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Research article

Do odour impact criteria of different jurisdictions ensure analogous separation distances for an equivalent level of protection?

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ABSTRACT

Governments are increasingly introducing odour impact criteria (OIC) to determine separation distances between odour sources and residential areas. Previous studies have shown the wide range of OIC available for this purpose, depending on the desired level of protection against odour annoyance. However, it is unclear whether OIC with similar levels of protection can ensure analogous separation distances, which would reasonably be expected. This study presents a comparative analysis of separation distances calculated at two sites for different OIC, but all related to an equivalent level of protection. Here, the equivalent level of protection was defined for urban residential areas (land use), swine odour (hedonic tone) and new facilities (facility type). In this manner, the regulatory criteria currently enforced in Germany, Ireland, and Queensland (Australia) were selected as references for the investigation. The results clearly show that, even for an equivalent level of protection, disparate separation distances can be obtained. Differences in separation distances were found to be greater in prevailing wind directions compared to distances in additional wind directions. Overall, the results demonstrate a risk of poor conclusions in odour assessments. This means that care must be taken when adopting OIC for decision making, principally in those countries that have not yet established specific regulations to manage environmental odours. Concomitantly, the results stress the need for better harmonisation of the concept of the odour impact criterion and components thereof. By using perturbation analysis, it has also been found that the stack exit temperature influences the separation distances in a distinct way, reliant on the criteria used to determine the distances. This finding is of significance for input data collection in future odour modelling studies. Furthermore, approaches used to derive OIC, equivalence between dispersion modelling and field inspections (European standard EN 16841-1), as well as implications of the findings for regulatory practice are summarised and discussed.

1. Introduction

Odour has become a major environmental issue for several agricultural and industrial sectors. Residents and odour sources are closer than in the past, which can cause serious conflicts. At large, these conflicts are disruptive to social coexistence (Keck et al., 2018). Notably, public complaints reported to authorities on odour pollution continue to increase in quantity and severity (Cai et al., 2015; Hayes et al., 2017). Direct toxicological mechanisms are unlikely to explain the association between exposures and health symptoms, as odours often reach residential areas at concentrations well below toxicity thresholds (Blanes-Vidal, 2015). In order to specify how odour exposure is related to adverse effects, earlier studies have supported indirect mechanisms. Exposure–symptoms associations were found to be mediated by odour annoyance (Aatamila et al., 2011; Blanes-Vidal, 2015; Luginaah et al., 2002; Neutra et al., 1991; Steinheider et al., 1998; Sucker et al., 2009). Namely, annoyance has been recognised as one of the most important psychosocial effects after a resident is exposed to odour (Cantuaria et al., 2017; Shusterman, 1992).

In order to handle odour annoyance, regulatory authorities can impose separation distances between odour sources and residential areas (Schauberger et al., 2012a). The separation distance is intended to encompass the area within which odour annoyance can be expected, relying on a certain level of protection (Piringer et al., 2016). Dispersion modelling is a technique in extensive use for calculating separation distances in a direction-dependent manner. Based on appropriate meteorological data and source information, a dispersion model can be used to predict time series of ambient odour concentrations (Capelli

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et al., 2013). This time series of ambient odour concentrations is evaluated by exposure limits for odour, so-called odour impact criteria (OIC), thereby obtaining the direction-dependent separation distances (Piringer et al., 2015).

The OIC are defined by an odour concentration threshold (C_T), the exceedance probability (p_T) of this threshold and the averaging time (A_T) used to predict concentrations. Values of concentration thresholds from 0.25 to 35 $ou_E m^{-3}$ and exceedance probabilities from 0.1 to 35% are in use (Brancher et al., 2017; Sommer-Quabach et al., 2014). No exceedance of a predefined C_T can be found in some jurisdictions (i.e., the 100th percentile), although this is considered impractical due to the vast array of annoyance sensitivity of individuals (EPA Ireland, 2001). Commonly, hourly meteorological datasets are used as input for dispersion modelling so that the outputs are hourly-mean odour concentrations. However, hourly concentrations may mask peak odour episodes because the odour perception of the human nose occurs in seconds (Mainland and Sobel, 2006). The odour concentration can fluctuate above and below the predicted mean concentration within each modelled hour (Sarkar et al., 2003). The ratio between a short-term mean value (relevant for odour perception) and the long-term mean value (predicted by a dispersion model), called peak-to-mean factor (F), is widely used to describe these fluctuations (Schauberger et al., 2012b). Until recently, several peak-to-mean factors have been derived, resulting in averaging times from 1 s to 1 h (Brancher et al., 2017). This disparity highlights the lack of a meaningful A_T for considering exposure. In addition, it has been shown that the hedonic tone influences exposure–annoyance and exposure–symptom associations (Miedema et al., 2000; Sucker et al., 2008a). Consequently, the OIC can be adapted in a way to reflect the hedonic tone, too.

In this context, the wide variability of the three components of the OIC has been well demonstrated. However, it remains largely unexplored if different jurisdictional criteria, but with similar levels of protection, are able to determine analogous separation distances. Only one study has been found in the literature on this subject, suggesting that separation distances might differ for similar levels of protection (Sommer-Quabach et al., 2014). The present study complements and extends this issue by presenting a comparative analysis of direction-dependent separation distances related to OIC that are representative of a broader range of legislative limit values. Here, the equivalent level of protection is defined for urban residential areas (land use), swine odour (hedonic tone) and new facilities (facility type). As such, the OIC currently enforced in the jurisdictions of Germany, Ireland, and Queensland (Australia) are selected as references. The comparative analysis is performed for two sites and four emission scenarios, outlining eight opportunities for comparison.

For each selected criterion, the influence of the stack exit temperature on separation distances was also investigated. By means of an emission scenario specifically designed for this purpose, perturbation analysis was used to examine such influence.

2. Approaches to derive OIC

Typically, three approaches have been used to set OIC (Brancher et al., 2017; Griffiths, 2014). The ***first approach*** focuses on associating dose (exposure to odour) with effect (prevalence of annoyance in the exposed population) by deriving dose–response curves. Importantly, the epidemiological root is key. The fundamentals of dose–response studies on environmental odour can be found in preceding studies[1] (Blanes-Vidal et al., 2012; Cavalini et al., 1991; Miedema et al., 2000; Sucker et al., 2008a). The German OIC have empirical significance from dose–response studies, in which the assignment of exposure was based on both field measurements and dispersion modelling (Janicke et al., 2004; Sucker et al., 2008a, 2008b). The baseline criterion used in Germany for "residential areas and mixed areas" is defined by a $p_T = 10\%$, which can be adapted according to the hedonic tone. In the case of livestock farms, weighting factors (f) are used in this adaptation for individual kinds of animals. For fattening pigs f = 0.75, leading to a $p_T = 13.3\%$.

