Weighting of odour sensation by the time of the day and time of the year to improve the reliability of the calculated separation distance

G. Schauberger*, M. Piringer**, and E. Petz**

* Medical Physics and Biostatistics, Department of Biomedical Sciences, University of Veterinary Medicine Vienna, Veterinärplatz 1, A 1210 Vienna, Austria (E-mail: *gunther.schauberger@vu-wien.ac.at*)
** Central Institute for Meteorology and Geodynamics, Department of Environmental Meteorology, Hohe Warte 38, A 1190 Vienna, Austria (E-mail: *martin.piringer@zamg.ac.at; erwin.petz@zamg.ac.at*)

Abstract In a recently published paper we compared odour complaint statistics of various sites in Europe, South Africa, and North America with calculated odour sensation at a site in Austria which can be used as a typical example of a well ventilated area with prevailing west wind and a superimposed weak influence of a mountain wind system. The assessment of odour perception by the AODM does not always coincide with the real time of nuisance complaints because the behavioural response of the neighbours to the odours was not included in the model. Here, the Austrian odour dispersion model AODM is used to calculate separation distances for an odour threshold of 1 odour unit (OU) per cubic metre exceeded in 3% of the year. At a site in the Austrian North-alpine foreland, direction-dependent separation distances for a 1000 head pig unit (calculated on the basis of a two-year time series of meteorological data) lie between 99 m for northerly winds and 362 m for westerly winds. This model output is weighted by a temporal weighting function with the time of the day and time of the year as predictors. This weighting function considers the nuisance potential of odour due to the behaviour of the neighbours in a more realistic way. During warm daytime the weight is close to unity, which means, that the threshold stays unchanged. During cold nights the threshold values of the impact criteria is increased by a factor of 10. Under the assumption, that the weighting functions maps the behaviour of humans and with it the sensitiveness to environmental odour this approach will improve considerably the assessment of nuisance potential to achieve a more realistic evaluation of the nuisance.

Keywords odour, livestock, pig, annoyance, separation distance, dispersion model, complain

INTRODUCTION

The goal of the application of a dispersion model is the assessment of the separation distance between an odour source and residential areas. This distance depends on the protection level which is defined by the odour impact criteria. An impact criterion is based on the threshold concentration and the exceedance probability of this ambient odour concentration.

In a recently published paper the time pattern of complaints in various countries was compared to the time pattern of odour sensation calculated by the Austrian Odour Dispersion Model AODM (Schauberger et al. 2001 and 2002). The 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 using the Austrian Gaussian regulatory dispersion model, and the last transforms the mean odour concentration of the dispersion model to instantaneous values that depend on wind velocity and atmospheric stability. The direction-dependent separation distance is defined as the distance from the source where a sensation level dependent on a pre-selected odour impact criterion occurs. The odour impact criteria used in this study are a combination of odour threshold (1 OU/m^3) and probability of threshold exceedance (3%) (Schauberger et al., 2006).

Reports about complaints caused by odour emissions show similar time patterns in various contries (Strauss et al., 1986; Schiffman, 1994; Lohr 1996), concentrated during the warm season and in the afternoon and evening hours. The reported complaints don't fit to the calculated odour sensation. Reasons for this discrepancy lie in the temperature sensitivity of odour perception and in the behaviour of neighbours which cannot be taken into account by the AODM.

To improve time pattern of the modelled odour sensation we introduced a weighting procedure to consider the nuisance potential of odour due to the behaviour of the neighbours. Therefore the odour sensation is weighted by the time of the day and time of the year, as is done in a similar way with the limit values for environmental noise (e.g. EU Directive 2002/49/EC, 2002).

