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Research Paper

Impact of global warming on the odour and ammonia emissions of livestock buildings used for fattening pigs☆

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Ammonia and odour are the most relevant pollutants emitted from livestock buildings used for monogastric animal production. Whereas odour can cause annoyance in the close vicinity of the source, emission of ammonia is a precursor for the formation of particulate matter and acidification on a regional scale. Because of clean air regulation in Europe, total ammonia emissions reduced by 23% between 1990 and 2015 whilst, over the same period, anthropogenic warming became more and more evident. By a simulation of the indoor climate of a confined livestock building with a mechanical ventilation for 1800 fattening pigs, the modification of the odour and ammonia emission was calculated for the period between 1981 and 2017. For ammonia emission, a relative increase of 0.16% per year was determined. But following the clean air endeavour between 1990 and 2015 emissions over that period were reduced by 23%. The global warming signal counteracting this reduction in the range of 4% during over this period, which means that the overall reduction for the ammonia emission was only 19%. For Austria with a global warming increase of 1% from 1990 to 2015, this gives an increase in emissions of 5% instead. Odour emissions also increased by about 0.16% per year. The relative increase of the separation distances for the four cardinal directions was about 0.06% per year, the related increase for the separation

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area was 0.13% per year. This case study on the fattening pigs shows that the global warming signal has a negligible impact on separation distances.

Nomenclature

m_{start} (kg) body mass values at the beginning of the fattening period
m_{end} (kg) body mass values at the end of the fattening period
t_A (d) duration of the fattening period
t_S (d) duration of the service period
t_{FP} (d) overall duration of a fattening period
n_{FP} number of fattening periods per year
$e_{OD,0}$ (ou $s^{-1}LU^{-1}$) reference body mass specific emission factor for odour
$e_{NH3,0}$ (kg $a^{-1}AP^{-1}$) reference body mass specific emission factor for ammonia
R (–) release modification factor
T_i (°C) temperature
V (m^3/h) ventilation rate
A (–) physical activity of animals
t (h) daytime
F_T (–) modification factor for the indoor temperature
F_V (–) modification factor for the ventilation rate
F_A (–) modification factor for the relative animal activity
T_R (°C) reference temperature
V_n (–) normalised ventilation rate
V_d (m^3/h) reference ventilation rate
a (–) amplitude
τ (h) period
φ (h) time lag
A_0 (–) daily mean of the relative animal activity
r (–) relative release modification factor
R_{1981} (–) mean modification factor for 1981
E_{OD} (ou s^{-1}) odour emission rate of the entire livestock building
E_{NH3} (kg a^{-1}) ammonia emission rate of the entire livestock building
N (–) number of animals
m_M (kg) mean body mass
D_{Sep} (m) separation distance
F (%) relative frequency
W (m s^{-1}) mean wind velocity for each 10° sector of the wind direction
P (%) exceedance probability for odour perception
A_{Sep} (m^2) separation area
RG release factor of Gyldenkærne et al. (2005)
v_i (m/s) air velocity at animal level
a and b exponents for the RG for pigs
NH_3 ammonia
PM particulate matter
AP (–) animal place
LU (–) livestock unit LU, 1 LU = 500 kg

1. Introduction

The most important pollutants that impact on the environment that are emitted from livestock buildings used for the production of monogastric animals are odours and ammonia (NH_3) (Blanes-Vidal, Nadimi, Ellermann, Andersen, & Løfstrøm, 2012). Whereas odorous substances are more relevant on a local scale causing annoyance to nearby residents, NH_3 is predominantly relevant as a pollutant on a regional scale.

NH_3 is an important precursor of fine particulate formation in the atmosphere (Backes et al., 2016a, 2016b; Xu & Penner, 2012). It plays a crucial role in the acidification and eutrophication of ecosystems, and contributes to indirect emissions of nitrous oxide. The relation between emission and concentration of NH_3 shows a complex pattern. After the emission, NH_3 is transported in the atmosphere. It is chemically transformed into secondary non-gaseous inorganic aerosols such as ammonium nitrate and ammonium sulphate and it is removed from the atmosphere by dry and wet deposition (van Zanten, Wichink Kruit, Hoogerbrugge, Van der Swaluw, & van Pul, 2017).

Agriculture has been identified as the major source of atmospheric NH_3, contributing 55–56% of the global emissions (Sutton et al., 2013). For Europe, about 94% of NH_3 emissions are related to agriculture (EEA, 2017), although natural odour sources are not included into this inventory (Sutton et al., 2013). The major part is caused by livestock housing, stored manure, and animal exercise areas. About 10% of the agricultural emissions are related to synthetic fertilisers. In the near range of agricultural sources, NH_3 emission causes considerable ambient concentrations (Fowler et al., 1998; Geels et al., 2012; Hallsworth et al., 2010; Kryza, Dore, Błaś, & Sobik, 2011).

