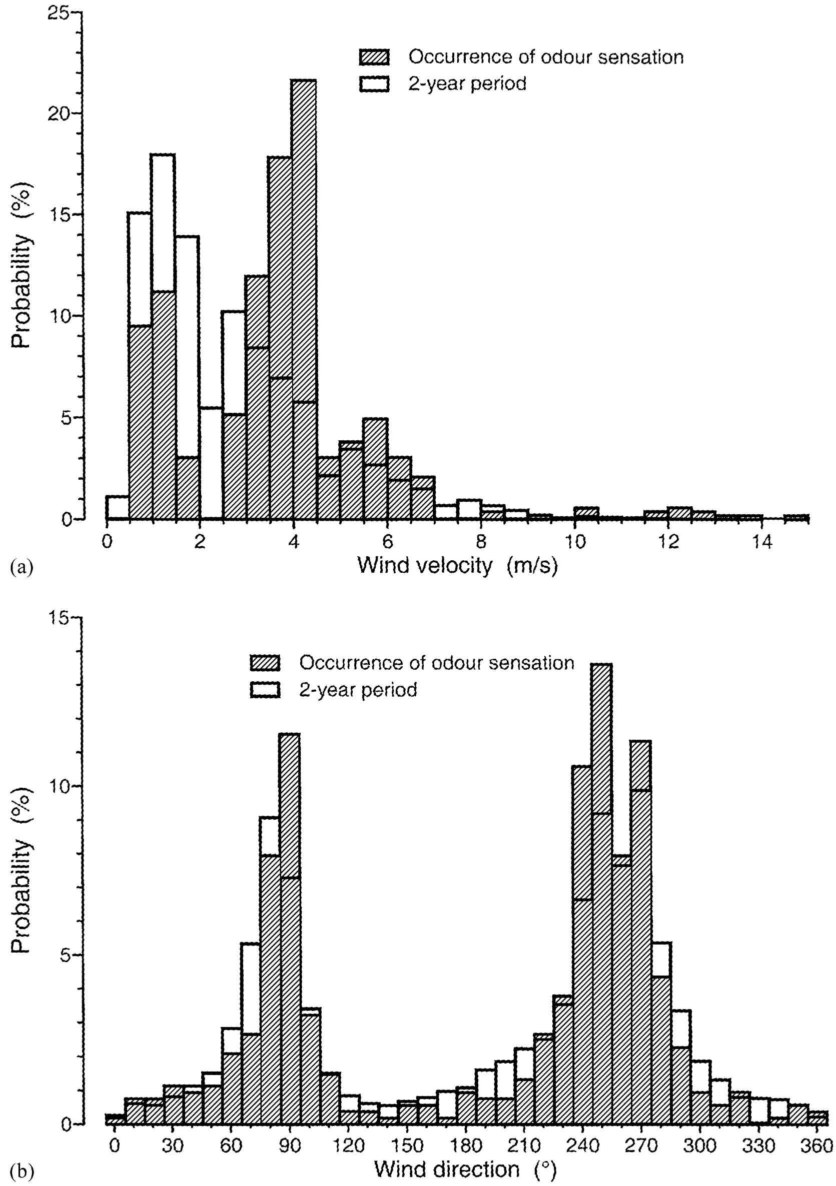


Fig. 4. Wind velocity and wind direction: comparison of the frequency distribution for the entire data (empty bars) set and the occurrence of odour sensation (hatched bars; G-PURE) for wind velocity (a) and for wind direction (b).