MATERIALS AND METHODS

Short description of the Austrian odour dispersion model AODM

The calculation of odour release is based on a steady-state balance of the sensible heat flux, used to calculate the indoor temperature, and the ventilation rate of the livestock unit (Schauberger et al., 2000b). The corresponding odour flow in OU/m³ is assessed by a simple model for odour release described by Schauberger et al. (1999 & 2000b). The chosen system parameters typical for a livestock building in middle Europe can be found in detail in Schauberger et al. (2001b and 2002). The results were calculated for a mechanically ventilated pig fattening unit with 1000 pigs. The following parameters were calculated every half-hour over the two year period: outlet air temperature, outlet air velocity, volume flow of the ventilation system, odour concentration of the outlet air. The odour flow in OU/s is calculated by the product of the volume flow of the building in m³/s and odour concentration of the outlet air in OU/m³.

The mean ambient odour concentrations are calculated using the Austrian Gaussian regulatory dispersion model (ÖNorm M 9440, 1992/96), a Gaussian plume model for single stack emissions. The model has been validated internationally. The mean odour concentrations of the dispersion model are transformed to instantaneous values depending on wind velocity and atmospheric stability. The meteorological background to calculate the instantaneous values using a peak-to-mean parameterisation is described in detail by Schauberger et al. (2000a).

Weighting procedure

Each half hour value was weighted by the time of the day and time of the year. For the time of the day we selected the solar height to take into account the duration of daylight which will modify the behaviour of humans. The sigmoid weighting function w_t is given by

$$w_t = w_0 + \tfrac{1}{2}\left(1 - w_0\right)\left[\tanh\left(2 s_t \left(h - h_0\right)\right) + 1\right]$$

with the off-set of the weighting function w_0 which was selected by 0.5, by the shape factor $s_t = 0.25$ of the function, and the mid-point of the function $h_0 = -6°$. The slope can be calculated at the mid-point h_0 by $s_h\,(1-w_0)$. The mid point was selected by the solar height of the civil twilight, which is defined when the centre of the sun has a depression angle of 6° below an ideal horizon. At this solar height $h = -6°$ the weighting function gets $w_t = ½\,(w_0+1) = 0.75$.

The weighting function for the time of the year is using the air temperature w_T as predictor. The function is defined analogously by

$$w_T = w_0 + \tfrac{1}{2}\left(1 - w_0\right)\left[\tanh\left(2 s_T \left(T - T_0\right)\right) + 1\right]$$

with the shape factor $s_T = 0.6$ and the mid-point $T_0 = 10°C$.

The total weight w is calculated by the product of the two weighting functions w_t and w_T, respectively.

Calculating sensation and separation distance

The separation distance is calculated for eight wind direction classes (sectors of 45°) in two steps: First, sensation distances X, defined as distances from the source where the momentary odour concentration is 1 OU m^{-3}, are calculated for each half–hourly period of the meteorological 2-year time series. The sensation distance X is weighted by $X_W = w\,X$. In the unweighted case the weight w gets 1. The second step is the calculation of the separation distance. Therefore, selected limits of the combination of odour concentration threshold T and probability of the threshold exceedance p_T are taken. For the calculation presented here we selected a threshold of 1 OU/m^3 and a probability of the threshold exceedance of 3% indicating that, during a typical year, there are 525 out of 17520 half hourly periods (3%) during which the ambient odour concentrations will be momentarily above 1 OU/m^3. On the basis of the cumulative probability of the sensation distances for each of the eight wind direction sectors, the separation distances are calculated for the selected odour impact criterion. For a selected wind direction sector, the distance at which this definition is fulfilled, is called separation distance. E.g. for North wind, the corresponding separation distance points to the South of the odour source (Schauberger et al., 2002).

Meteorological conditions

The meteorological data for January 30, 1992 to January 31, 1994 were collected at Wels, a site representative of the Austrian flatlands north of the Alps. The sample interval was 30 minutes. The city of Wels in Upper Austria is a regional shopping and business centre with a population of about 50,000. The surrounding area is rather flat and consists mainly of farmland. The mean wind velocity 10 m above the mean roof top level of 15 m is 2.2 m/s with a maximum velocity of about 13 m/s. The distribution of wind directions is shown in Fig. 3.