Practical considerations, such as modelling limitations and logical deliberations, are used in some jurisdictions to define criterion component values (***second approach***). Often these considerations attempt to contemplate so-called FIDOL factors into limit values (Freeman and Cudmore, 2002; Watts and Sweeten, 1995). In Queensland, the 99.5th percentile ($p_T = 0.5\%$) is said to be used merely as a statistical parameter that filters out extreme predictions (DEHP, 2013). The accompanying concentration threshold $C_T = 5$ $ou_E m^{-3}$, with a perception–response A_T, is selected considering that this level of odour can cause general annoyance. The C_T is converted to hourly concentrations based on peak-to-mean arguments. The R_{QUE} belongs to a restrictive group of OIC, defined by low odour concentration thresholds and low exceedance probabilities of this threshold.

A combination of the prior approaches gives rise to the ***third approach***. In this case, conclusions and data from existing dose–response relationships are used as a starting point to set limit values. The OIC for use in Ireland are based on two dose–response studies. The first study addressed (bio-)industrial odour sources (Miedema et al., 2000), while the second aimed at pig odour (Bongers, 2001). More information on the Irish OIC can be found in EPA Ireland (2001).

Thus, as noted by Griffiths (2014), empirical data shows significant associations between levels of annoyance and both the concentration (Cavalini et al., 1991; Miedema et al., 2000) and frequency (Sucker et al., 2008a) of odour events over time intervals such as a year.

3. Methodology

3.1. Location of sites

Separation distances were calculated at two sites. One is situated in Groß-Enzersdorf (48.203° N, 16.564° E, at 151 m ASL), east of Vienna, Austria. This site is mostly within flat terrain, typically farmland. Surrounding dwellings and a few industrial facilities, mainly in the south-westerly and south-easterly directions, are present ~350–500 m from the odour source. The other is located in São José dos Pinhais (25.555° S, 49.132° W, at 906 m ASL), close to Curitiba, southern Brazil. This site is within flat and elevated terrain. Land uses such as farmland, remaining forest, woody wetlands, low residential areas, and a few industries can be found distributed around the odour source. We have conducted other investigations at these two sites, however, for different purposes (Brancher et al., 2018a, 2018b).

3.2. Dispersion modelling

In this study, dispersion calculations were undertaken using the AERMOD modelling system (version 18081), which is the U.S. Environmental Protection Agency regulatory air quality model (Cimorelli et al., 2005; Perry et al., 2005). AERMOD is a steady-state Gaussian plume model. It uses the Monin–Obukhov similarity theory in order to estimate the stability of the atmospheric boundary layer continuously.

Time series of ambient odour concentrations were calculated on a polar grid, with a minimum distance from the source of 50 m, totalling 2160 receptors. The receptors were positioned 1.5 m above the ground to reflect the average height of the human nose. Digital elevation models were created using the AERMAP terrain processor (version

[1] Until now, the general objective of odour policies has been to reduce the proportion of the population "highly annoyed" due to odour exposure to less than ~10%, typically. The population to be protected from odour annoyance is normal sensitive individuals. The 10% value has been argued as a pragmatic value, and its definition is crucial when reading dose–response curves for setting OIC.

18081) with terrain elevation data in SRTM1 format which has a resolution of ~30 m. Land surface characteristics (surface roughness length, albedo and Bowen ratio) were determined using the AERSURFACE utility (version 13016) according to recommended procedures. Possible building downwash effects were not taken into account.

3.2.1. Meteorology

The dispersion calculations were based on three years of meteorological observations (2013–2015). For the Austrian site, the Austrian Meteorological Service ZAMG (Zentralanstalt für Meteorologie und Geodynamik, Vienna, Austria, www.zamg.ac.at) provided the surface meteorological dataset. Air temperature, atmospheric pressure, wind direction and speed were collected by a weather station positioned ~0.6 km from the site (48.199° N, 16.559° E). Cloud cover was collected by a weather station located at the Vienna International Airport (~10 km from the site; 48.110° N, 16.569° E). Upper air data were obtained from the NOAA/ESRL Radiosonde Database for Wien-Hohe Warte (~16 km from the site; 48.248° N, 16.356° E). For the Brazilian site, surface meteorological observations (air temperature, atmospheric pressure, cloud cover, wind direction and speed) were obtained from the NOAA database for Afonso Pena International Airport (~4.5 km from the site; 25.531° S, 49.167° W). Upper air data were attained from the NOAA/ESRL Radiosonde Database for Afonso Pena International Airport as well. The meteorological datasets were processed using AERMET (version 18081).

Surface wind measurements at the two sites were used for plotting wind roses (Fig. 1). Winds characterised as calms ($< 0.5\,m\,s^{-1}$) amounted to ~0.3% and 4% of the observations at the Austrian and Brazilian sites, respectively. Calms were adjusted into a minimum speed threshold of $0.5\,m\,s^{-1}$ and uniformly redistributed around the compass to preserve the wind profile. At the Austrian site, the prevailing winds are northwesterly (NW) and southeasterly (SE), directions for which high wind speeds can be experienced. The average wind speed is $3.3\,m\,s^{-1}$, and the highest speed is $12.7\,m\,s^{-1}$. At the Brazilian site, winds from east (E) to southeast (SE) are dominant. Secondary maxima of directions are from the northeast (NE) and east-northeast (ENE). The average wind speed is $3.2\,m\,s^{-1}$; high speeds can be experienced from nearly all quadrants, with a maximum of $19.0\,m\,s^{-1}$ for the period.

3.2.2. Emissions

Four emission scenarios were considered for the dispersion calculations. For all scenarios, a single-point source (stack) was assumed, with the odour emission rate (OER) given by an annual mean value. Source configurations attempt to reproduce odour emissions from typical mechanically-ventilated livestock buildings. Table 1 shows the source release parameters related to each emission scenario.

The first emission scenario (ES_1) has an OER = 22,060 $ou_E\,s^{-1}$. This value is based on field sampling campaigns performed in a pig-fattening shed by Oettl et al. (2018). The pig farm was reported to have a total of 1225 pigs on average, and the mean body mass of the pigs was 65 kg during the sampling period.

The second emission scenario (ES_2) has an OER = 10,045 $ou_E\,s^{-1}$. This value is based on the work of Hove et al. (2016), in which an average emission factor of 28.7 $ou_E\,s^{-1}$ $animal^{-1}$ has been derived for pig odour. This OER corresponds to a shed with 350 fattening pigs.

The third emission scenario (ES_3) has an OER = 18,750 $ou_E\,s^{-1}$. This value was calculated by using an odour emission factor of 50 $ou_E\,s^{-1}\,LU^{-1}$ reported in the German standard VDI 3894 Part 1 (2011) for pig fattening (branch of production) and liquid/solid manure technique (housing system). In this case, one livestock unit (LU) corresponds to a standardised animal mass of 500 kg. A total of 2500 pigs with a mean body mass of 75 kg gives 375 LU. Consequently, 50 $ou_E\,s^{-1}\,LU^{-1}$ multiplied by 375 LU equals to 18,750 $ou_E\,s^{-1}$.

