

Odour emissions from a waste treatment plant using an inverse dispersion technique

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ABSTRACT

The determination of the in situ emission rate of pollution sources can often not be done directly. In the absence of emission measurements, the emission rate of the source can be assessed by an inverse dispersion technique using ambient concentration measurements and meteorological parameters as input. The dispersion model used is the Austrian regulatory Gaussian model. The method is applied to a thermal waste recycling plant. Seven chemical species (butyl acetate, benzene, ethyl acetate, toluene, m/p-xylene, o-xylene and α -pinene), are identified as odorants and measured over a period of 1½ years in the prevailing wind direction leeward of the plant. The overall odour emission rate is calculated by adding the odour emission rate of all single species, using the individual odour threshold concentration. The estimated odour emission rates range between 206 and 8950 OU s^{-1} , caused by the wide variety of the odour thresholds of the seven species. The higher value is in the upper range of odour emission rates of modern thermal treatment plants for waste.

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1. Introduction

Sometimes, in the case of an environmental survey of an industrial site, measured ambient concentration data are available but in situ emission data are not. One can then attempt to reconstruct the emission fluxes from the measured ambient concentrations leeward of the plant by an *inverse dispersion technique*. Shankar Rao (2007) gives an overview of the methodology and its application. The geographic scales of the application are wide-spread, starting from the local scale (Flesch et al., 2005; Thomson et al., 2007) over the meso-scale of some 10 km (O'Neill et al., 2001) up to continental distances (Issartel, 2003, 2005; Seibert and Frank, 2004; Shankar Rao, 2007). On a smaller scale, inverse dispersion modelling is used to locate gas sources (Thomson et al., 2007; Yee and Flesch, 2010), to quantify the emission rate of the pollution of area sources like agricultural settings (Flesch et al., 2005, 2007; Harper et al., 2009; McGinn et al., 2009), land-fills (Lehning et al., 1994; Sarkar and Hobbs, 2003), and to assess the release of chemical, biological and radiological agents (Guo et al., 2009; Zheng and Chen, 2010).

In the present example, concentration time series of various species emitted by a thermal treatment plant for waste which caused

a severe odour problem are available to reconstruct the emission rate. This plant consists of various buildings, situated in an industrial zone in a village in Southern Austria. Apart from the fact that the company running the plant refused to allow taking direct measurements of the emissions, such measurements would give only an estimate for one or a few single situations as systematic measurements would exceed reasonable expenses. The refusal of industrial site operators to allow measurements is an important problem for potential regulators. According to Austrian law, regulatory authorities can prescribe such measurements only if the magnitude or the production line of an existing plant is altered, causing changed or new emissions. Otherwise, no pressure on a company can be exerted to conduct such measurements, and alternative methods as the one described here are needed to assess the emissions.

By using long-term measurements of ambient concentrations leeward of the source, a characterisation of the emission is derived. An estimate of the odour emission is achieved by superposing the emissions of the seven species, an assumption justified by their frequently simultaneous occurrence.

2. Material and methods

2.1. Description of the waste recycling plant and the site

The thermal waste recycling plant is situated in the industrial zone of Arnoldstein, in the province of Carinthia in the South of

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Austria. The plant consists of various buildings. Other companies are situated in a distance up to 400 m in the North, East, and South of the thermal treatment plant (depicted as rectangle in Fig. 1).

The plant is approved for commercial and industrial hazardous waste. The waste, predominantly solid and paste-like, is shredded and conditioned to ensure a constant calorific value. This mix of materials is burned in one of two different thermal treatment devices (rotary (RF) and fluidised-bed furnace FBF). The exhaust air is conditioned by dry flue gas cleaning, scrubber, catalytic NO removal and activated charcoal filter. Typical emission concentrations are (RF: CO 1 mg m^{-3} ; SO₂ 7 mg m^{-3} , NO₂ 155 mg m^{-3} , TOC 1 mg m^{-3} , PM₁₀ 2 mg m^{-3} ; FBF: CO 10 mg m^{-3} , SO₂ 16 mg m^{-3} , NO₂ 26 mg m^{-3} , TOC 3 mg m^{-3} , PM₁₀ 1 mg m^{-3}). The maximum emission concentrations approved by the authorizing agency for both devices (RF and FBF together) are: CO 100 mg m^{-3} , SO₂ 50 mg m^{-3} , NO₂ 200 mg m^{-3} , TOC 10 mg m^{-3} , PM₁₀ 10 mg m^{-3} .