Discrete stability classes have been determined based on sun elevation angle, cloud cover and low cloud base height, and wind speed (Reuter, 1970). The cloud data are measured at the Linz-Hörsching airport, about 13 km from Wels. Within the Reuter scheme, classes 2 to 7 can occur in Austria. Stability classes 2 and 3, which by definition occur only during daylight hours in a well-mixed boundary layer, class 3 allowing also for cases of high wind velocity and moderate cloud cover, occur in 26% of all cases. Stability class 4, representing cloudy and/or windy conditions including precipitation or fog, occurs day and night (43 %). Class 5 occurs with higher wind velocity during nights with low cloud cover, a situation which is not observed frequently at Wels (6 %). Classes 6 and 7 are relevant for clear nights, when a surface inversion, caused by radiative cooling, traps pollutants near the ground. Such situations occur in 25% of all cases.

RESULTS

The two weighting functions for the time of the day w_t and the time of the year w_T were depict in Fig. 1. The weighting function for the daylight w_t, as an alias for the time of the day, is reaching 0.50 for the nautical twilight (h = -12°), 0.75 at the civil twilight (h = -6°), and 1.00 for the sunrise and sunset (h = 0°), respectively. For the time of the year the weighting function w_T gives 0.50 for $T = 7.5$°C, 0.75 for the midpoint $T = 10.0$°C, and 1.00 for $T = 12.5$°C. The maximum of the weighting function $w = w_t\ w_T$ gives 1.0, the minimum 0.25, which results in a range of the factor of 4.

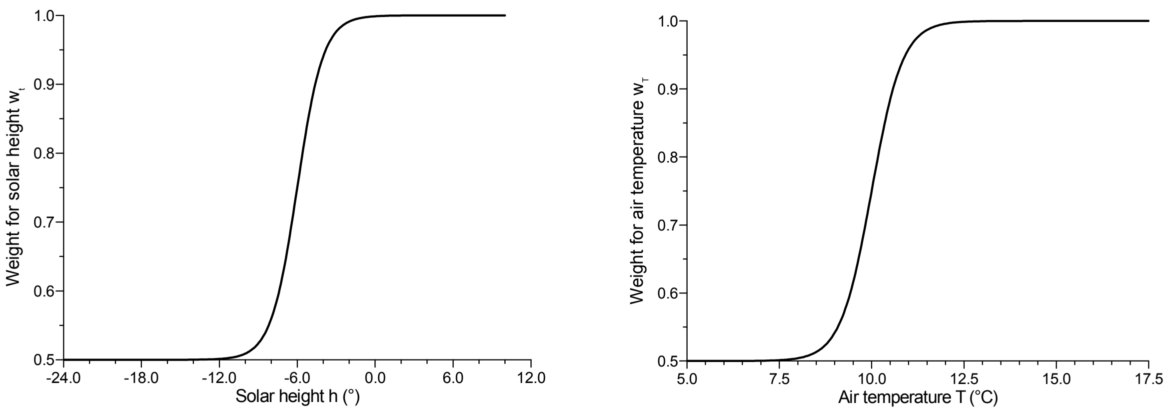

Figure 1. Weighting function w_t for the time of the day by using the solar height *h* (left) and for the time of the year by using the ambient air temperature w_T (right)

The total weighting function *w*, defined by the product of the two individual weights, was calculated for the two year period of meteorological data (ambient air temperature) and presented in Fig. 2. The isopleth $w = 0.95$ circumscribes the area with a higher impact of odour sensation (summer and daytime).