The fourth emission scenario (ES_4) has an OER = 13,500 $ou_E\,s^{-1}$. According to Schauberger et al. (2018), farms with 1800 pigs are typical for Central Europe. This OER was calculated using the odour emission factor of 50 $ou_E\,s^{-1}\,LU^{-1}$ and a mean body mass of 75 kg (VDI 3894 Part 1, 2011), which corresponds to 270 LU.

3.3. Odour impact criteria

The determination of separation distances relies on the required level of protection against odour annoyance. Different jurisdictions have different provisions for the level of protection. First, we defined three provisions to constitute an equivalent level of protection: urban residential areas (land use), swine odour (hedonic tone) and new facilities (facility type). Second, we selected OIC which are able to attend these provisions. Thus, the separation distances were calculated for the OIC currently set in Germany, Ireland and Queensland (Australia):

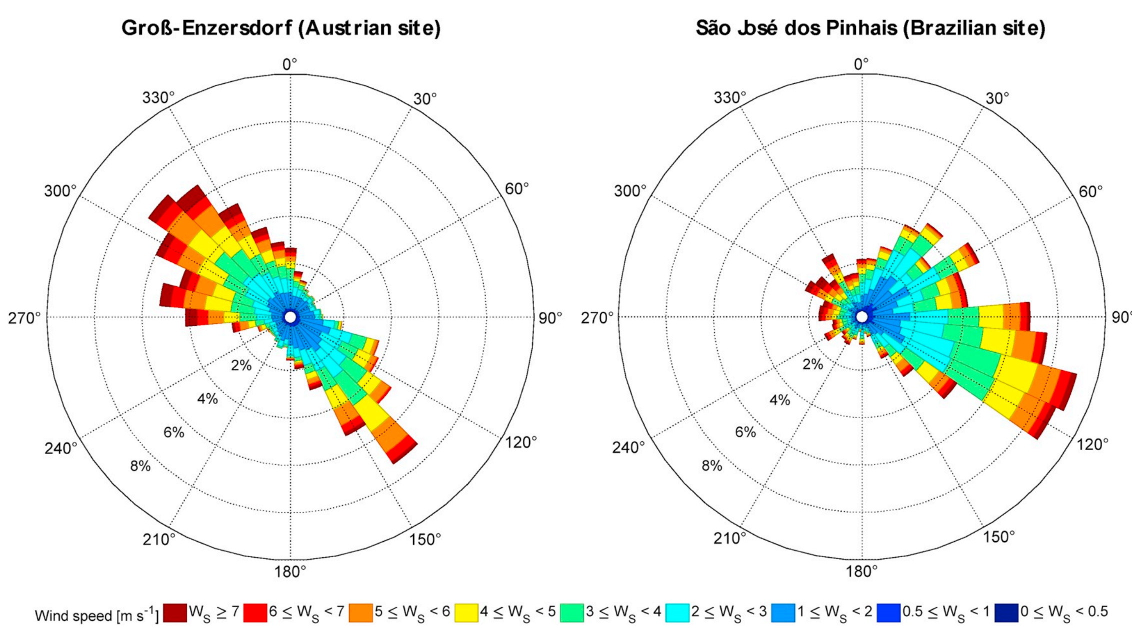

Fig. 1. Wind roses for Groß-Enzersdorf (Austrian site) and São José dos Pinhais (Brazilian site) during 2013–2015. Legend denotes wind speed (W_s) categories and their associated colours. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Emissions scenarios considered for the comparative analysis.

Emission scenario	Odour emission rate [$ou_E\,s^{-1}$]	Flow rate [$m^3\,s^{-1}$]	Stack height [m]	Stack diameter [m]	Exit velocity [$m\,s^{-1}$]	Exit temperature [°C]
ES_1	22,060	14.1	8.5	2.1	4.0	20
ES_2	10,045	6.3	6.0	2.0	2.0	25
ES_3	18,750	12.0	11.0	3.0	1.7	25
ES_4	13,500	17.2	8.0	2.7	3.0	20

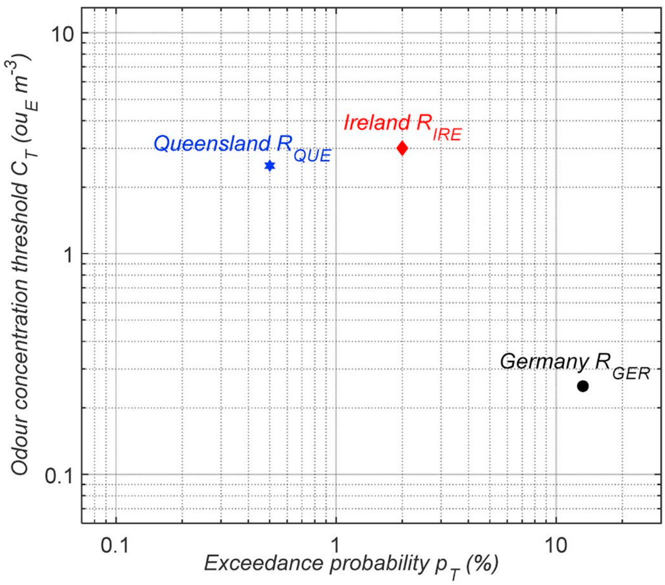

Fig. 2. Odour impact criteria OIC selected as references for the comparative analysis. The OIC are shown by the odour concentration threshold C_T on an hourly basis and the exceedance probability p_T of this threshold.

i. The first criterion is based on the German guideline[2] (GOAA, 2008). This criterion is defined by a concentration threshold of $C_T = 1$ ou_E m^{-3} (as a peak value) with a peak-to-mean factor $F = 4$, which results in an hourly mean of $C_T = 0.25$ ou_E m^{-3}. The tolerated exceedance probability is $p_T = 13.3\%$ taking into account the hedonic tone of pig odour. The German reference criterion is named R_{GER};
ii. The second criterion is used in Ireland (EPA Ireland, 2001). A $C_T = 3$ ou_E m^{-3} is used along with a $p_T = 2\%$ and an $F = 1$. The Irish reference criterion[3] is named R_{IRE};
iii. The third criterion is used in Queensland. It is defined by a $p_T = 0.5\%$ with a $C_T = 5$ ou_E m^{-3} (as a peak value). This C_T is converted to hourly concentrations of 2.5 ou_E m^{-3} for ground-level sources and wake-affected stacks by using an $F = 2$ (DEHP, 2013). The reference criterion of Queensland is named R_{QUE}.

Fig. 2 compares the reference OIC. All reference criteria are specified on an hourly basis ($A_T = 1$ h) to allow a direct comparison of results. Also, the criteria of these jurisdictions were chosen as references because they have fundamentally different concepts when establishing OIC. Either a constant C_T (Germany) or a constant p_T (Ireland and Queensland) is used. In each case, the other parameter is used to adapt the OIC to the desired level of protection. Although for practical reasons the present investigation has been conducted for a specific level of protection, representativeness of the reference OIC is therefore attained (Brancher et al., 2017).

Note that, for each emission scenario, the methodological arrangement employed herein allows the predicted time series of ambient odour concentrations to be the same at each receptor. Under this condition, the evaluation of such time series by the OIC is what plays a vital role in the determination of separation distances.