For clean air initiatives and climate related investigations, emission inventories have been conducted on various spatial scales (Backes et al., 2016a; Bouwman et al., 1997; Kang et al., 2016; Pinder, Adams, Pandis, & Gilliland, 2006; Sutton et al., 2013). Depending on the availability of data, the complexity of these inventories varies extensively. Especially on a global scale, inventories are based on the use of an emission factor (e.g. an animal place related emission factor) for a certain type of NH_3 emission and the related activity value (e.g. number of animals inside a grid cell) and this is used for scaling the emission values (Faulkner & Shaw, 2008; Mikkelsen, Albrektsen, & Gyldenkærne, 2014; Misselbrook et al., 2000; US EPA, 2004; Webb & Misselbrook, 2004). These emission factors are not temperature sensitive and are assumed constant over the years. More sophisticated emission models include the indoor temperature modifying the NH_3 release and include the spatial distribution of local agricultural practice

(Gyldenkærne, Skjøth, Hertel, and Ellermann, 2005). These inventories show a higher accuracy (Skjøth et al., 2011), but have a greater need for input data.

Such inventories are carried out on an annual basis to monitor the national effort to reduce NH_3 emissions. Thus, for Europe, it has been shown that NH_3 emissions have dropped by 23% between 1990 and 2015, although between 2014 and 2015, emissions increased by 1.8% (EEA, 2017). This trend of NH_3 emissions has an impact on the production of particulate matter (PM) as well, which is a major environmental health threat (Hendriks et al., 2013).

Ammonia emissions have been shown to be climate sensitive (Sutton et al., 2013) with a global emissions increasing about 42% for a warming of 5 °C. This means, that the expected global warming is counteracting the efforts to reduce agriculturally emitted NH_3.

Odour is one of the major nuisances from livestock husbandry, especially in the pig industry (Cantuaria, 2017). The final report of the Iowa State University and The University of Iowa Study Group (2002) defined odour, along with hydrogen sulphide and NH_3, as an emission which is a major concern of residents living in the vicinity of livestock production facilities. Blanes-Vidal, Suh, et al. (2012) also showed that NH_3 can be used as a proxy for other odorous substances due to their strong relationship.

Odour emissions have been known to reduce the quality of life of local residents (Blanes-Vidal, Nadimi, et al., 2012; Blanes-Vidal, Suh, et al., 2012; Cantuaria, Brandt, Løfstrøm, & Blanes-Vidal, 2017; Wing et al., 2008) and also self-reported health problems (Wing, Lowman, Keil, & Marshall, 2014). This negatively impacts on economic development close to livestock production facilities (Gómez & Zhang, 2000; Herriges, Secchi, & Babcock, 2005).

Here the impact of the Earth's climate change in the form of global warming on the emission of odour and NH_3 is investigated. Fattening pigs were selected for this case study because this type of animal husbandry shows a high impact on the two pollutants due to the fact that mechanically ventilated livestock buildings contribute to 34%–43% of the European agricultural NH_3 emissions (Skjøth & Geels, 2013), and on a global scale fattening pigs contribute most by about 70% to the pig related NH_3 emissions (Philippe, Cabaraux, & Nicks, 2011).

The investigation is based on model calculations which are performed in two steps. In the first step, a simulation model of the indoor climate is driven by a time series of more than three decades of meteorological data to investigate the inter-annual variability and the relationship with the global warming signal. In the second step, the subsequent NH_3 and odour emission model is driven by these indoor parameters to provide the emission flow rate on an hourly basis. The analysis seeks to answer the question if the expected global warming signal will counteract the efforts to reduce these emissions.

2. Materials and methods

2.1. Meteorological data

Meteorological data are needed on an hourly basis (air temperature and relative humidity) for the calculation of the indoor climate and the related emissions of odorous substances and NH_3. The Austrian Meteorological Service ZAMG (Zentralanstalt für Meteorologie und Geodynamik, Vienna, Austria) provided measurements for the weather station close to the city of Wels (48.16°N, 14.07°E) for the time period 1981 to 2017. Following the climate classification of Köppen and Geiger (c.f. Kottek, Grieser, Beck, Rudolf, & Rubel, 2006), the station is located within class Cfb (warm temperature, fully humid, warm summers) which is representative for large areas in Central Europe excluding the Alps. The annual mean temperature is 8.8 °C and the mean annual precipitation amount is 979 mm/year. At this location the lowest and highest observed temperatures for the time period 1981 to 2017 are −27.8 °C and 38.2 °C respectively. For the whole area of Upper Austria is expected to have a mean increase in temperature of ~+1.4 °C (~± 0.5 °C) by the middle of the 21st century. The number of hot days (daily maximum temperature ≥ 30 °C) is expected to increase in this region of up to 4.7–5.0 d a compared to the reference period of 1971–2000 with a mean value of 3.3 hot d a^{-1} (Chimani et al., 2016).