(impact criterion for G-PURE) had two maxima, the absolute one around 4 m/s and a local maximum around 1 m/s. This result suggested 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 (Fig. 4b) were not large. For the main wind directions, slightly larger probabilities were calculated in case odour sensation occurs. The result of Fig. 5 suggested that odour sensation only

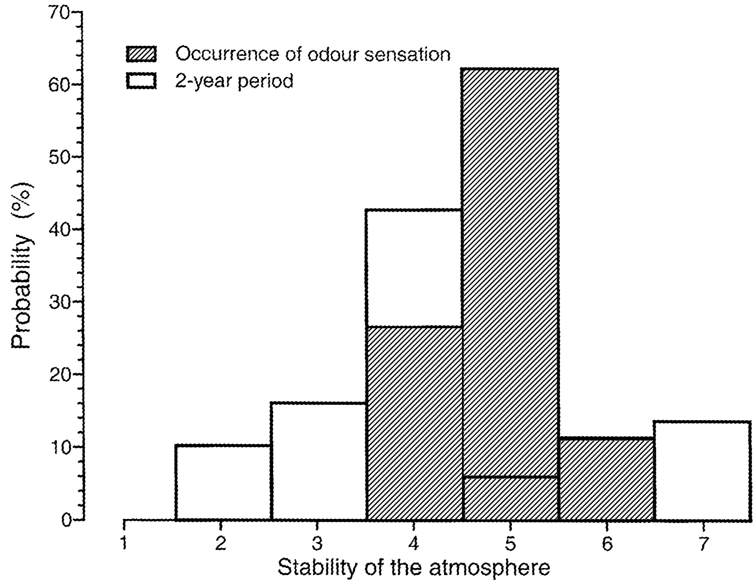


Fig. 5. Stability of the atmosphere: comparison of the frequency distribution for the entire data (empty bars) set and the occurrence of odour sensation (hatched bars; G-PURE) for the classes of stability (Reuter, 1970).

occurs for stability classes 4–6. More than 60% of all odour sensation was 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 was frequent (Fig. 3a).

## 4. Discussion

### *4.1. Odour emission and dispersion model*

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, 2000a). Other models use a constant emission scenario (Krause and Lung, 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.

The use of the Gaussian regulatory model ÖNorm M 9440 (1992/1996) 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 odoriphores calibrated by field measurements]), 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.

### 4.2. Odour impact criteria

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/m$^3$) as a function of the exceeding probability $p$ (h/a) is calculated by $T_{\mathrm{rural}} = 800/p$ and $T_{\mathrm{urban}} = 400/p$. 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 Fig. 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 3–5% 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 Fig. 6. Besides the odour impact criteria, the separation distances for the exceeding probabilities and the corresponding odour thresholds (Table 4) are added to Fig. 6 (filled circles labelled with the separation 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 (3–5 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,

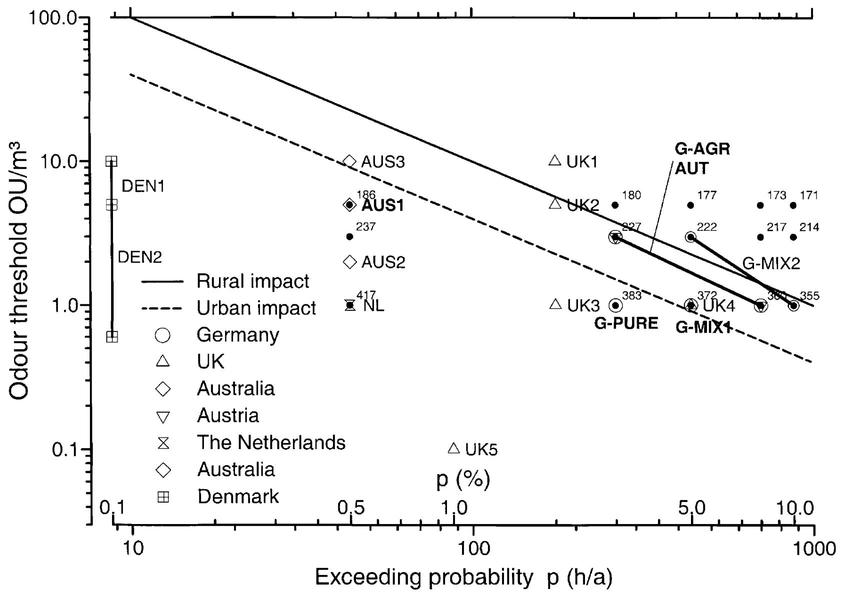


Fig. 6. Impact criteria of various countries defined by an odour threshold and its exceeding probability (Table 2) and the criteria for rural and urban impact, suggested by Watts and Sweeten (1995). The impact criteria discussed in this paper are highlighted in bold. The separation distances (m) calculated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