3.4. Statistical analysis

The transport direction (T_d) is that direction to which emissions spread. The separation distances were measured for eight cardinal transport directions (in steps of 45°). The odour source was considered the reference point for distance determination (Schauberger et al., 2006; VDI 3894 Part 2, 2012). Scaling factors, dimensionless, were then calculated to show the magnitude of the differences in separation distances. The R_{IRE}-related distances were assumed as the baseline for comparison purposes. It means that changes in R_{GER}- and R_{QUE}-related distances were quantified with respect to R_{IRE}-related distances.

In the context of a sensitivity analysis, perturbation analysis can be useful because it allows identifying key parameters that influence the results. Each parameter is varied one-at-a-time by a predefined increment, and the consequence of that change on the results can be expressed using a sensitivity ratio (SR) according to the following equation (Clavreul et al., 2012):

$$SR_i = \frac{\frac{\Delta\,Result}{Baseline\ result}}{\left(\frac{\Delta\,Parameter}{Baseline\ parameter}\right)_i} \tag{1}$$

while the stack exit temperature is the perturbated parameter i, our result is the separation distance for each odour impact criterion and T_d.

4. Results and discussion

4.1. Site-specific surface winds and inter-annual variability

The Austrian site displays a bimodal distribution of wind directions usually observed in Central Europe. This behaviour is due to the west wind belt at these latitudes with alternating low and high-pressure influence. Whereas the SE wind is regularly observed with anticyclonic conditions, the NW wind is mainly associated with cloudy or rainy periods (Brancher et al., 2018a). The Brazilian site displays wind directions mainly from E–SE along with secondary maxima of wind directions from NE–ENE. A thermal–orographic low-pressure system, known as the northwestern Argentinean low, is an almost permanent area of low pressure, generally stationary to the east of the Andes on dry plains (mean annual position at ~30° S, 66° W). This depression is caused by the blockade of the general circulation imposed by the Andes mountains and accentuated by the intense heating of the low altitude plains of this region. The atmospheric pressure gradient between the northwestern Argentinean low and the semi-permanent South Atlantic anticyclone (high-pressure system) induces a persistent flow from E–NE throughout the southern region of Brazil. This general profile of atmospheric circulation can evidently have peculiarities in meso- and microscale due to surface features (COPEL, 2007; Escobar and Seluchi,

[2] At the time of this writing, the German air pollution regulation TA-Luft (Technical Instructions on Air Quality Control) is undergoing legal reform. It is to be expected that the OIC today defined in the GOAA (Guideline on Odour in Ambient Air) will be introduced in the new TA-Luft.

[3] In the United Kingdom the same criterion as in Ireland is in use for “moderately offensive” odours, a hedonic tone category for which “intensive livestock rearing” is classed.

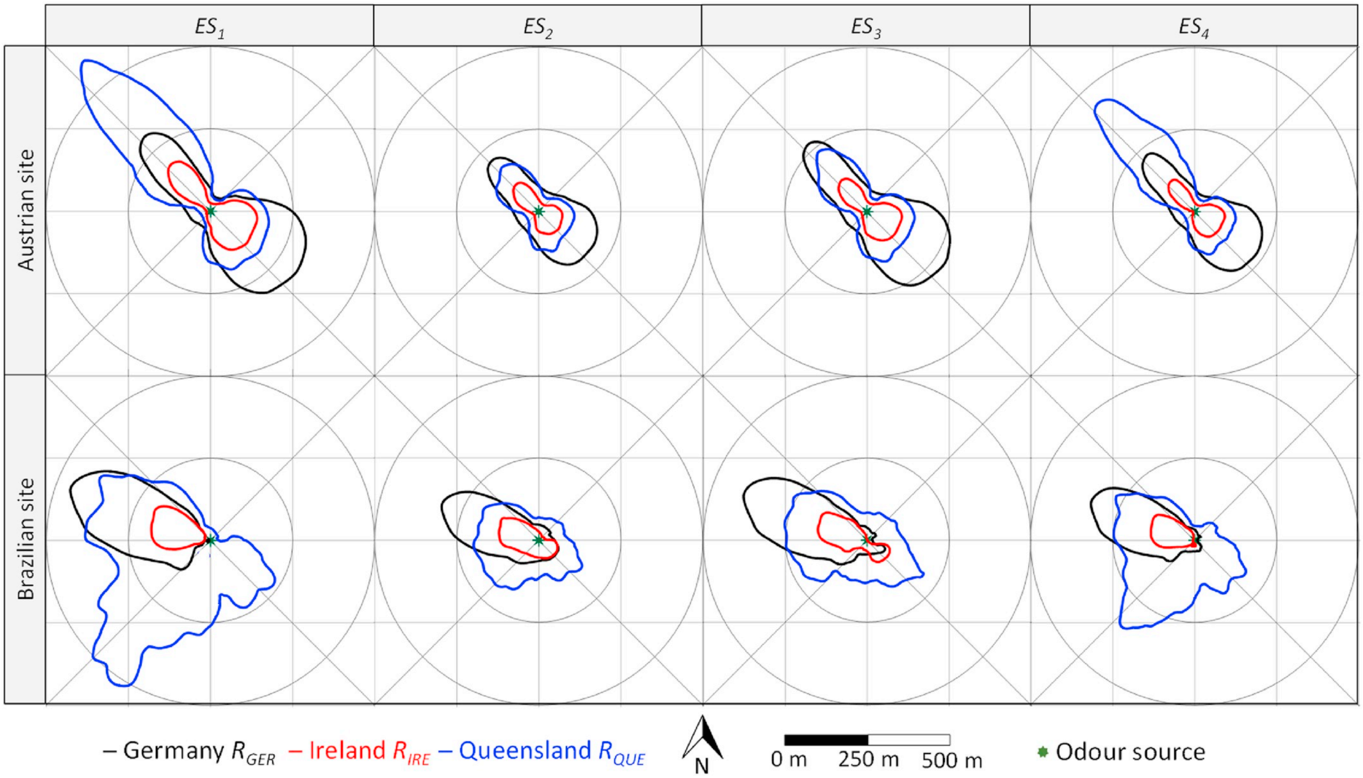

Fig. 3. Separation distances at the Austrian and Brazilian sites. The centre of each plot indicates the odour source. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2012; Repinaldo et al., 2015; Salcedo-Castro et al., 2015; Seluchi et al., 2003).

Determining reliable separation distances by a far-reaching reduction of the length of meteorological input data challenges current research. A single year of hourly meteorological observations has been recently shown to be a good compromise for this purpose (Brancher et al., 2018a, 2018b). Due to the availability of meteorological observations, we used three years of meteorology for each site and by this means accounting for inter-annual variability.

4.2. Required distances to residential areas

The direction-dependent separation distance can be regarded as a practical approach for decision making on odour pollution because it easily communicates for all stakeholders the area within which odour annoyance can be expected. It summarises a multifaceted chain starting with the OER, transport and dilution in the atmosphere, and evaluation of the time series of ambient odour concentrations by the OIC. Fig. 3 compares the separation distances as contour lines, enclosing the area of exceedance of the given OIC. An increase in (tolerated) exceedance probability or concentration threshold will reduce the affected area (Piringer et al., 2016).