Arnoldstein is a small city in the West of Villach at the crossing of the two valleys Unteres Gailtal and Kanaltal. The plant is situated in the industrial zone between the rivers Gailitz and Arnoldstein. The measuring station is Eastnortheast (with an azimuth of 70°) of the plant, at a distance of about 950 m. The ambient concentrations and the meteorological parameters were measured at this station (Fig. 1). The wind was measured at 10 m above ground according to WMO standards.

2.2. Meteorological data

The orographic situation (Fig. 1) of the site is reflected in the distribution of the wind directions shown in Fig. 2. There are three prevailing wind direction sectors, of which the south-westerly

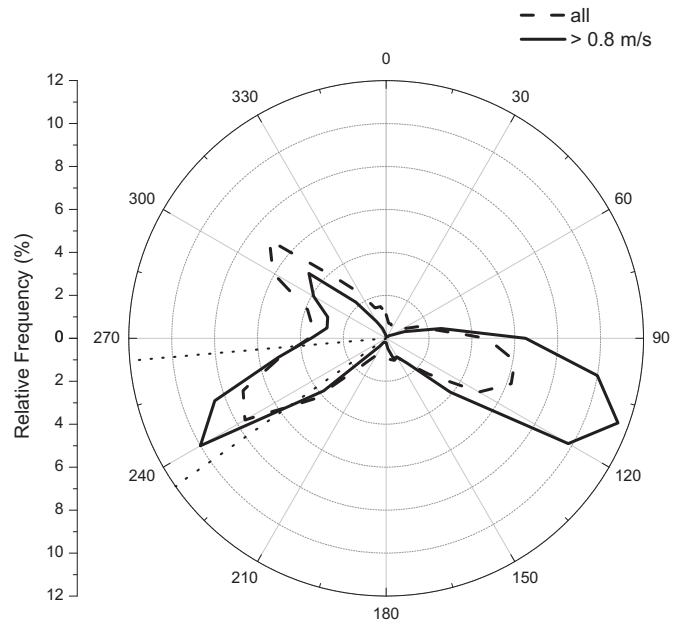


Fig. 2. Relative frequency (percent) of the wind direction for 10° sectors (all data, dashed line; for wind velocity above 0.8 m s^{-1} , full line) at the site Arnoldstein/Gailitz between 1.1.2005 and 22.8.2006. The sector of the wind directions ($235\text{--}265^\circ$) which is selected for the inverse dispersion technique is delimited by dotted lines.