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 0.52–0.71. The relationship between odour concentration and the degree of annoyance seems to be weak in general because a covariance of only 10–20% 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.

### *4.3. Comparison with national guide lines*

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).

### 4.4. Occurrence of odour sensation

The diurnal variation of odour sensation at the calculated separation distance (data sample G-PURE, Fig. 3a) is in accordance with the observed time of complaints. Schiffman (1998 cit. after Wilson, 1995) 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 4–6 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.

## 5. Conclusions

The AODM and the subsequent assessment of the ambient odour concentration by the odour impact criteria describes the chain of the odour release inside the livestock building to the nose of the neighbours and the prospective annoyance by odour sensation with varying levels of quality and uncertainties.

- The odour emission model is based on view data. Up till now no long-term measurements are available to evaluate and to improve the model.
- Dispersion models which are in use for odour emissions are well validated. This chain-link needs no further improvement compared to the other model steps.
- The model to calculated the instantaneous odour concentration is based on view experiments, most of them were done for neutral stratified atmosphere. For an improvement, additional measurements for stable and unstable atmosphere seems necessary.
- The odour impact criteria which are used to evaluate the calculated odour concentrations in the vicinity livestock building, are based on very simple statistical criteria (exceeding probability and odour concentration threshold). Additionally a weighting of odour sensation by the time of the day and time of the year, in a similar way as it is done for noise, seems to be appropriate to improve the assessment.

- The national guide lines should be harmonised to reduce the deviation between each other as well as between model calculations, as it is presented in this paper.

## Acknowledgements

The work was partly funded by the Austrian Federal Ministry of Environment, Youth and Family Affairs under Contract No. 14 4444/14-I/4/99.

## References

Briggs, G.A., 1975. Plume rise predictions. Lectures on air pollution and environmental impact analysis. AMS, Boston, pp. 59–111.

Bundy, D.S., Chen, Y.C., Hoff, S.J., Zhu, J., 1997. Modelling odour intensity for swine units. In: Voermans J.A.M., Monteny, G.J. (Eds.), Ammonia and Odour Emission from Animal Production Facilities. NVTL, Rosmalen, pp. 83–91.

Carson, J., Moses, H., 1969. The validity of several plume rise formulas. J. Air Pollut. Control Ass. 19, 862–866.

CEN prEN13725, 1999. Air quality — determination of odour concentration by dynamic olfactometry. Comitté Européen de Normalisation.

Chen, Y.C., Bundy, D.S., Hoff, St., 1998. Development of a model of dispersion parameters for odour transmission from agricultural sources. J. Agric. Eng. Res. 69, 229–238.

Fang, L., Claosen, G., Fanger, P.O., 1998. Impact of temperature and humidity on the perception of indoor quality during immediate and longer whole-body exposure. Indoor Air 8, 276–284.

Hagen, G., van Belois, H.J., 1998. Die rechtliche Regelung der Niederlande zur Verringerung der geruchsbelästigung: wie man einen akzeptablen Belästigungsindex findet. In: Gerüche in der Umwelt, VDI-Bericht 1373, Düsseldorf, pp. 385–390.

Hangartner, M., 1988. Odour measurement and assessment of odour annoyance in Switzerland. In: Nielsen, V.C., Voorburg, J.H., L'Hermite, P. (Eds.), Volatile Emissions from Livestock Farming and Sewage Operation. Elsevier Applied Science, New York.