By visual inspection (Fig. 3), marked differences between the separation distances for each emission scenario and each site are observed. These differences were found to be more pronounced in the prevailing winds, whereas for the additional winds the opposite behaviour was detected. In addition, at the two sites, R_{IRE}-related distances are smaller than R_{QUE}- and R_{GER}-related distances for nearly all directions.

Comparing Fig. 1 against Fig. 3, it is clear that the distribution of wind directions is a primary factor driving the shape of the separation distances. Typically, the elongation of the distance tended to be greater in the prevailing winds, which is in agreement with earlier results of modelling and field studies (Badach et al., 2018; Brancher et al., 2018a, 2018b; Capelli and Sironi, 2018; Danuso et al., 2015; Oettl et al., 2018; Piringer et al., 2015, 2016; Schauberger et al., 2012a, 2018; Sommer-Quabach et al., 2014). Hence, it is reasonable to anticipate that the higher the frequency of a specific wind direction, the larger the prolongation of the separation distance will be in that direction. Knowledge of the prevailing winds of a site can thus provide an initial indication of where odour emissions will have more potential to annoy residents. Worth mentioning, this information is also of significance for epidemiological studies on odour pollution. It substantiates that exposure assessment approaches based on simple measures of proximity can be imprecise methods for identifying exposed populations (Cantuaria et al., 2016). Accordingly, exposure to environmental odour in the vicinity of a source is more a meteorological problem than a problem of the source strength.

Brancher et al. (2018a) indicated that the final distance extent, however, is possibly a combination of many factors: the frequency distribution of atmospheric stability and wind speeds per wind direction sector, on top of the selection of the OIC. Piringer et al. (2016) showed that atmospheric stability and peak-to-mean attenuation curves play a role in this context; they concluded that separation distances are the result of a complex interaction amongst these two factors plus wind conditions.

Interestingly, at both sites, in particular for ES_1 and ES_4 when using R_{QUE} ($p_T = 0.5\%$), the by far largest distances are determined in the secondary maxima of prevailing wind directions. Conversely, the same pattern is not observed for ES_1 and ES_4 when using R_{GER} ($p_T = 13.3\%$) and R_{IRE} ($p_T = 2\%$). The p_T has the capability to select/limit the meteorological conditions underlying the determination of separation distances (Griffiths, 2014). For low exceedance probabilities, such as $p_T \leq 2\%$, the separation distance has the potential to be driven by a few distinct, uncommon meteorological conditions (Sommer-Quabach et al., 2014). Very low exceedance probabilities (e.g., $p_T \leq 0.5\%$) are recommended in some jurisdictions to assess odour annoyance due to intermittent emissions, even though very little is known about dose–response relationships for this case (Miedema, 1992). Note that the uncertainty increases at the tail of the cumulative distribution function of the ambient odour concentrations. Contrary, Schauberger et al. (2006) showed that for high exceedance probabilities (~10–20%) nearly all stability classes can contribute to the determination of separation distances. According to Griffiths (2014), the choice of the p_T to favour particular meteorology for selection in separation distances has some advantages as the maximisation of the degree to which calculations are model-agnostic and in this manner minimising uncertainties.

As previously described, the separation distances as a result of ES_2 and ES_3 refer to a stack exit temperature of 25 °C, while the ES_1 and ES_4 distances refer to 20 °C. For R_{QUE}, in particular, a notable change in the shape of the separation distances amongst these scenarios can be seen (Fig. 3). At this point, however, any inference regarding the influence of the stack exit temperature on the separation distances is premature because all input parameters are varying. To pinpoint and quantify the suspected influence, we carried out a perturbation analysis (Section 4.5).

Fig. 4 compares the separation distances, measured in full metres, at the two studied sites for eight transport directions. Although a polar grid with a minimum distance from the source of 50 m was used, some separation distances smaller than 50 m emerged. This can be mainly attributed to the source release parameters of these scenarios.

At the Austrian site, the following is summarised:

- For T_d = NW, the maximum distance is 549 m when using R_{QUE} for ES_1, whereas the minimum distance is 88 m when using R_{IRE} for ES_4;
- For T_d = SE, the maximum distance is 311 m when using R_{GER} for ES_1, whereas the minimum distance is 76 m when using R_{IRE} for ES_2;
- All in all, the separation distances vary in T_d up to 549 m.

At the Brazilian site, in turn, the following is summarised:

- For T_d = SW, the maximum distance is 512 m when using R_{QUE} for ES_1, whereas the minimum distance has a negligible value when using R_{GER} for ES_1;
- For T_d = W, the maximum distance is 377 m when using R_{QUE} for ES_1, whereas the minimum distance is 117 m when using R_{IRE} for ES_2;
- All in all, the separation distances vary in T_d up to 512 m.

The magnitude of the differences in separation distances was estimated by scaling factors (Fig. 5). Gaussian plume models have the implicit assumption that the longitudinal diffusion is negligible compared to the lateral and vertical diffusion. At distances very close to the source, this assumption is no longer valid (Piringer et al., 2014). This is why the separation distances ≤50 m were set to 50 m as a lower limit for this evaluation.

The closer the scaling factor value is to one, the greater the similarity of the R_{GER}- *and* R_{QUE}-related distances to R_{IRE}-related distances, and vice versa. At the Austrian site, the minimum and maximum scaling factors are 1.0 and 4.9, respectively, whereas at the Brazilian site scaling factors in the range of 0.7–10.2 occur. For example, the scaling factor of 4.9 means that the distance for T_d = NW is 88 m for R_{IRE}, while for R_{GER} it is 429 m (Austrian site, ES_4). The scaling factor of 10.2 means that the distance for T_d = SW is 50 m for R_{IRE}, while for R_{GER} it is 512 m (Brazilian site, ES_1). Although scaling factors other than one are calculated for all transport directions, a greater abundance of them was found to occur for the prevailing winds of each site, as shown in Fig. 5.