2.2. Simulation of the indoor climate

The indoor climate was simulated by a steady state model which calculates the thermal indoor parameters (air temperature, humidity) and the ventilation flow rate. The thermal environment inside the building depends on the livestock, the thermal properties of the building, and the ventilation system and its control unit. The core of the model can be reduced to the sensible heat balance of a livestock building (Schauberger, Piringer, Heber, 2014; Schauberger, Piringer, Petz, 2000, 2001). The model calculations were performed for a typical livestock building for fattening pigs for Central Europe for 1800 heads, divided into 9 sections with 200 animals each for an all-in-all-out production cycle. The model calculation was performed for meteorological data on an hourly basis for three decades between 1981 and 2017.

The body mass values at the beginning and end of the fattening period were selected to be $m_{start} = 30$ kg for $t = 0$ d and $m_{end} = 120$ kg for $t_A = 108$ d with the corresponding time of the Gompertz model (Mikovits et al., 2018). The duration between two consecutive fattening periods, when the livestock building is serviced (cleaning and disinfection), is assumed as $t_S = 10$ d. Hence the overall duration of a fattening period is given by $t_{FP} = t_A + t_S$ which results in $t_{FP} = 108$ d $+ 10$ d with a duration of $t_{FP} = 118$ d. Therefore the number of fattening periods per year is given by $n_{FP} = 365/t_{FP}$ with $n_{FP} = 3.09$.

A detailed description of the simulation model was given in Mikovits et al. (2018).

2.3. Airborne emissions

The most relevant emissions of fattening pigs are the two airborne pollutants: NH_3 and odorous substances. In general, the airborne emission rate of a pollutant due to a livestock building is calculated by a body mass specific emission factor e_0 which is related to the body mass (livestock unit LU, 1 LU = 500 kg) (for odour) or to one animal place AP (for NH_3). These reference emissions rates are annual mean values. For NH_3 we selected an emission factor with $e_{NH3,0} = 3.64$ kg a^{-1} per AP and for odour with $e_{OD,0} = 50$ ou $s^{-1}LU^{-1}$ (VDI 3894 Part 1, 2011).

The release of these two pollutants is also modified by the indoor climate (e.g. temperature, ventilation rate and time of the day) of the livestock building (Gyldenkærne et al., 2005; Schauberger et al., 2013). The modifications by these predictors were considered with the release modification factor R according to $e = e_0 R$.

The release modification factor R was calculated on the basis of the indoor air temperature T_i, ventilation rate V, and physical activity of animals A as a function of daytime t (Schauberger et al., 2013, 2014) by $R = F_T\ F_V\ F_A$ with F_T for indoor temperature, F_V for ventilation rate and F_A for relative animal activity. This release modification factor R was derived for the odour emission for fattening pigs. By the fact that the release of odour and NH_3 take place predominantly in the same way, the modification factor R was applied to NH_3 as well.

The exponential function for the indoor temperature F_T describes the increase of the odour release with the indoor temperature T_i (°C) given by $F_T = e^{c_T(T_i - T_R)}$ where $c_T = 0.0314$ is the coefficient for the exponential function, and the reference temperature $T_R = 20$ °C. The function for the ventilation rate F_V is parameterized by the normalised ventilation rate V_n per AP using the following power function $F_v = V_n^{c_v}$ where the exponent is $c_v = 0.318$. The ventilation rate per animal place V is normalised to unity by V_d, according to $V_n = V/V_d$ using $V_d = 200$ m^3 h^{-1} per AP. The diurnal variation of animal activity F_A is described by a function which was used for the diurnal variation of the energy release as well (Mikovits et al., 2018),

$$F_A = A_0 + a \sum_{i=0}^{k} \frac{\sin\left(\frac{2\pi}{\tau}(2i+1)(t+\varphi)\right)}{2i+1}$$

with the amplitude a, the period $\tau = 24$ h, time of day t (h), time lag φ (h), and $k = 1$. The reference value for the daily mean of the relative animal activity is $A_0 = 1$.