Hangartner, M., 1990. Zusammenhang zwischen Geruchskonzentration, Intensität und hedonischer Geruchswirkung. In: Gerüche-Stand der Erkenntnisse zur Ermittlung von Belastung und Belästigung. VDI-Kommission Reinhaltung der Luft, Düsseldorf, Band 12.

Heber, A.J., 1997. Setbacks for sufficient swine odor dispersion and dilution. In: Proceedings of the Livestock and Environmental Symposium, University of Nebraska, USA.

Heber, A.J., 1998. Setting a Setback. National Hog Farmer, pp. 62–66.

Jiang, J.K., Sands, J., 1998. Report on odour emissions from poultry farms in western Australia. Odour Research Laboratory, University of New South Wales, Sydney.

Jiang, J.K., Sands, J.R., 1999. Controlling noxious animal odours: an imperative at the rural–urban interface — Review. Asian Austr. J. Anim. Sci. 12, 633–641.

Knauer, W., 1994. Prognose und Bewertung von Geruchsemissionen and Geruchsimmssionen. In: Immissionschutz in der Landwirtschaft. Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL), Darmstadt, Arbeitspapier 207.

Kolb, H., 1981. Ein normatives Modell zur Simulierung der Ausbreitung von Schadstoffen in der atmosphäre unter besonderer Berücksichtigung der Verhältnisse in Österreich (A regulative model to simulate the dispersion of pollutants in the atmosphere for the situation in Austria). Publ. 29, Abteilung für Theoretische Meteorologie, University of Vienna, Vienna.

Kowalewsky, H.H., 1981. Messen und Bewerten von Geruchsimmissionen. Chemische und sensorische Bestimmung des Geruchs in der Umgebung von Ställen, offenen Füllbehältern und begüllten Feldern (Measuremenrt and evaluation of odour concentration. Chemical and sensorial evaluation of odour in the vicinity of livestock housings, open slurry tanks and fields dunged with slurry). KTBL-Schrift 260, Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. KTBL, Darmstadt.

Krause, K.H., Lung, Th., 1993. Immissionsprognostik von Geruchsstoffeintägen im Rahmen von Genehmigungsverfahren. Staub-Reinhaltung der Luft 53, 323–419.

Kypke, J., 1994. Die Anwendung des Bundes-Immissionsschutzgesetzes in Meklenburg-Vorpommern. In: Immissionschutz in der Landwirtschaft. Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL), Darmstadt, Arbeitspapier 207.

Lohr, L., 1996. Perception of rural air quality: what will the neighbors think? J. Agribusiness 14, 109–128.

Lotze, J., Schwinkowski, K., 1998. Die Thüringer vorläufige Verwaltungsvorschrift zur Feststellung und Beurteilung von Geruchsemissionen und Geruchsimmisionen. In: Gerüche in der Umwelt, VDI-Bericht 1373, Düsseldorf, pp. 401–412.

Lung, Th., 1999. Personal communication.

Martinec, M., Hartung, E., Jungbluth, Th., 1998. Geruchsemissionen aus der Tierhaltung (Literaturstudie) (Odour emission of livestock husbandry (a literature survey)). Ministerium für Umweld und Verkehr, Baden-Würthenberg, Germany, pp. 68.

Miedema, H.M.E., Ham, J.M., 1988. Odour annoyance in residential areas. Atmos. Environ. 22 (11), 2501–2507.

Miner, J.R., 1995. A review of literature on the nature and control of odors from pork production facilities. National Pork Producer Council, Des Moines, IA, USA.

Ministrie van Landbouw, 1991. Richtlijn Ammoniak en Veehouderij. Ministrie van Landbouw, Naturbeheer en Visserij, Den Haag en Ministrie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, Leidschendam.

Misselbrook, T.H., Clarkson, B.F., Pain, C.R., 1993. Relationship between concentration and intensity of odour for pig slurry and broiler houses. J. Agric. Eng. Res. 55, 163–169.