Based on the aforementioned results and the insights given in Section 2, the following inferences can now be given:

- The use of R_{IRE} does not necessarily mean a "relaxed standard" when compared to the use of R_{GER} and R_{QUE};
- The R_{GER} and R_{IRE} have an epidemiological basis. These criteria are

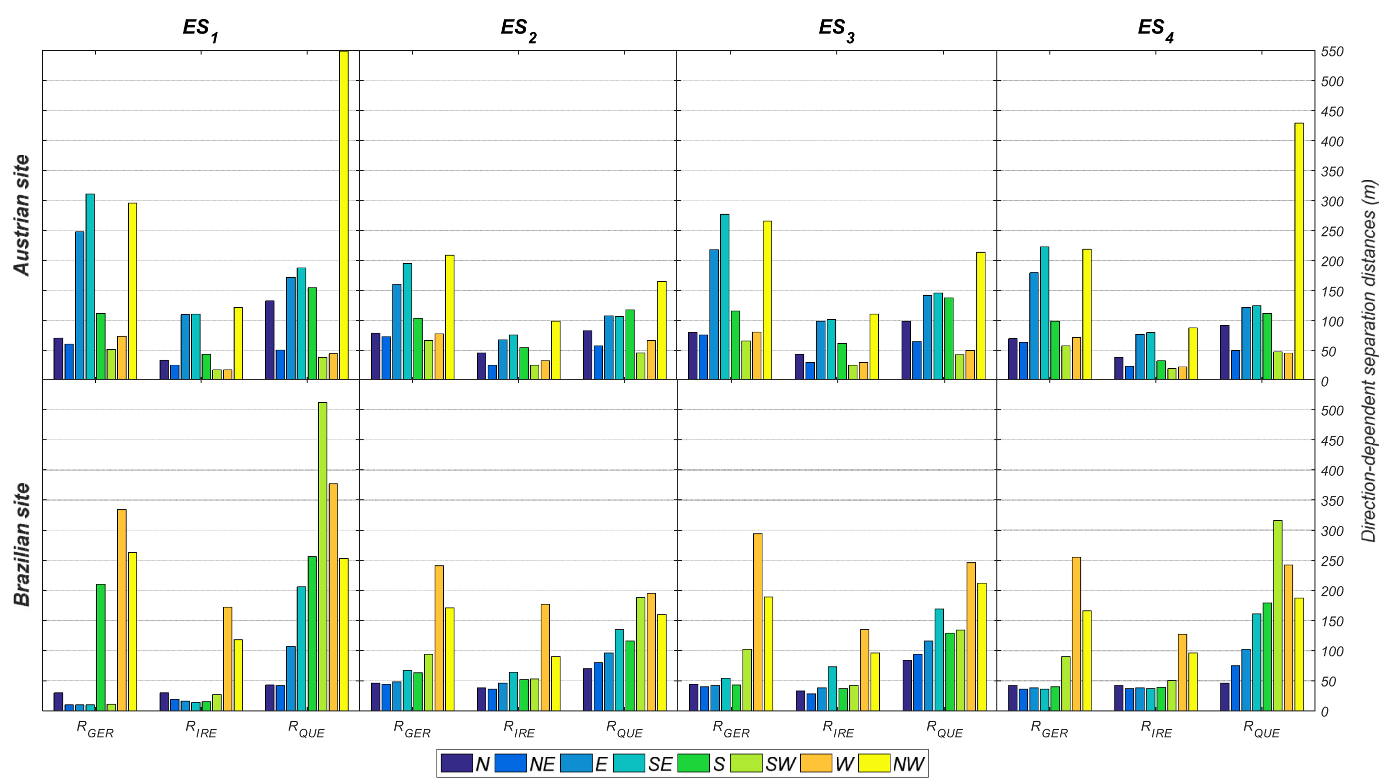

Fig. 4. Separation distances at the Austrian and Brazilian sites towards eight transport directions. Legend denotes transport directions and their associated colours. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

T_d	Austrian site								Brazilian site							
	ES_1		ES_2		ES_3		ES_4		ES_1		ES_2		ES_3		ES_4	
	R_{GER}	R_{QUE}	R_{GER}	R_{QUE}	R_{GER}	R_{QUE}	R_{GER}	R_{QUE}	R_{GER}	R_{QUE}	R_{GER}	R_{QUE}	R_{GER}	R_{QUE}	R_{GER}	R_{QUE}
N	1.4	2.7	1.6	1.7	1.6	2.0	1.4	1.8	1.0	1.0	1.0	1.4	1.0	1.7	1.0	1.0
NE	1.2	1.0	1.5	1.2	1.5	1.3	1.3	1.0	1.0	1.0	1.0	1.6	1.0	1.9	1.0	1.5
E	2.3	1.6	2.4	1.6	2.2	1.4	2.3	1.6	1.0	2.1	1.0	1.9	1.0	2.3	1.0	2.0
SE	2.8	1.7	2.6	1.4	2.7	1.4	2.8	1.6	1.0	4.1	1.0	2.1	**0.7**	2.3	1.0	3,2
S	2.2	3.1	1.9	2.1	1.9	2.2	2.0	2.2	1.0	5.1	1.2	2.2	1.0	2.6	1.0	3.6
SW	1.0	1.0	1.3	1.0	1.3	1.0	1.2	1.0	1.0	**10.2**	1.8	3.5	2.0	2.7	1.8	6.3
W	1.5	1.0	1.6	1.3	1.6	1.0	1.4	1.0	1.9	2.2	2.1	1.7	2.2	1.8	2.0	1.9
NW	2.4	4.5	2.1	1.7	2.4	1.9	2.5	**4.9**	2.2	2.1	1.9	1.8	2.0	2.2	1.7	1.9

$S_f < 1.5$

$1.5 \leq S_f \leq 2.5$

$S_f > 2.5$

Fig. 5. Scaling factors expressing the magnitude of the differences in separation distances for eight transport directions. For this comparison, the R_{IRE}-related distances are assumed as the baseline. Legend denotes scaling factors (S_f) categories and their associated colours.

more focused on odour from fattening pigs, while the R_{QUE} has been developed through practical considerations;

- The R_{QUE} can be regarded as a broader and more conservative criterion, which aims to comprise different odour sources and hedonic tones;
- Theoretically, using R_{GER} and R_{IRE} the extent of predicted annoyance due to pig odour can be better captured than using $R_{QUE.}$

4.3. Fluctuation of emissions over time

Odour emissions from livestock buildings are known to fluctuate over time (Romain et al., 2013; Schauberger et al., 2014). The use of time-varying OERs, however, is not yet the state-of-the-art in odour modelling. Because of the lack of such data most odour modelling studies are typically based on annual mean values for the OER (Hayes et al., 2006; Nicolas et al., 2008; Sommer-Quabach et al., 2014; VDI 3894 Part 1, 2011). Hence, the four emission scenarios represent today's standard practice in odour modelling and, most importantly, they are capable of addressing the research question of this study.

Besides, constant OERs have been considered to derive the dose–response relationships which in turn led to existing OIC. On top of what our results reveal, with the convenience of variable OERs, future research will be required to derive updated dose–response relationships. This is further highlighted by the fact that in previous odour dose–response studies the assignment of exposure was done in some cases using old-generation Gaussian models, whereas today latest-generation models are more and more applied.

4.4. Equivalence between dispersion modelling and the grid method (EN 16841-1)

Field inspections have been recently standardised at the European Union level (EN 1684-1, 2016), thereby providing a common basis for the member states to assess odour in ambient air. Empirical field measurements by using the “grid method” allow assessing frequencies of odour-hours. Based on the concept of odour-hour, the results from either the grid method or dispersion modelling are generally considered equivalent, in this manner (Frechen, 2000; GOAA, 2008; Oettl et al., 2018; Schauberger et al., 2012b):

- Grid method: One odour-hour is defined if a ***recognisable*** odour (unambiguously identified) is smelled during at least 10% of the measurement interval, which corresponds to 6 min of recognisable odour within one hour;
- Dispersion modelling: Modelling the baseline odour-hours necessitates the determination of the 90th percentile (p_T = 10%) of the corresponding cumulative frequency distribution of the ambient odour concentrations. Then, if the odour concentration exceeds the C_T = 0.25 $ou_E\ m^{-3}$ (= ***detection*** threshold of 1 $ou_E\ m^{-3}$ / factor of 4) this hour is counted as one odour-hour.