The release modification factor $R = F_T\ F_V\ F_A$ is thus given by

$$R = \exp(0.0314(T_i - T_R))V_n^{0.318}\left(1 + 0.25\sin\left(\frac{2\pi}{24h}(t-6h)\right) + \frac{0.25}{3}\sin\left(\frac{2\pi}{24h}3(t-6h)\right)\right)$$

The three functions of the modification release factor R take the value "1.0" for the accordant reference values of these functions, which are $T_i = 20$ °C for indoor temperature, $A_0 = 1$ for the daily mean relative animal activity, and $V_d = 200$ m^3 h^{-1} per pig (Schauberger et al., 2013). The release modification factor was normalised to unity by the annual mean value of R_{1981} for the year 1981, using a linear regression for the annual mean values R_i between 1980 and 2017. This relative release modification factor $r = R/R_{1981}$. The emission factor for odour and NH_3 was calculated by $e_{OD} = e_{OD,0}\ r$ and $e_{NH3} = e_{NH3,0}\ r$, respectively.

The odour emission rate of the entire livestock building was calculated by $E_{OD} = N\ m_M\ e_{OD}$ (ou s^{-1}) with the number of animals $N = 1800$, the mean body mass $m_M = 75$ kg ($m_M = 0.15$ LU) and the body mass specific odour emission factor e_{OD}. The NH_3 emission of the building is calculated according to $E_{NH3} = N\ e_{NH3}$ (kg a^{-1} AP^{-1}) with the AP related emission factor e_{NH3}.

2.4. Determination of the separation distance

For odour emissions, the direction dependent separation distances can be calculated on an annual basis. These distances can be used to determine the area, which is essential to operate such a livestock building. The separation distances were calculated by an empirical model, which was developed for Austria (Schauberger, Piringer, Jovanovic, & Petz, 2012). The necessary input parameters are the annual mean value of the odour emission rate E_{OD}, the wind statistics for the site for 10° sectors, and the odour impact criterion, which is given by the odour exceedance probability P (%), describing the odour protection level for residents.

The equation for the separation distance D_{Sep} (m) reads as

$$D_{Sep} = P^{-0.386}\left(165F^{0.0289} - 3.63W - 150\right)E^{\frac{1}{-0.0381F+0.0191P+2.31}}$$

depending on the relative frequency F (%) and the mean wind velocity W (m s^{-1}) for each 10° sector of the wind direction, as well as the exceedance probability for odour perception P (%) = 15%, which is a typical value for agricultural areas (GOAA, 2008).

The separation distance $D_{Sep,i}$ was calculated for all 36 wind directions i (10° sectors). The separation area A_{Sep} which is needed to conduct animal husbandry without complaints by the neighbours was calculated by

$$A_{Sep} = \frac{\pi}{36}\sum_{36}^{i=1} D_{Sep,i}^2$$

To emphasize the impact of the meteorological situation on the direction depending separation distance D_{Sep} and the separation area A_{Sep}, the calculations were performed using the wind statistics of 1993 which do not vary with time.

The temporal variability of the separation distance D_{Sep} is shown for the two prevailing wind directions (East and West) and the two additional wind directions North and South which are influenced by a thermal driven wind regime (valley winds) at this site (Schauberger, Piringer, & Petz, 2006).

2.5. Model calculations and sensitivity analysis

The model calculations were performed for the entire growing-fattening period for a body mass between 30 and 120 kg. The calculations were done for 1981 to 2017 to determine the trend for the 37 year period. Additionally the years 1984 and 2015 were selected, as being one of the coldest and warmest years, respectively, for summertime temperatures, to show specific results outside of the trend calculations.

The trend is estimated with a linear function $x_{trend} = b\,x + a$ for the period 1981 to 2017. The inter-annual variability was calculated for the detrended values x' with $x' = x\ x_{trend}$, and described by the coefficient of variation CV (quotient of the standard deviation and the mean value of the detrended values x').

3. Results and discussion

The investigation was carried out to clarify if and to what extent the global warming signal, mainly the increase in air temperature, will counteract the observed decrease of NH_3 emissions in Central Europe (shown for a site in Austria) and how it will modify odour emission rates.