Mylne, K.R., 1988. Concentration fluctuation measurements of a tracer plume at up to 1 km range in the atmosphere. In: Proceedings of the 9th Symposium on Turbulence and Diffusion, Roskilde, pp. 168–171.

Mylne, K.R., 1992. Concentration fluctuation measurements in a plume dispersing in a stable surface layer. Boundary-Layer Meteorol. 60, 15–48.

Mylne, K.R., Mason, P.J., 1991. Concentration fluctuation measurements in a dispersing plume at a range of up to 1000 m. Q. J. R. Meteorol. Soc. 117, 177–206.

Nicell, J.A., 1994. Development of the odour impact model as a regulatory strategy. Int. J. Environ. Pollut. 4, 124–138.

Oldenburg, J., 1989. Geruchs- und Ammoniak-Emissionen aus der Tierhaltung (Odour and ammonia emission of livestock husbandry). KTBL-Schrift 333, Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. KTBL, Darmstadt.

ÖNorm M 9440 1992/1996. Ausbreitung von luftverunreinigenden Stoffen in der Atmosphäre; Berechnung von Immissionskonzentrationen und Ermittlung von Schornsteinhöhen (Dispersion of pollutants in the atmosphere — calculation of the ambient air concentrations and determination of stack heights). Österreichisches Normungsinstitut, Vienna

Paduch, M., 1988. Present state of VDI-guide lines on odour assessment. In: Nielsen, V.C., Voorburg, J.H., L'Hermite, P. (Eds.), Volatile Emissions from Livestock Farming and Sewage Operation. Elsevier Applied Science, New York.

Pechinger, U., Petz, E., 1999. Model evaluation of the Austrian Gaussian plume model ON M 9440: comparison with the Kincaid dataset. Int. J. Environ. Pollut. 5, 338–349.

Pedersen, S., 1996., Døgnvariationer i dyrenes aktivitet i kvæg-, svine-og fjerkræstalde (Diurnal variation of the animal activity of calve, pig and poultry). Internal report 66, Danish Institute of Animal Science, Horsens, Denmark

Pedersen, S., Takai, H., 1997. Diurnal variation in animal heat production in relation to animal activity. In: Bottcher, R.W., Hoff, S.J. (Eds.), Proceedings of the 5th International Livestock Environmental Symposium, Bloomington, MN.

Piringer, M., Schauberger, G., 1999. Comparison of a Gaussian diffusion model with guidelines for calculating the separation distance between livestock farming and residential areas to avoid odour annoyance. Atmos. Environ. 33, 2219–2228.

Pulles, M.P.J., Cavalini, P., 1990. Geruchstoffkonzentration und Geruchsbelästigung: ergebnisse von zwei Feldstudien. In: Gerüche-Stand der Erkenntnisse zur Ermittlung von Belastung und Belästigung. VDI-Kommission Reinhaltung der Luft, Düsseldorf, Band 12.

Reuter, H., 1970. Die Ausbreitungsbedingungen von Luftverunreinigungen in Abhängigkeit von meteorologischen Parametern (Dispersion conditions of airborne pollutants in dependence on meteorological parameters). Archiv für Meteorologie und Geophysik. Bioklimatol. A 19, 173–186.

Richner, B., Schmidlin, A., 1995, Mindestabstände von Tierhaltungsanlagen. Empfehlungen für neue und bestehende Betriebe. Eidgenössische Forschungsanstalt für Betriebswirtschaft und Landtechnik, Tänikon, FAT-Bericht 476.

Rieß, G., Maier, B., Neser, St., Zeisig, H.-D., Gronauer, A., Schön, H., 1999. Bewertung von Geruchsemissionen verschiedener Tierhaltungssysteme mittels Multisensorarray am Beispiel von Mastschweinehaltungen mit Ober- und Unterflurabsaugung. In: Bau, Technik und Umwelt. München-Weihenstephan, Germany.