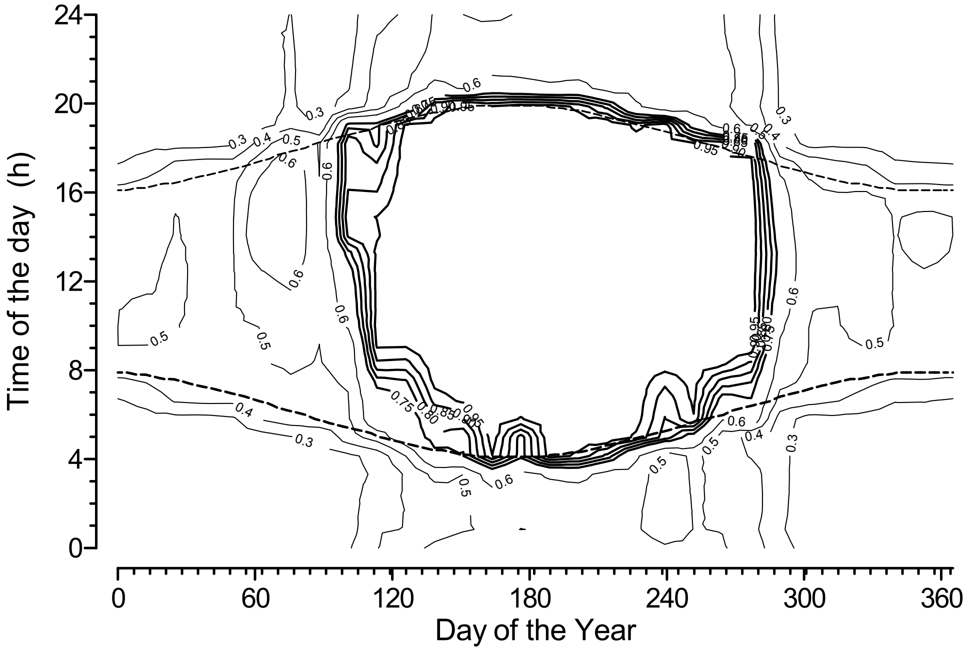

Figure 2. Weight *w* of the sensation distances as a function of the day of the year and the time of the day. The dashed lines mark sunrise and sunset. The weight values *w* were depicted in the range between 0.75 and 1.0, with intervals of 0.05 and by thick lines in the range between 0.3 and 0.6, with intervals of 0.10 (thin lines)

First of all the separation distances for the 8 wind direction sectors were calculated). In Fig. 3 (upper left corner) and Tab. 1, the unweighted *S* and the weighted S_w separation distances can be compared with the distribution of the wind direction, centred at Wels. For northerly winds (for a southward separation distance), the separation distance is lowest, caused by low average wind speeds and predominantly unstable conditions associated with this wind direction sector. The highest of the direction-dependent separation distances are found for the prevailing wind directions West and East, respectively.

Table 1. Direction depending separation distance for the weighted S_w and the unweighted calculation S. Relative frequency of the eight classes (class width 45°) of wind directions and direction-dependent separation distances on the basis of an odour threshold of 1 OU/m³ and a probability of threshold exceedance of 3%. The maximum and the minimum distances are marked in bold.

Wind direction	Relative frequency (%)	Direction for the separation distance	Unweighted direction dependent separation distance S (m)	Weighted direction dependent separation distance S_w (m)
N	**2.6**	**S**	**100**	**37**
NE	6.8	SW	219	122
E	25.9	W	348	224
SE	3.4	NW	154	62
S	5.5	N	225	106
SW	15.6	NE	340	184
W	**34.1**	**E**	**362**	**339**
NW	6.2	SE	209	162