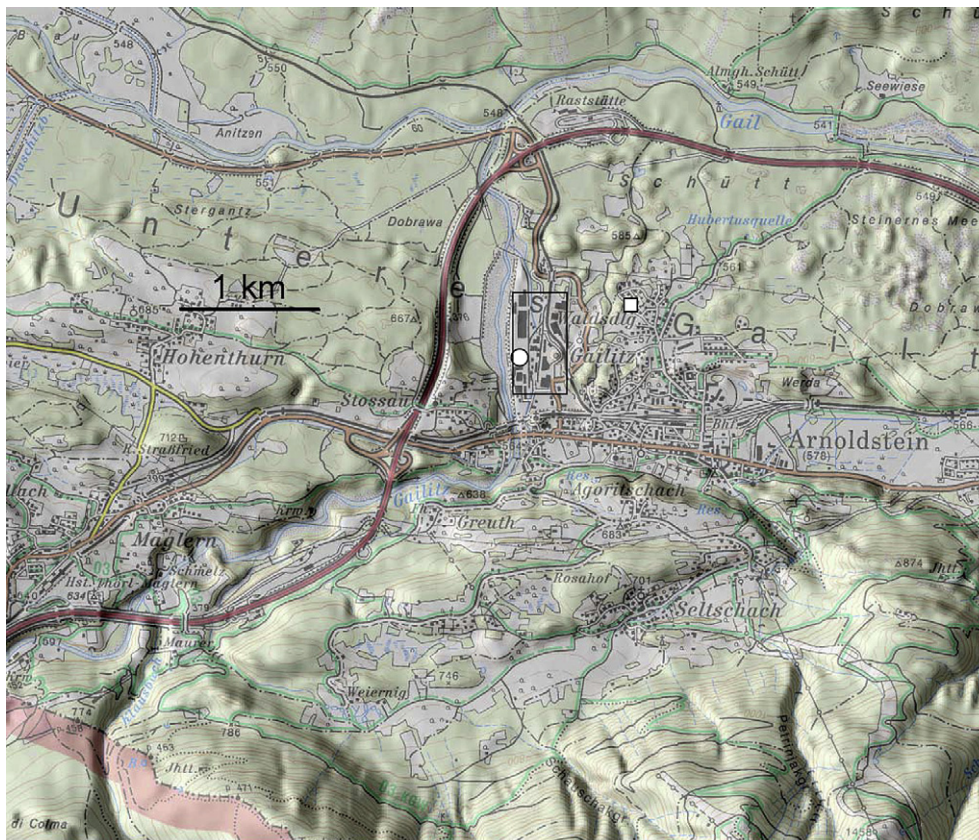


Fig. 1. Map showing the emission source (circle) in the industrial zone (rectangle) and the site (square) where the ambient concentrations and the meteorological data were measured. The distance between the emission source and the measuring site is approximately 950 m.

winds (235–265°) are most relevant for this investigation as the air pollution monitoring station is leeward of this sector. Wind speeds are fairly low, with weak winds less than 0.8 m s^{-1} amounting to 60% of all cases. This is a common value in Austrian basins south of the main Alpine chain, which, especially during autumn and winter, can show long periods of calms caused by the decoupling of the flow at higher levels from conditions near the ground. The connection between wind velocity and stability classes for Arnoldstein can be seen in Table 1.

Discrete stability classes have been determined based on sun elevation angle, cloud cover and low cloud base height, and wind speed (Reuter, 1970). Details of the scheme are given in Section 4.6 of Piringer and Joffre (2005); a discussion of stability classes determined by different methods is found in Piringer et al. (2007). Due to a lack of systematic long-term ultrasonic measurements at routine meteorological stations (as it is also the case for Arnoldstein), discrete stability classification schemes as the one described here are still in use. The cloud data are measured at Klagenfurt Airport, about 55 km from the site. This is the nearest station with available cloud data. In reality, cloud cover at Klagenfurt might differ from that at Arnoldstein in certain situations, especially in convective conditions during summertime or during fog in autumn and winter; Arnoldstein is expected to show less fog than Klagenfurt. However, the overall effect on the relative frequencies of stability classes for the whole year as shown in Fig. 2 will be negligible. Within the Reuter scheme, classes 2–7 can occur in Austria. Stability classes 2 (unstable) and 3 (slightly unstable), which by definition occur only during daylight hours in a well-mixed boundary layer, class 3 allowing also for cases of wind velocities up to 6 m s^{-1} and moderate cloud cover, together occur in 34% of all cases. Stability class 4 (neutral), representing cloudy and/or windy conditions including precipitation or fog, is by far the most common single dispersion category because it occurs day and night (33%). Wind speeds above 6 m s^{-1} occur with class 4 only. Class 5 (slightly stable) occurs with higher wind velocity during nights with low cloud cover, a situation which is not observed frequently at Arnoldstein (2%). Classes 6 (stable) and 7 (very stable) are relevant for clear nights, when a surface inversion, caused by radiative cooling, traps pollutants near the ground. Such situations occur in 32% of all cases. The occurrence of these stability classes is summarised in Table 1.

2.3. Ambient concentration measurements

Initially, it was necessary to characterise the composition of the chemical components of the emission of the thermal waste recycling plant. The chemical composition of the emission was identified by several probes of the outlet air of the plant. The following seven species were determined as the prevailing airborne pollutants

Table 1
Two dimensional frequency distribution of wind velocity and stability class for Arnoldstein.

Wind velocity (m s^{-1})	Stability class						
	2	3	4	5	6	7	All
0.0–0.7	5.4	10.6	18.7	0.0	10.5	13.7	58.9
0.8–1.4	4.5	4.1	3.3	0.0	1.8	2.6	16.3
1.5–2.4	3.5	3.1	5.8	1.0	1.6	0.7	15.7
2.5–3.4	0.9	1.0	3.2	0.7	0.6	0.0	6.4
3.5–4.4	0.2	0.5	1.3	0.1	0.0	0.0	2.1
4.5–5.4	0.0	0.1	0.3	0.0	0.0	0.0	0.4
5.5–6.4	0.0	0.0	0.2	0.0	0.0	0.0	0.2
>6.5	0.0	0.0	0.0	0.0	0.0	0.0	0
Sum	14.5	19.4	32.8	1.8	14.5	17.0	100

which are responsible for odour nuisance: butyl acetate, benzene, ethyl acetate, toluene, m/p-xylene, o-xylene and α -pinene.