Schauberger, G., Piringer, M., 1997a. Assessment of the protection distance to avoid annoyance by odour sensation caused by livestock husbandry by the Austrian guide line. In: Voermans, J.A.M., Monteny, G.J. (Eds.), Ammonia and Odour Emission from Animal Production Facilities. NVTL, Rosmalen, 1997.

Schauberger, G., Piringer, M., 1997b. Guideline to assess the protection distance to avoid annoyance by odour sensation caused by livestock husbandry. In: Bottcher, R.W., Hoff, S.J. (Eds.), Livestock Environment, Vol. V. ASAE, St. Joseph, MI.

Schauberger, G., Piringer, M., Eder, J., Fiebiger, H., Köck, M., Lazar, R., Pichler-Semmelrock, F., Quendler, T., Swoboda, M., Thiemann, G., Teufelhart, J., 1997. Österreichische Richtlinie zur Beurteilung von Immissionen aus der Nutztierhaltung in Stallungen. Gefahrstoffe-Reinhaltung der Luft 57 (10), 399–408.

Schauberger, G., Piringer, M., Petz, E., 1999. Diurnal and annual variation of odour emission of animal houses: a model calculation for fattening pigs. J. Agric. Eng. Res. 74 (3), 251–259.

Schauberger, G., Piringer, M., Petz, E., 2000a. Steady-state balance model to calculate the indoor climate of livestock buildings demonstrated for fattening pigs. Int. J. Biometeorol. 43, 154–162.

Schauberger, G., Piringer, M., Petz, E., 2000b. Diurnal and annual variation of the sensation distance of odour emitted by livestock buildings calculated by the Austrian odour dispersion model (AODM). Atmos. Environ. 34, 4839–4851.

Schiffman, S.S., 1998. Livestock odors: implications for human health and well-being. J. Anim. Sci. 76, 1343–1355.

Skinner, J.A., Lewis, K.A., Bardon, K.S., Tucker, P., Catt, J.A., Chambers, B.J., 1997. An overview of the environmental impact of agriculture in the UK. J. Environ. Manage. 50, 111–128.

Smith, M.E., 1973. Recommended Guide for the Prediction of the Dispersion of Airborne Effluents. ASME, New York.

Stangl, N., Köck, M., Pichler-Semmelrock, F., 1993. Geruchsbelästigung bei Anlagen. Ecolex, 277–282.

Strauss, G., Cervinka, R., Haider, M., 1986. Erhebung über die Geruchsbelästigung in der Umgebung von Massentierhaltungen-eine Feldstudie. Institute of Environmental Hygiene, University of Vienna, Vienna.

TA Luft, 1986. 1. Allgemeine Verwaltungsvorschrift zum Bundes-Immisionsschutzgestez (Technische Anleitung zur Reinhaltung der Luft) GMBl. 37.J Nr 7 28.2.1986, 95–143.

VDI 3471 1986. Emissionsminderung Tierhaltung-Hühner. Beuth, Berlin.

VDI 3472 1986. Emissionsminderung Tierhaltung-Schwein. Beuth, Berlin.

VDI 3473 1994. Emissionsminderung Tierhaltung-Rinder. Beuth, Berlin.

VDI 3940 1993. Bestimmung der Geruchsstoffimmission durch Begehungen. Beuth, Berlin.

Watts, P.J., Sweeten, J.M., 1995. Toward a better regulatory model for odour. In: Proceedings of the Feedlot Waste Management Conference, Queensland, Australia.

Wilson, L., 1995. Swine CAFO odors: guidance for environmental impact assessment. US EPA, Region 6, Dallas.

Winneke, G., Harkort, W., Ratzki, E., 1990. Zusammenhänge zwischen Gruchshäufigkeit und Belästigungsgrad (Relationship between odour probability and the degree of annoyance). In: Gerüche-Stand der Erkenntnisse zur Ermittlung von Belastung und Belästigung. VDI-Kommission Reinhaltung der Luft, Düsseldorf, Band 12.