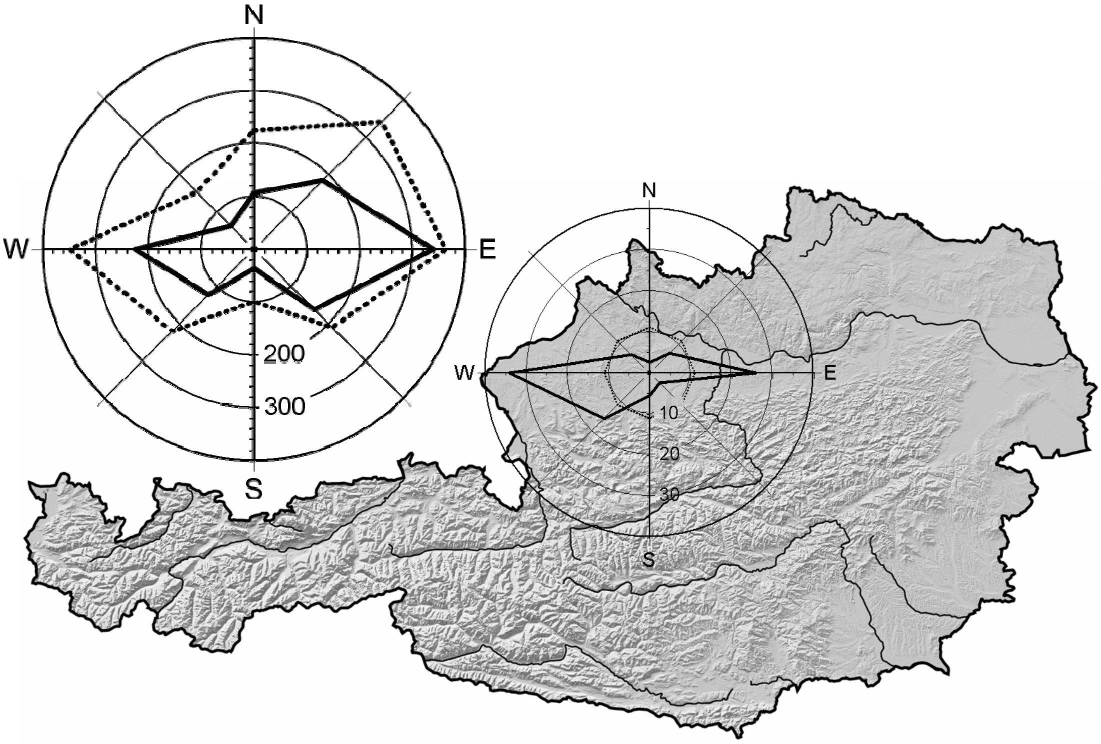

Figure 3. Map of Austria with a polar diagram of the relative frequency distribution (in %) of the wind direction (for 8 sectors with 45°), centred at Wels (site of the livestock) (Calm conditions (less than 0.7 m/s) as dotted line) and the weighted (line) S_w and the unweighted S (dashed) separation distances (in m) in the upper left corner (for 8 sectors with 45°).

An important parameter describing the nuisance potential of odour is the duration of consecutive odour episodes (Fig. 4). The duration of odour episodes (for the unweighted and the weighted case) was investigated in relation to the time of the day and the day of the year. It is expressed by the size of the circles in the graph. The lines, marking the time of sunset and sunrise, separate daytime from night-time, which changes the character of the dispersion process in the atmosphere, expressed by the stability class. For the unweighted situation following time patterns could be found for all four wind directions: The two wind directions (N and S) influenced by the valley wind system show a distinct diurnal pattern: For North wind, episodes occur predominantly at daytime (Fig. 4a), for South wind, at night-time (Fig. 4c). The occurrence of long lasting odour episodes is much smaller than for the prevailing wind directions (West and East). For the prevailing wind directions, the influence of solar radiation on the occurrence of odour episodes is less pronounced but still present (Fig. 4b, 4d). For these directions, the occurrence of odour episodes shows a minimum at midday in summer. Due to the weighting, the occurrence of odour episodes could be concentrated to those particular times when the weight is close to 1 (Fig. 2).

On the right side of Fig. 4 the weighted odour episodes are depicted. The probability for North wind (2.6 %) (Fig. 4a) is less than the probability of the threshold exceedance of 3% of the selected odour impact criterion. This means that all the time with North winds, odour episodes occur, and the relative frequencies of the expected and the observed odour episodes are the same. The separation distance for North wind is reduced by 63% due to the weighting w (Tab. 1). The most pronounced influence due to weighting can be seen for East wind. Nearly all odour episodes are concentrated during daytime and summer. For South wind (Fig. 4c) only very few situations exist during daytime in the warm season. Therefore not all odour episodes are lying in the area with a high weight w (Fig. 2). Only those odour episodes were eliminated by the weighting, which occur during night time in wintertime. For the prevailing wind direction coming from the West (Fig. 4d), the weighting shows an effective change. Nearly all odour episodes during night time were eliminated.