These species were measured over a period of more than 1½ years between 1.1.2005 and 22.8.2006 at the measuring station in the ENE of the plant with an integration time of 30 min. 88.6% of all half-hour mean values were available for the analysis.

The VOCs (C_2 – C_{12}) are detected with the commercially available fully automatic gas chromatography unit of type airmoVOC 2010 (Airmotec). Parallel sampling is conducted on two adsorption lines with different adsorbent packages (C_2 – C_5 , C_6 – C_{12}). The VOCs are alternately enriched on 6 with Carbotrap and Carbosieve S-III packed adsorption tubes and desorbed at 350°C . While the sampled air is sucked into the tubes, the sample taken in the previous cycle is being desorbed. After desorption the sample is lead together with hydrogen (as a carrier gas) in a cooling trap (Cryotrap), which is cooled by relaxation of CO_2 down to -25°C . For further desorption, the cooling trap is suddenly heated to 350°C and the gas mixture is conducted on a capillar column of type DB-5 to separate the components. Detection is done by a FID. A sampling cycle takes about 25 min.

The instrument including the sampling system was calibrated with a certified standard mixture (Linde Austria) containing 12 different C_2 – C_{10} hydrocarbons. The relative uncertainty of the calibration gas was between 2 and 5%, depending on the species. The measurements were conducted by the environmental protection agency of the provincial government of Carinthia according to the guidelines of the Federal Ministry of Environment, which are based on the German Standard DIN 33963.

2.4. Inverse dispersion technique

The recalculation of the emission rate is done with the Austrian regulatory dispersion model (ÖNorm M 9440, 1996; Kolb, 1981). The regulatory model is a Gaussian plume model applied for single stack emissions and distances up to 15 km. Plume rise formulae used in the model are a combination of formulae suggested by Carson and Moses (1969) and Briggs (1975). The model uses a traditional discrete stability classification scheme with dispersion parameters developed by Reuter (1970). Meteorological input parameters to the model are half-hourly values of the wind direction, the wind velocity, and the stability class. The model has been validated for flat terrain with internationally available data sets (Baumann-Stanzer et al., 2008; Pechinger and Petz, 1995, 1997) and for complex terrain with a data set from the caloric power plant Trbovlje in Slovenia (Hirtl et al., 2007). An evaluation for the near field is reported in Piringer and Baumann-Stanzer (2009). All these evaluations show results for the Gaussian model which are mostly comparable to those of more complex models like Lagrangian or CFD models. A critical analysis of the use of the simple Gaussian model in the rather complex environment of Arnoldstein (Fig. 1) is given in the discussion section.

The emission rate Q (mg s^{-1}) was calculated from the measured ambient concentration at the measuring site C, the unity emission Q_0 and the corresponding ambient concentration C_0 according to the following equation (Flesch et al., 2005)

$$Q = C \frac{Q_0}{C_0} \quad (1)$$

The relation between the unit emission Q_0 and the corresponding ambient concentration C_0 is calculated by the dispersion model. The calculation of the ambient concentration C_0 of the unity emission Q_0 was performed for a point source with a height of 10 m without plume rise, to resemble the diffuse emission characteristics of the buildings as accurately as possible in respect of the model used. The back-calculation of the emissions is done under the

assumption that no other relevant sources emitting the seven defined species or odour exist windward of the measurement site.

The calculation according to the aforementioned equation was applied to every half-hour mean value for the entire time series of the meteorological parameters wind velocity, wind direction and stability class.

3. Results

In the following part the calculated time series of the emission of the seven chemical species is analysed.

3.1. Intermittence factor

An important parameter to describe the time series of ambient concentration measurements is the intermittence factor IF. This factor describes the fraction of values above a certain threshold. In many cases this threshold is assumed to be 0 or taken as the detection limit of the measurement device.

The intermittence factor for each chemical species is determined as a function of the wind direction (Fig. 3). For all species, the highest values are observed for the wind direction classes (class width 10°) 240°, 250° and 260°. Only these directions are therefore relevant for further analysis. In this way, 31% of the entire data set is taken into account.

To restrict the calculations to those cases where the centreline of the plume is close to the measuring site, only those wind directions are taken into account which lie in the sector between 235° and 265°.