The two parameters, indoor air temperature T_i and volume flow rate V, which are the main predictors for the release of odorous substances and NH_3, show a relative annual increasing trend (Table 1) of 0.12% and 0.26% per year, respectively. The NH_3 and odour release shows a non-linear relationship for the indoor air temperature and volume flow rate, which results in a relative annual increasing trend of the modification factor by 0.16%. The two extremes of the annual mean value of the relative release modification factor r lie in the range of 98% for 1984 as a cold year and 108% for the hottest year in 2015. The annual time course of NH_3 and odour are shown in Fig. 1. Due to the fact that the relative release modification factor r is the same for odour and NH_3, the relative change is the same. The two black lines show the annual mean value of the odour and NH_3 emission factors with $e_{NH3,0} = 3.64$ kg a^{-1} and $e_{OD,0} = 50$ ou s^{-1}LU^{-1}, respectively.

The linear trend of the outdoor temperature was determined by 0.048 K/a, the annual trend for the NH_3 emission was estimated by 0.16%. A 5 °C warming results in an increase of the NH_3 emission of livestock buildings of 17%. In comparison Sutton et al. (2013) found a global emission increase of about 42% for a warming by 5 °C, however, Sutton et al. (2013) included emissions from non-agricultural emissions as well. For the storage of slurry, Aarnink and Elzing (1998) found a 10% increase of the emission rate for an increase of the storage temperature of 1 K.

The comparison of the seasonal variations of the hourly NH_3 emissions for confined livestock buildings (Geels et al., 2012; Skjøth et al., 2011) shows a distinct difference to the calculation presented in this paper (Fig. 1). The seasonal variability is much lower compared to our simulation. On one hand the sensitivity of the NH_3 emission to temperature and wind velocity inside the livestock buildings is very similar, on the other the resulting NH_3 emission shows a different temporal behaviour.

In Europe, the emission of NH_3 reduced by 23% between 1990 and 2015. Improvements in livestock management were counteracted by global warming in the past with similar trends expected for the future. Taking into account the increase of the ambient temperatures by the global change and the related increase of the NH_3 emissions by 4% between 1990 and 2015 this results in an overall NH_3 reduction of 19% instead of the assumed 23%. Thus, this global change effect cannot be neglected in future. For Austria, an increase of annual NH_3 emission by 1% for 1990 to 2015 gives an overall increase by 5% instead (EEA, 2017). For this estimate, we expect that the livestock related NH_3 emission behaves in a similar way which is based on the assumption that for Austria about 50% of NH_3 emission is related to animal husbandry and 23% is caused by confined livestock buildings. Skjøth et al. (2011) summarised the relative portion of agricultural NH_3 sources for European countries. Studies on the expected future NH_3 emission trends show varying results. The epidemiological relevance for human health of the climate signal for the NH_3 emission was shown by Geels et al. (2015) for a simulation for the 2080s. In regions with high NH_3 emissions (e.g., Germany, Poland, Netherlands and Belgium), $PM_{2.5}$ concentrations will be affected which will result in a Europe-wide increase of chronic mortality by 4%.

For the 2050s, the NH_3 emissions from confined livestock buildings, as they are used predominantly for fattening pigs and poultry, are expected to increase by about 15–20% (relative to 2007) due to the increase of temperature (Simpson et al., 2014). Skjøth and Geels (2013) expect an increase up to 40% due to the global warming signal. Under the assumption of a constant linear trend of the anthropogenic warming till 2050, NH_3 emissions will increase by about 11% between 1981 and 2050 from livestock buildings. Entire NH_3 emissions are therefore expected to stay constant until the middle of this century, when compared to 2005, due to the increase in agricultural production, the greater release due to higher temperatures, and on the other hand clean air activities. Sutton

Table 1 – Statistics of the predictors and the related odour and NH_3 emission by the use of the mean annual linear trend, the mean relative trend (% per year) the reference value for 1981, minimum (Min), and maximum (Max) between 1981 and 2017 for the indoor air temperature T_i (°C), the cumulated volume flow rate per AP V_a (103 m^3 a^{-1}), the AP related NH_3 emission factor e_{NH3} (kg a^{-1}), the animal mass related odour emission factor e_{OD} (ou s^{-1} LU–^{1}), the release modification factor r, the separation distances D_{Sep} (m) for the four cardinal directions, and the separation area A_{Sep} (ha).