Table 2. Direction depending proportion of meteorological situations which show a weight w in the interval between 0.95 and 1.00. For the entire dataset and those meteorological situations which are taken into account to determine the separation distance (occurrence of odour sensation in 3% of the time). Relative frequency of the eight classes (class width 45°) of wind directions.

Wind direction	Relative frequency (%)	Proportion of meteorological situations which show a weight w in the interval between 0.95 and 1.00	
		Entire data set (%)	Odour episodes (%)
N	**2.6**	49	49
NE	6.8	35	57
E	25.9	27	81
SE	3.4	33	37
S	5.5	22	37
SW	15.6	21	67
W	**34.1**	29	100
NW	6.2	54	75

In Tab. 2 the wind direction depending proportion of those meteorological situations is shown, which are laying within the 0.95 isopleth of Fig. 2. Northerly and southerly winds show a behaviour which suggests an influence of the North-South oriented Alm river valley running into the Alpine foreland south of Wels. Northerly up-valley winds are more frequent during daytime, southerly down-valley winds more frequent during night. Therefore the proportion of northerly winds show the highest values, southerly winds the lowest values. The higher the proportion of high weights ($0.95 < w \leq 1.00$) the closer lies the weighted separation distance S_w to the unweighted S (Tab.1).

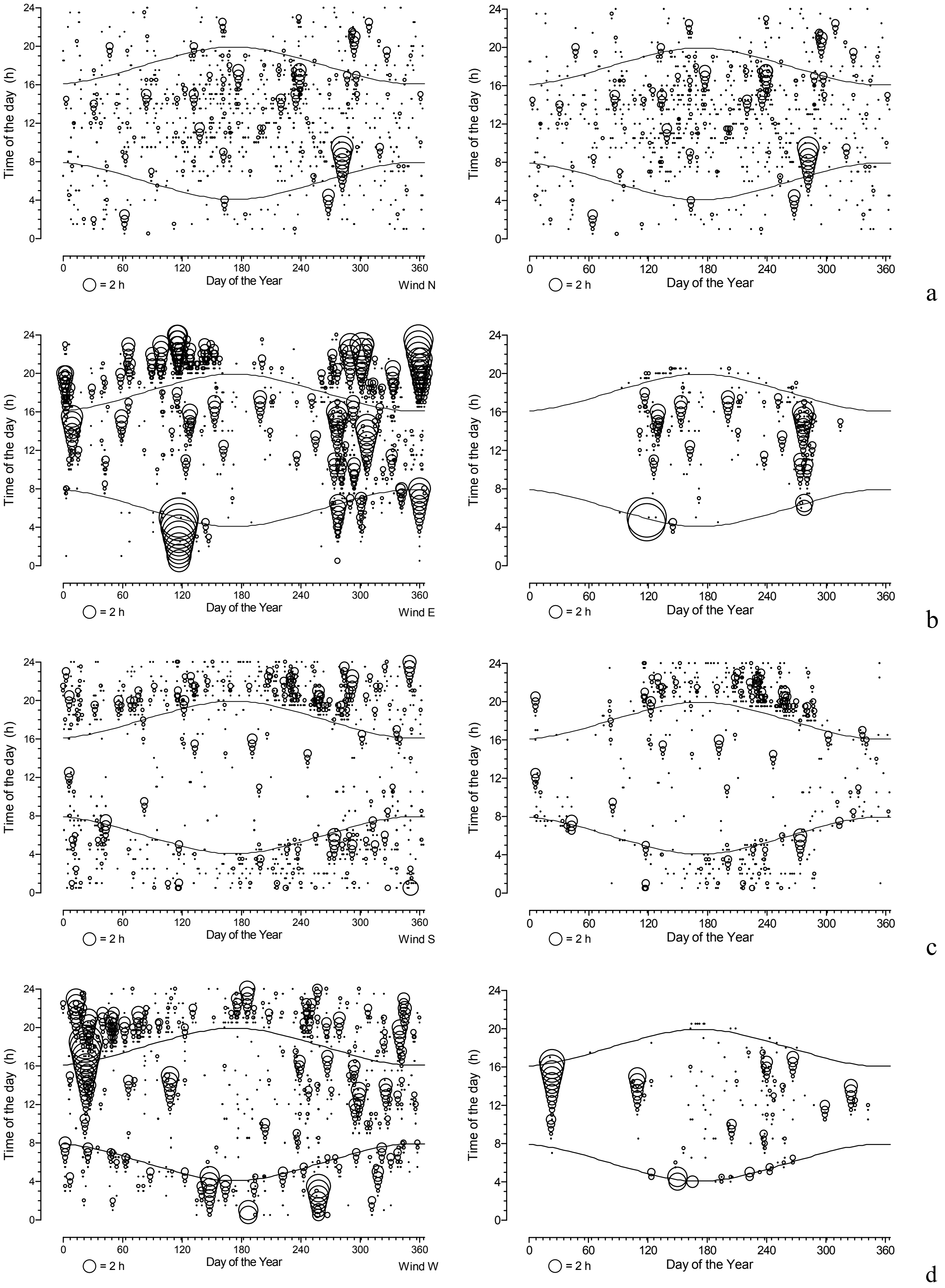

Figure 4. Duration of odour episodes for unweighted (left side) and weighted (right side) as a function of the day of the year and the time of the day. The diameter of the circles is proportional to the duration of odour episodes. (a) North wind, (b) East wind, (c) South wind, and (d) West wind (all 45° sectors). The lines mark sunrise and sunset.

DISCUSSION

In this paper, the Austrian odour dispersion model (AODM), a Gaussian model suitable for the prediction of ambient odour concentrations, is used to calculate direction-dependent separation distances, defined by odour impact criteria chosen as a combination of odour threshold and probability of threshold exceedance. The separation distance was defined by an impact criterion of 1 OU/m³ and an exceedance probability of 3%. The calculated separation distance depends strongly on the wind statistics (Fig. 2 and Tab.1). For the four cardinal directions the occurrence of odour sensation was calculated at the specific separation distance.