3.2. Statistics of the emission rate

Table 2 shows the emission rate statistics for the seven species. The statistical analysis of the emission rates Q shows a good agreement with a log-normal distribution, with the mean value μ and the standard deviation σ . As estimators for these two parameters, the mean value MW_{log} and the standard deviation SD_{log} of the logarithmically transformed emission rate Q are used (Table 2).

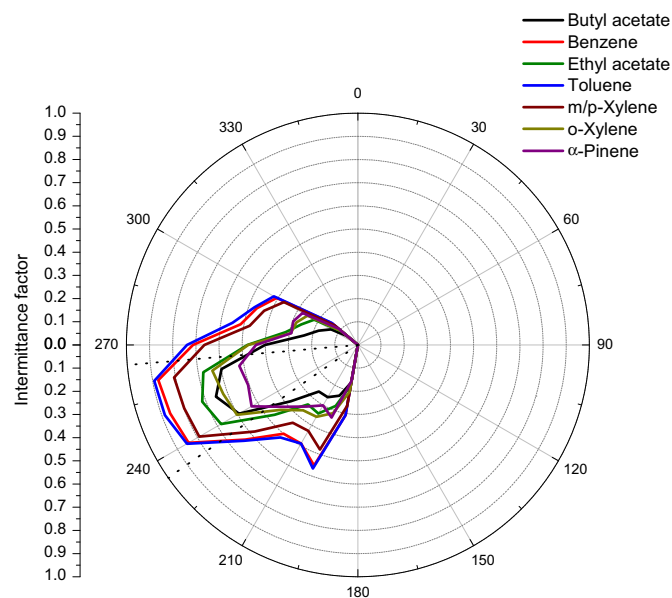


Fig. 3. Intermittence factor IF of the emission rates as a function of the wind direction for the seven species. The sector of the wind directions (235–265°) which is selected for the inverse dispersion technique is delimited by dotted lines.

Table 2

Descriptive statistics of the logarithmically transformed emission rates Q (mg s^{-1}) for seven species (MW_{log} mean value, SD_{log} standard deviation) (wind direction 235°–265°).

Quantil	Species						
	Butyl	Benzene	Ethyl	Toluene	m/p-Xyl	o-Xyl	α -Pinene
Maximum	5.801	4.491	4.833	5.121	5.417	4.362	4.732
0.99	3.864	3.339	4.026	3.875	3.655	3.362	3.587
0.98	3.687	3.192	3.778	3.683	3.460	3.125	3.398
0.95	3.426	2.933	3.434	3.433	3.192	2.824	3.176
0.90	3.125	2.699	3.125	3.187	2.921	2.598	2.965
0.85	2.950	2.522	2.949	3.000	2.745	2.420	2.803
0.80	2.824	2.394	2.803	2.875	2.617	2.265	2.681
0.75	2.657	2.276	2.651	2.749	2.494	2.134	2.524
0.70	2.539	2.173	2.511	2.646	2.377	2.018	2.398
0.65	2.420	2.079	2.398	2.522	2.262	1.919	2.276
0.60	2.314	2.000	2.279	2.415	2.155	1.820	2.176
0.55	2.223	1.919	2.193	2.320	2.068	1.708	2.064
0.50	2.112	1.839	2.097	2.223	1.959	1.602	1.957
0.45	2.007	1.756	2.013	2.124	1.863	1.519	1.875
0.40	1.903	1.663	1.903	2.025	1.763	1.431	1.799
0.35	1.792	1.556	1.813	1.929	1.672	1.322	1.699
0.30	1.672	1.447	1.699	1.813	1.556	1.230	1.613
0.25	1.547	1.322	1.580	1.699	1.455	1.114	1.491
0.20	1.398	1.146	1.438	1.556	1.322	0.954	1.380
0.15	1.204	0.954	1.230	1.398	1.167	0.778	1.230
0.10	0.954	0.699	1.000	1.204	0.954	0.602	1.041
0.05	0.699	0.477	0.699	0.903	0.699	0.301	0.778
0.02	0.477	0.301	0.477	0.699	0.477	0.000	0.477
0.01	0.301	0.000	0.301	0.477	0.301	0.000	0.320
Minimum	0.000	0.000	0.000	0.000	0.000	0.000	0.000
MW_{log}	2.091	1.779	2.101	2.214	1.960	1.617	1.995
SD_{log}	0.823	0.741	0.815	0.758	0.757	0.751	0.733

Butyl – Butyl acetate; Ethyl – Ethyl acetate; m/p-Xyl – m/p-Xylene; o-Xyl – o-Xylene.