	Trend (per year)	Rel. trend (% a^{-1})	Reference 1981	Min (year)	Max (year)
Predictors					
Indoor air temperature T_i (°C)	0.023 ± 0.004	0.12 ± 0.023	18.69	19.3 (1996)	20.7 (2015)
Volume flow rate V_a (10^3 m^3 a^{-1})	0.881 ± 0.157	0.26 ± 0.046	340	325 (1984)	379 (2015)
Airborne emission					
NH_3 emission factor e_{NH3} (kg a^{-1})	0.006 ± 0.001	0.16 ± 0.03	3.64	3.56 (1984)	3.92 (2015)
Odour emission factor e_{OD} (kg s^{-1} LU^{-1})	0.079 ± 0.001	0.16 ± 0.03	50	48.8 (1984)	53.9 (2015)
Relative release modification factor r (–)	0.002 ± 0.000	0.16 ± 0.03	1.0	0.98 (1984)	1.08 (2015)
Separation distance D_{Sep} (m)					
North	0.079 ± 0.015	0.06 ± 0.01	136	133 (1984)	139 (2015)
East	0.176 ± 0.033	0.07 ± 0.01	270	265 (1984)	278 (2015)
South	0.045 ± 0.008	0.06 ± 0.01	79	78 (1984)	81 (2015)
West	0.202 ± 0.038	0.06 ± 0.04	313	308 (1984)	323 (2015)
Separation area A_{Sep} (ha)	0.0133 ± 0.0025	0.13 ± 0.024	10.19	9.99 (1984)	10.86 (2015)

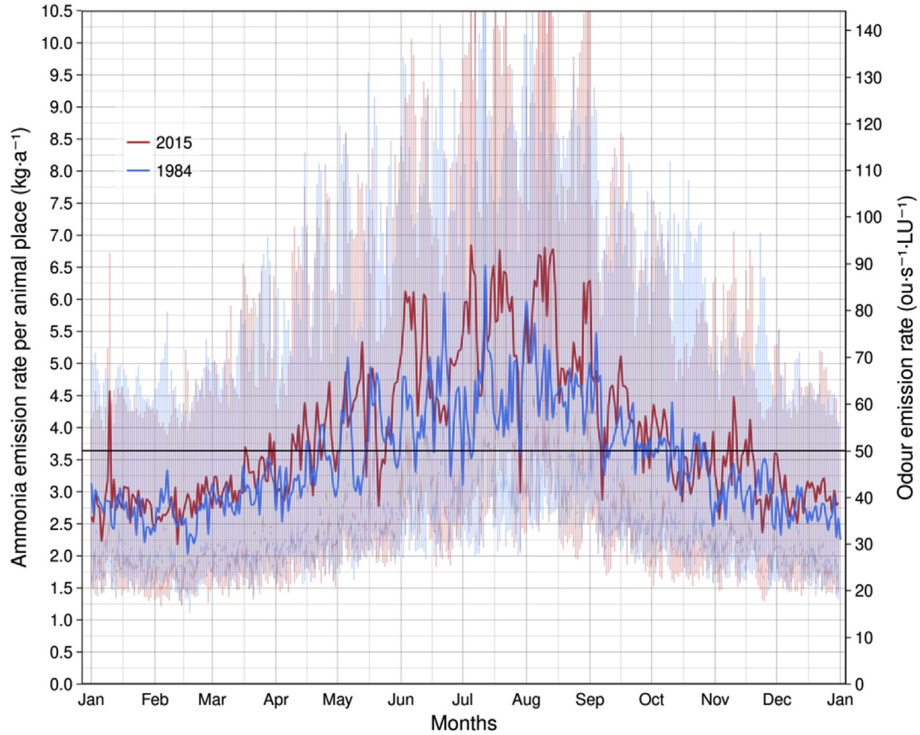

Fig. 1 – Time trend of the hourly values of the NH_3 emission rate per AP e_{NH3} (kg a^{-1}) and the body mass related odour emission rate e_{OD} (ou s^{-1} LU^{-1}) for 1984 (cold, in blue) and 2015 (warm, in red). The reference values for NH_3 and odour emission factors are $e_{NH3,0} = 3.64$ kg a^{-1} and $e_{OD,0} = 50$ ou $s^{-1}LU^{-1}$, respectively, which are depicted by a thin black line. The two lines for 1984 and 2015 represent diurnal mean values of the odour and NH_3 emission.

et al. (2013) predicted an increase of the NH_3 emission by about 100% due to global warming impact and anthropogenic activities by 2100 on a global scale. As can be seen by the NH_3 emissions in Europe over recent decades, these reduction efforts need to be intensified much further to counteract the global warming signal and the increase of the agricultural production level.