The calculated occurrence of odour sensation differs from various odour complaint statistics which show odour to occur predominantly during daytime of warm summer days. Reasons for this discrepancy lie in the temperature sensitivity of odour perception and in the behaviour of neighbours which cannot be taken into account by the AODM. As a result, the evaluation of these values by the odour impact criteria should not only be based on statistical limits as it is done today but also by considering the nuisance potential of odour due to the behaviour of the neighbours. Therefore the odour sensation was weighted by the time of the day and time of the year, as is done with the limit values for environmental noise (EU Directive 2002/49/EC, 2002).

The necessity of different protection levels, depending of the sensitivity of the neighbours, can be shown for environmental noise. During daytime the protection level is lower with a limit value of 55 dB, during night time the limit value is 45 dB. This difference of 10 dB means that the sound level during daytime is 10 times higher compared to night time. In the case of odour perception we assume a protection level, which goes parallel with the complaint statistics. This was parameterised by two transient functions, using air temperature and solar height as predictors for the time of the year and the time of the day.

By weighting of the sensation distance with the weight *w* the ambient odour concentration at this distance is modified. By a lower distance as the sensation distance, the ambient odour concentration will be higher than 1 OU/m³. The relationship between the ambient concentration *C* and the distance *d* can be described by power function according to $d \propto C^a$. The exponent *a* lies in the range between 0.3 and 0.6, depending of the exceedance probability. For an exceedance probability of 3%, which was used for these calculations, the exponent can be assumed with $a = 0.6$ (Piringer et al., 2008). The overall range of the ambient concentration due to the weighting function lies in the same range of about 10 as for environmental noise.