Inconsistencies between modelled and observed odour-hours have been shown (Oettl et al., 2018; Piringer et al., 2016). The $F = 4$ is applied over the entire range of stability conditions and receptor distances from the source. It has been reported that applying $F = 4$ has an overall tendency to overestimate frequencies of odour-hours in the far field.

Now recall that many member states of the European Union set the 98th percentile (p_T = 2%) for odour modelling (Brancher et al., 2017). Moreover, it is thought-provoking to note that validation of dispersion calculations against empirical field measurements is limited to those OIC with an exceedance probability of no less than p_T = 10% (Piringer et al., 2015). If equivalence may not be achieved even within the current concept of odour-hour, the inference is that European Union jurisdictions setting high percentiles for assessing odour annoyance are vulnerable to substantial discrepancies between dispersion modelling and the grid method (EN 16841-1).

4.5. Sensitivity of separation distances to stack exit temperature

For the perturbation analysis, an additional emission scenario (ES_{EXIT}) was designed to be used as a baseline. Table 2 shows the source release parameters related to ES_{EXIT}. The stack exit temperature is varied between 20 and 30 °C in steps of 2 °C, whereas the other input parameters are maintained fixed. ES_{EXIT} is justified because when considering high stack exit temperatures for the previous four emission scenarios (Section 3.2.2), the separation distance envelope is not always shaped.

Fig. 6 presents the *SRs* of the stack exit temperatures. The vast majority of the separation distances are ≥50 m, making the consideration of 50 m as a lower limit unnecessary under this analysis. Positive *SRs* mean that the input parameter and the result vary in the same sense, i.e. both positive or both negative, which is not the case here. The *SRs* are negative once the increase of the stack exit temperature shortens the separation distance. This is explained by the increase of effective stack height due to buoyancy plume rise. An $SR = 1$, as an absolute value, reflects a linear influence of a certain parameter

Table 2
Emission scenario ES_{EXIT} considered as the baseline for the perturbation analysis.

Emission scenario	Odour emission rate [$ou_E\ s^{-1}$]	Flow rate [$m^3\ s^{-1}$]	Stack height [m]	Stack diameter [m]	Exit velocity [$m\ s^{-1}$]	Exit temperature [°C]
ES_{EXIT}	30,000	9.8	9.0	2.5	2.0	20

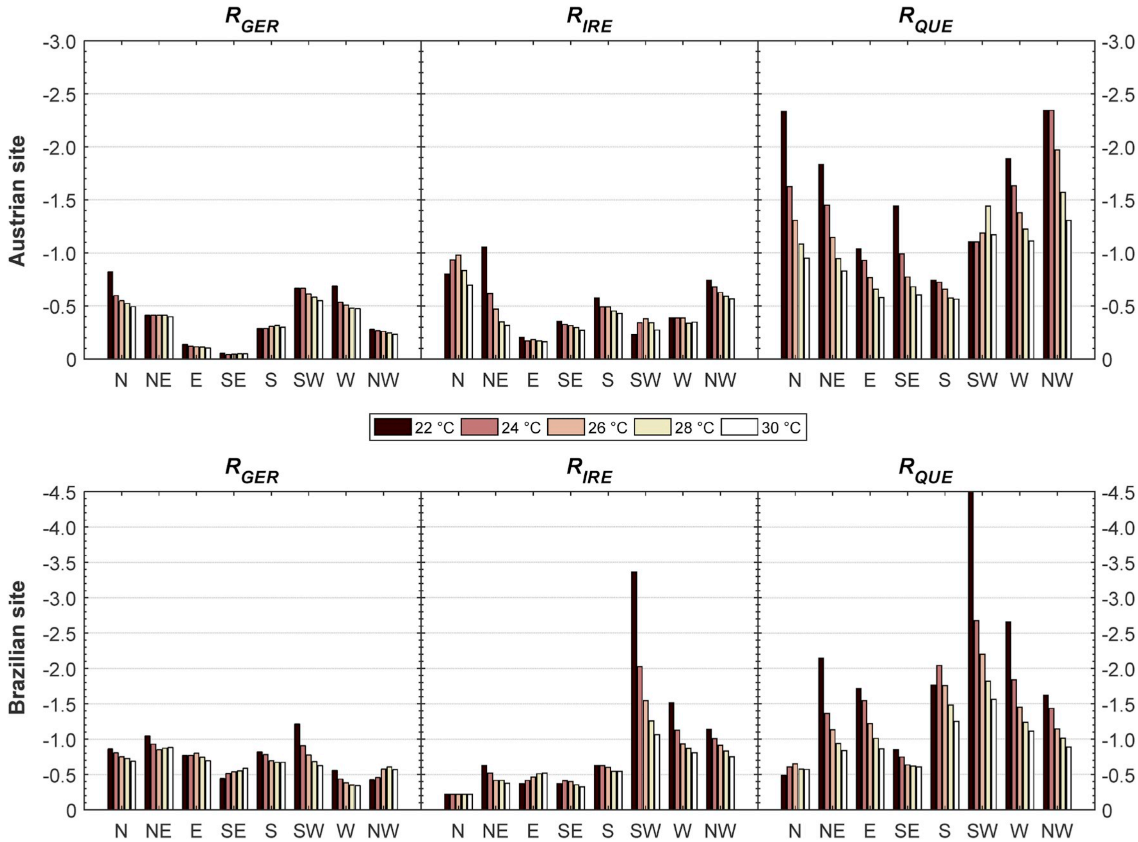

Fig. 6. Sensitivity ratios of the stack exit temperature. Legend denotes stack exit temperatures and their associated colours. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Carpentieri et al., 2012).

It is difficult to define an *SR* value above which one can show that results are sensitive to a certain parameter. In other fields, a parameter $SR \geq |1|$ has been used to indicate that a variation of the parameter value induces a greater relative variation in the result (Clavreul et al., 2012; Turner et al., 2017). Here, a perturbation of 2 °C (from 20 °C to 22 °C meaning a +10% perturbation) in the parameter value was able to cause a significant influence on some of the results. For the two sites, with values for the *SR* well above |1|, the R_{QUE}-related distances were found to be much more sensitive to stack exit temperature than R_{GER}- and R_{IRE}-related distances. At the Austrian site when using R_{QUE} the highest *SR* is |2.3|, meaning that a 2 °C perturbation causes a reduction in T_d = NW from 781 m to 598 m. At the Brazilian site when using R_{QUE} the highest *SR* is |4.5| so that a 2 °C perturbation caused a reduction in T_d = SW from 1040 m to 570 m.