For time resolved inventories, the NH_3 emission of confined livestock buildings are parameterised by Skjøth, Hertel, Gyldenkærne, and Ellermann (2004) and Gyldenkærne et al. (2005). The NH_3 release factor of Gyldenkærne et al. (2005), RG for mechanically ventilated buildings is calculated by $RG = T_i^a v_i^b$ with the air velocity at animal level v_i and the indoor air temperature T_i, and the two exponents for pigs $a = 0.89$ and $b = 0.26$, respectively. These two predictors are calculated by the use of a simple step function which is driven by the diurnal mean outdoor temperature. In Fig. 2 the release modification function R is compared with the parameterisation for NH_3 showing the influence of the indoor air temperature T_i (left panel) and the wind velocity at animal level v, (right panel) which is derived by the ventilation flow rate per AP V (m^3/h) according to $v_i = 0.0976\ V^{0.3}$. The animal activity is assumed as constant $A = 1$. The comparison of the release factor RS (Gyldenkærne et al., 2005) and R (this study) shows a good agreement. The parameterisation of the indoor air velocity v_i shows an underestimation by the use of the exponent of 0.3. Yu, Liao, and Liang (2003) show that the air velocity at floor level v_i can be expressed by the jet momentum power (which depends on the volume flow rate V) of 0.5. This means that the ratio between maximum and minimum air velocity is in the range of about 3.3 (according to the maximum $V_{max} = 110$ m^3 h^{-1} and the minimum ventilation $V_{min} = 10$ m^3 h^{-1} rate for fattening pigs which gives $(V_{max}/V_{min})^{0.5}$), whereas the parametrisation of Gyldenkærne et al. (2005) gives a ratio of 1.9 (=0.38 m s^{-1}/0.20 m s^{-1}). This results in an underestimation of the release modification factor for the impact of the air velocity.

The annoyance due to the emission of odorous substances is handled in most of the jurisdictions by use of a separation distance. The direction dependent separation distance between odour sources and residential areas is used to divide the circumjacent area around a source in a zone which is widely protected from annoyance and a zone closer than the separation distance where annoyance can be widely expected. The protection level (Brancher, Griffiths, Franco, & de Melo Lisboa, 2016; Sommer-Quabach, Piringer, Petz, & Schauberger, 2014) depends also on the land use category. The higher the protection level, the farther the separation distance to reduce the frequency of odour sensation. The calculation of the separation distance can be performed by the use of an annual mean value of the odour emission flow rate and a dispersion model (Piringer & Schauberger, 2013) or by a simplified empirical model (Schauberger, Piringer et al., 2012, Schauberger, Schmitzer et al., 2012). To analyse the impact of global warming we used the Austrian empirical model (Schauberger, Piringer et al., 2012) and the wind statistics from Wels with the frequency of the wind direction for 10° classes and the corresponding mean wind velocities for 1993. By this

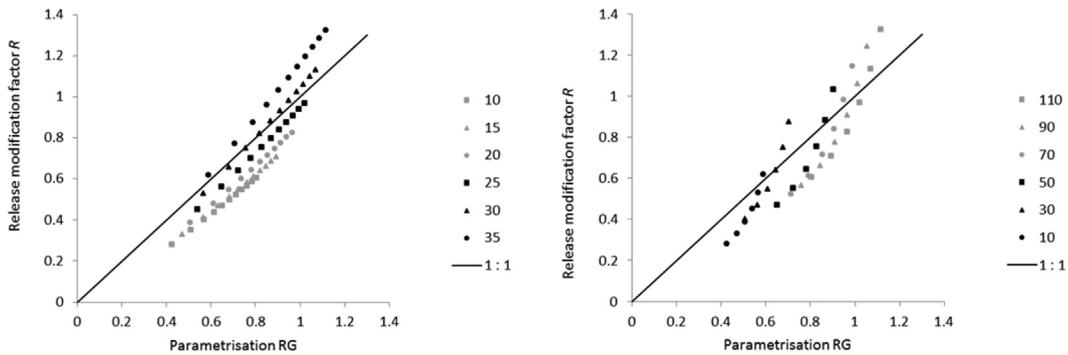

Fig. 2 – Comparison of the release modification factor R, which was derived for odour emission (Schauberger et al., 2013) and the parametrisation by Gyldenkærne et al. (2005) for the NH_3 emission shown for an indoor temperature T_i between 10 °C and 35 °C (left) and for a volume flow rate per AP V between 10 m^3/h and 110 m^3/h (right).