To compare the relationship between the measured ambient concentrations, the meteorological parameters which modulate the dilution process in the atmosphere and the calculated emission, a short period (15.2.2006 11:00 to 16.2.2006 19:30) was selected to show these time series. In Fig. 4 the three meteorological parameters are depicted. The wind velocity is in the range between 0.4 and 5.3 m s^{-1} with a mean value of 3.0 m s^{-1} . The stability of the

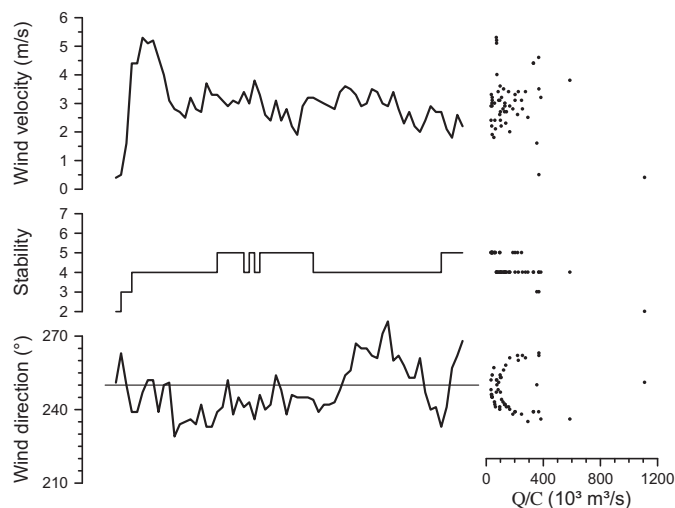


Fig. 4. Selected period (15.2.2006 11:00 to 16.2.2006 19:30) to demonstrate the time course of the three meteorological parameters which are used as input parameters for the dispersion model: wind velocity (m s^{-1}), stability of the atmosphere in classes according to Reuter (1970), and wind direction ($^{\circ}$). The direction from the source to the measuring site is indicated by a thin line. The scattergrams on the right side show the relationship of the three meteorological parameters to the ratio Q/C ($10^3 \text{ m}^3 \text{ s}^{-1}$). The ratio Q/C ($10^3 \text{ m}^3 \text{ s}^{-1}$) describes the dilution process of the atmosphere.

atmosphere shows a maximum (64%) in class 4 (neutral) and 32% for class 5 (slightly stable). The two remaining classes 2 (unstable) and 3 (slightly unstable) are in sum below 5%. The wind direction lies between 229° and 276°, with a mean value of 248°.

To show the influence of the meteorological parameters, the ratio Q/C between the calculated emission rate Q (mg s^{-1}) and the measured ambient concentration C (mg m^{-3}) is calculated (Eq. (1)). This ratio Q/C gives the air flow ($\text{m}^3 \text{s}^{-1}$) which is used to dilute the emission rate. This ratio is depicted for all meteorological parameters as a scatter plot (Fig. 4). The displayed Q/C ratio (e.g. Q/C versus wind direction) shows how Q/C changes with wind direction during the selected period. The highest value is found for the unstable situation (stability class 2) combined with a very low wind velocity of 0.4 m s^{-1} and a wind direction of 251° (which is the direction between source and measuring site). The wind direction shows a distinct influence on the ratio Q/C with a minimum for the centreline of the plume, which is marked by the thin line. This relationship depicts the influence of the lateral dilution of the plume. 95% of all values of this time series Q/C lie in the interval between 37×10^3 and $522 \times 10^3 \text{ m}^3 \text{ s}^{-1}$, respectively. In Fig. 5 the measured ambient concentration C (mg m^{-3}), the calculated emission rate Q (mg s^{-1}) and the ratio Q/C are shown for this selected time period.

3.3. Odour emission

Hitherto the seven chemical species are handled and analysed separately. As all these species are quite strong odouriphores their combination has to be taken into account to estimate the odour emission. As a working hypothesis the superposition of the single species is assumed. This means that the overall odour emission is calculated by adding the odour emission of all single species.