For the used weighting function *w* it can be assumed, that the threshold value is unchanged during day time and summertime (Fig. 2) in the range of 1 OU/m³. For night time and low air temperatures, when the weighting function is close to the minimum of 0.25, the threshold will be in the range of 10 OU/m³. The perception of the odour intensity goes with the logarithm of the odour concentration according to the Weber-Fechner law (e. g., Misselbrook et al., 1993). Based upon laboratory-based experiments on perceived intensity, the Environment Agency, UK (2002), defines: 1 OU/m³ is the point of detection, 5 OU/m³ is a faint odour, and 10 OU/m³ is a distinct odour. This means, that for winter nights the ambient concentration must exceed 10 OU/m³ (a intensity of distinct odour) to count for the exceedance probability.

It should be emphasised here that a dispersion model (in our case the AODM) is designed to predict odour perception at receptor points (e. g. neighbours) due to the ambient odour concentration, but not the occurrence of complaints at the neighbours. The assessment of odour perception by the AODM does not always coincide with the real time of nuisance complaints because the behavioural response of the neighbours to the odours cannot be included in the model. Under the assumption, that the weighting functions maps the behaviour of humans and with it the sensitiveness to environmental odour this approach will improve considerably the assessment of nuisance potential to achieve a more realistic evaluation of the nuisance.

REFERENCES

Environment Agency, 2002. *Integrated Pollution Prevention and Control (IPPC). Horizontal Guidance for Odour Part 1 – Regulation and Permitting (draft). Scientific and Technical Information Service,* Bristol, UK.

EU Directive 2002/49/EC *Assessment and management of environmental noise*. 25 June 2002

Lohr, L.; 1996. Perception of rural air quality: What will the neighbors think? *Journal of Agribusiness,* **14,** 109-128.

Misselbrook, T.H.; Clarkson, Pain, C.R.; B.F.; 1993. Relationship between concentration and intensity of odour for pig slurry and broiler houses. *J of Agricultural Engineering Research,* **55,** 163-169

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.

Piringer M., Schauberger G., Petz E. (2008): An empirical model to estimate the separation distance between livestock buildings and residential areas: An improved version of the Austrian guide line. This issue

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, Bioklimatologie A,* **19,** 173-186

Schauberger G., Piringer M., Petz E. (2006) Odour episodes in the vicinity of livestock buildings: a qualitative comparison of odour complaint statistics with model calculations. Agriculture, Ecosystems & Environment, 114 (2006)2-4: 185-194

Schauberger, G.; Piringer, M.; Petz, E.; 1999. Diurnal and annual variation of odour emission of animal houses: a model calculation for fattening pigs. *Journal of Agricultural Engineering Research,* **74 (3)** 251-259

Schauberger, G.; Piringer, M.; Petz, E.; 2000a. Diurnal and annual variation of the sensation distance of odour emitted by livestock buildings calculated by the Austrian odour dispersion model (AODM) *Atmospheric Environment,* **34 (28)** 4839-4851

Schauberger, G.; Piringer, M.; Petz, E.; 2000b. Steady-state balance model to calculate the indoor climate of livestock buildings demonstrated for fattening pigs. *International Journal of Biometeorology,* **43 (4)** 154-162

Schauberger, G.; Piringer, M.; Petz, E.; 2001. Separation distance to avoid odour nuisance due to livestock calculated by the Austrian odour dispersion model (AODM). Agriculture, *Ecosystems & Environment,* **87 (1)** 13-28

Schauberger, G.; Piringer, M.; Petz, E.; 2002. Calculating direction-dependent separation distance by a dispersion model to avoid livestock odour annoyance. *Biosystems Engineering,* **82 (1)** 1-24

Schiffman, S. S.; 1994. *Psychological effects of swine odor on humans.* International Round Table on Swine Odor Control. Proceedings p 8-11, Iowa State University

Strauss, G.; Cervinka, R.; Haider, M.; 1986. *Erhebung über die Geruchsbelästigung in der Umgebung von Massentierhaltungen – eine Feldstudie [Survey of odour nuisance in the vicinity of livestock – a field study].* Inst of Environm Hygiene, Univ Vienna, Vienna.