approach the inter-annual variability due to the change of the odour emission flow rate is determined. The results show nearly constant separation distances for the cardinal wind directions. Also the separation area doesn't show an influence due to the global warming signal. This means that the calculation of the separation distance is not sensitive to the impact of global warming. The meteorological dilution conditions, which are related to the wind direction, wind velocity, and stability of the atmosphere, show a much stronger inter-annual variability (Brancher et al., 2018). This promising result shows that the impact of the global warming signal on the local annoyance by odour emissions is quite low and that the determined separation distance will be valid even on a long term perspective. Due to the fact that these calculations are performed for zoning and licensing of livestock buildings, this is an important feature for a high predictability and reliability of legal decisions. The variability of the odour emission rate lies in the range of 98% (minimum) and 108% (maximum). The separation distance can be assessed by a power function with an exponent in the range of 0.3–0.6 for the odour emission rate. This means that the separation distance is reduced by these exponents. This yields to a reduction of the variability of the separation distance by a factor of about 2.5–5. In Fig. 3 the statistic of the direction depending separation distance is shown by the mean value and the two extremes for the period between 1981 and 2017. Due to the fact that the separation distance is calculated by the use of the annual mean value of the odour emission, the impact of anthropogenic warming is much weaker than for non-linear heat stress measures like THI, which are based on a threshold (Mikovits et al., 2018). Considering the other uncertainties in assessing separation distance, the impact of the global warming signal can therefore be neglected.

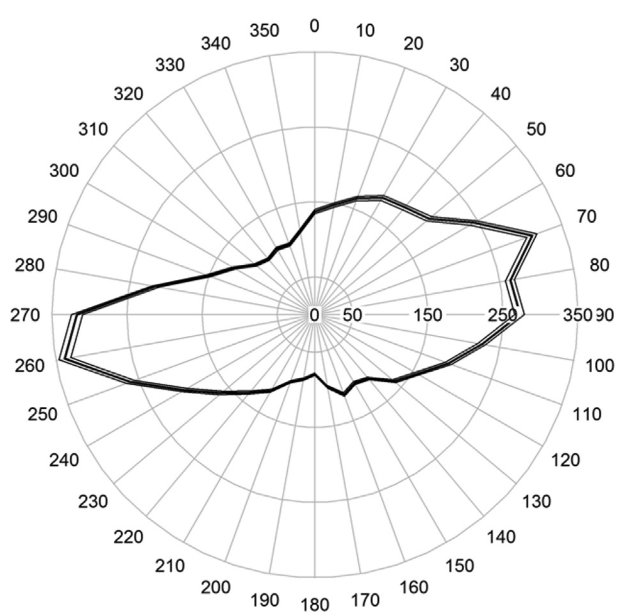

Fig. 3 – Polar diagram of the direction depending separation distance D_{Sep} (in m) by the mean value for the period between 1981 and 2017, and maximum and minimum. The odour source is situated in the centre of the diagram, North is at 0°.

Therefore, because odour emissions consume land to guarantee the separation distances, and create a loss in value due to odour annoyance, they have an economic impact (Bazen & Fleming, 2004; Hribar & Schultz, 2010). However global warming has no additional impact on these effects.

4. Conclusions

Global warming is a relevant issue in the field of air borne pollutants and the related clean air regulation activities. The impact of global warming to the two relevant emissions from livestock buildings, NH_3 and odorous substances, were investigated by examining a case study for fattening pigs. The assessment was performed by the simulation of the indoor climate and the related modification of the release of NH_3 and odour. The simulation of the indoor climate, instead of the meteorological parameters alone, is an appropriate tool to determine the impact of global warming on the emission of airborne pollutants in confined livestock buildings.

Because 1800 heads is a typical farm size in Central Europe, the presented results can be transferred to other fattening pig units at similar sites. Furthermore, the indoor temperature in such units will perform very similarly as the same limit values are often used for the ventilation control units. The results therefore show not only an episodic situation for Austria but the general trend which can be expected in the near future.

The impact of the global warming signals shows an increase of the NH_3 emission of confined livestock buildings. This increase lies in the range of about 4% which diminishes the reduction of 23% achieved between 1990 and 2015 by clean air activities. The distinct annual variation of the emission rate shows that a constant annual emission factor cannot be used to estimate the ambient NH_3 concentration by chemistry transport models.

The odour emission of livestock buildings was simulated for more than three decades to investigate the impact on the annual mean emission factor. In addition to meteorological factors, emission factors are relevant to calculating the separation distance to avoid odour annoyance. The economic consequences of odour was investigated by examining the separation area which is circumvented by direction dependent separation distances. The relative trend of the odour emission lies in the range of about +0.16% per year which gives an increase of about 3% between 1981 and 2017. The relative increase of the separation distances for the four cardinal directions is about 0.06% per year and the related increase for separation area is 0.13% per year. For this case study for fattening pigs it has been shown that the climate change signal has a negligible impact on separation distances. Therefore, the current and near future zoning and licensing of livestock buildings is based on reliable emission data.

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