In general, the lowest *SRs* are observed for R_{GER}-related distances. Therefore, an increase in *SRs* from R_{GER}-to R_{QUE}-related distances is detected (from left to right in Fig. 6 with respect to each site), revealing the OIC dependence. Accordingly, the sensitivity of separation distances to stack exit temperature shows growing importance from OIC with higher exceedance probabilities (i.e., lower percentiles) to OIC with very low exceedance probabilities (i.e., very high percentiles). The explanation for such outcomes relies essentially on the fact that separation distances determined for R_{QUE} are driven by a $p_T = 0.5\%$; thus, in the very upper tail of the cumulative distribution function. The amplified uncertainty when determining separation distances with low exceedance probabilities is further discussed in Schauberger et al. (2012b). In addition, Piringer et al. (2015) found in their work that differences in separation distances between a Gaussian plume model (AODM) and a Lagrangian particle model (LASAT) are reduced with an increasing p_T.

Some $SRs \geq |1|$ also occurred for R_{IRE}-related distances. The uncertainty in the stack exit temperature can thus play a role when using this criterion as well; however, in some transport directions more than in others, unlike the R_{QUE} for which high *SRs* occur practically in a generalised way. When using R_{GER} for determining the distances, $SRs < |1|$ occur for the majority of the directions, except for SW and NE directions at the Brazilian site where *SRs* slightly above |1| are observed. For many transport directions, we observed a decrease in the *SRs* as the stack exit temperature increases. This is due to the arrangement of Eq. 1: the *SR* is given by the ratio between the percentage change in the result and the percentage change in the input parameter.

A limitation of perturbation analysis, a local (one-at-a-time) sensitivity analysis, is that potential interactions between model input parameters are ignored (Pisoni et al., 2018). Even so, it can provide valuable information about the sensitivity of the result to parameter uncertainties, by indicating how parameter variation affects the result (Clavreul et al., 2012). Obviously, the results of the perturbation analysis are inherent to the range of the stack exit temperature and the plume rise algorithms of the model. A full description of how plume rise is calculated within AERMOD can be found in the software documentation (U.S. EPA, 2018).

4.6. Selected model and source parameters

The limitations of steady-state Gaussian plume models are broadly recognised. For the purposes of this study, the selected model has the necessary features to tackle the scientific question we wish to answer by its use. Thus, model selection was accomplished on the basis of "fitness for purpose". A detailed description of the model suitability for the two sites can be found in the study by Brancher et al. (2018a).

Modern dispersion models allow inputting nearly an unlimited number of sources. It has been shown that pollutant plumes from stacks in a line can combine at least partially, resulting in a higher plume rise.

Buoyancy enhancement depends upon stacks' proximity, wind angle relative to the alignment of the stacks, and individual stack plume rises (Paine et al., 2016). AERMOD in its current version (18081) cannot treat plume merging. A simpler approach for realising the modelling of a pollutant plume that is emitted from similar stacks is to assume that the emissions are released from a single, representative stack with an equivalent diameter. Therefore, in this study, the stack diameters were chosen for accommodating the OERs by a single-point source and concomitantly consider typical values for the exit velocity. Yet, we have performed extra dispersion calculations (results shown during the peer review process) for a scenario with stack diameter of 0.9 m (flow rate of $4.0\,m^3\,s^{-1}$, stack height of 8.0 m, exit velocity of $6.3\,m\,s^{-1}$ and exit temperature of 20 °C). Again, the same remarks as before were found which means that the conclusions are preserved.

4.7. Implications for regulatory practice

Under environmental odour regulations around the world, compliance assessment often takes the form of modelling (Brancher et al., 2017). In countries with no specific requirements for managing environmental odour, OIC may be adopted from other jurisdictions to guide the licencing of odour-emitting activities. For this intent, the present study shows that the arbitrary selection of OIC must be avoided as remarkable differences in separation distances can arise. Depending on the T_d, a scaling factor up to ~10.2 was found. The rationale behind the adoption of a specific criterion should be well discussed and justified, thereby minimising the risk of poor conclusions in odour assessments.

With the findings of this study in mind, it can also be argued that the wide range of OIC is contributing to the weakening of authority action in successfully tackling odour pollution. Inspired by remarks given in Barnes et al. (2018), we visualise an array of interrelated consequences that can be linked to this issue, including the (i) definition of over or undersized separation distances, (ii) delays in granting environmental compliance, (iii) conflicts with annoyed residents, (iv) waste of resources and, (v) in due course, potential worsening of public health.

5. Conclusions and outlook

This study shows that odour impact criteria (OIC) of different jurisdictions are incapable of determining analogous separation distances between odour sources and residential areas for an equivalent level of protection. Differences in separation distances at the two studied sites were found to be significant and cannot be considered within an acceptable range. Overall, differences in separation distances were greater for prevailing wind directions compared to non-prevailing wind directions. This remark indicates that the nature of odour exposure is intimately connected to the meteorology of a particular site.

Environmental odour is increasingly framed as a regulatory air pollutant. Although there may be a political context involved in establishing OIC, it seems common-sense that, as a minimum, alike separation distances should be determined for a similar level of protection against odour annoyance. Therefore, this study is of importance in drawing attention to the need for better alignment of the concept of the odour impact criterion and components thereof. Updated epidemiological dose–response relationships between odour exposure and population response (e.g., annoyance level) have the potential to support this need, since such relationships are the backbone for deriving OIC for public policy.

The results of the perturbation analysis indicated that the stack exit temperature is a parameter influencing separation distances in a distinct fashion, depending on the OIC. The use of OIC with higher exceedance probabilities (lower percentiles) was found to be more robust to counteract uncertainty in the stack exit temperature. Conversely, the use of OIC with very low exceedance probabilities (very high percentiles) showed a high sensitivity to small variations of the stack exit temperature in the range of 20–30 °C. It has to be underlined that, regardless of the reference OIC, stack exit temperature uncertainty asks attention. Even if for higher exceedance probabilities (lower percentiles) reduced sensitivity ratios were observed, a negligible influence of the stack exit temperature uncertainty on the separation distances could not be ruled out under the conditions investigated in this study. These outcomes are of significance for input data collection in future odour modelling studies.

It is important to bear in mind that the scope of this work does not consider the building downwash phenomenon, which acts upon modifying plume transport and dispersion considerably. When this is the case, simplifications of the modelling approach may show an influence on the exit temperature sensitivity. Future studies are encouraged to explore this problem, and in doing so will provide a useful basis for comparing results.

Finally, the results and findings of the present study should not be solely seen as evidence advocating the use of an odour impact criterion over another. This study in no way attempts to weaken the importance of existing odour regulations. The main goal here was on a detailed comparison of how odour annoyance is assessed with the use of different OIC, but with an equivalent level of protection, thereby providing scientific remarks that can be used to inform future research, policymaking and regulatory decisions in this field. While some countries have made substantial progress in managing environmental odour over the years, there is still much to be done.

Conflict of interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.03.102.

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