The simultaneous occurrence of the seven species is summarised in Table 3 showing that in the majority of all measurements, more than one species is detected (68%). In one third of the cases, all seven species are observed simultaneously; in $3/4$ of the cases 5 species are measured. Besides the coincidence of simultaneously measured species, the quantitative correlation of the species is analysed by a correlation and regression matrix (Table 4). The high correlation between the ambient concentrations of the species indicates that no other emission sources are strong contributors to

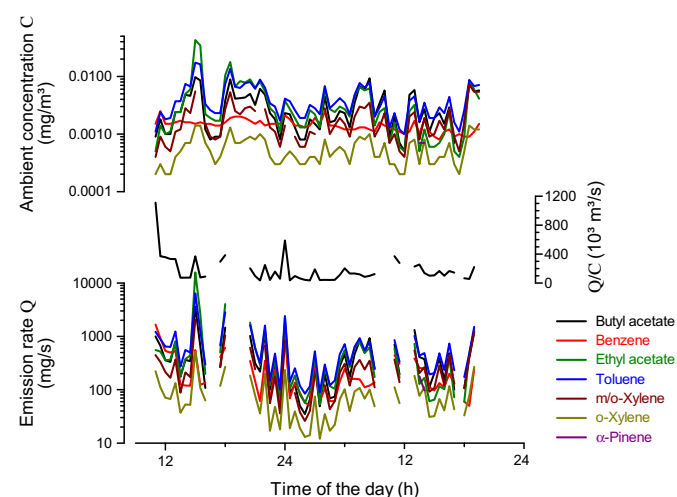


Fig. 5. Selected period (15.2.2006 11:00 to 16.2.2006 19:30) to show the time course of the measured ambient concentration C (mg m^{-3}) of the seven species as input for the inverse dispersion technique, the ratio Q/C ($10^3 \text{ m}^3 \text{ s}^{-1}$) calculated by the dispersion model, and the resulting emission rate Q of the source.

Table 3

Coincidence of simultaneously measured species (wind direction 235° – 265°).

Number of simultaneously measured species	Relative frequency (%)	Cumulative frequency (%)
1	2	100
2	4	98
3	8	95
4	12	87
5	16	75
6	27	59
7	32	32

this chemical suite. Even for benzene, omnipresent due to the emission by traffic, this influence can be neglected.

The correlation coefficient, for all combinations, takes on values between 0.819 and 0.973, all with a high significance ($p < 0.001$). The application of the superposition of all species to derive the odour emission is therefore reasonable.

In a literature research, the odour threshold concentrations of the seven species were surveyed (Table 5). For α -pinene, only one value could be found, for all other species, more references were available. In Table 6, the necessary constants are summarised. Two values of the odour threshold concentrations are used for the calculation of the odour emission, the lowest cited value C_{\min} and the mean value C_{mean} calculated by the geometric mean of all odour thresholds found. The odour threshold concentration (in $\mu\text{g m}^{-3}$) is the equivalent to 1 odour unit (OU) per cubic meter. Therefore the equivalent mass M of a certain species to 1 OU can be determined (e.g. for butyl acetate $C_{\min} = 30 \mu\text{g m}^{-3}$; the mass equivalent gives $M_{\min} = 30 \mu\text{g/OU}$).

Table 4

Correlation and regression matrix of the logarithmically transformed emission rates of the seven species (wind direction 235° – 265°) (Number of observations N , slope k , intercept d , correlation coefficient r).

	Species					
	Benzene	Ethyl	Toluene	m/p-Xyl	o-Xyl	α -Pinene
Butyl acetate						
N	2978	2978	2978	2978	2978	2512
k	0.739	0.941	0.859	0.876	0.817	0.685
d	0.232	0.159	0.529	0.238	-0.077	0.594
r	0.828	0.942	0.932	0.949	0.919	0.834
Benzene						
N		3352	4139	3859	2990	2512
k		0.903	0.876	0.861	0.857	0.817
d		0.489	0.670	0.433	0.087	0.622
r		0.819	0.856	0.840	0.852	0.866
Ethyl acetate						
N			3352	3352	2990	2512
k			0.849	0.851	0.817	0.689
d			0.511	0.235	-0.093	0.587
r			0.916	0.918	0.909	0.840
Toluene						
N				3859	2990	2512
k				0.973	0.930	0.776
d				-0.189	-0.533	0.283
r				0.973	0.946	0.859
m/p-Xylene						
N					2990	2512
k					0.945	0.783
d					-0.354	0.476
r					0.967	0.868
o-Xylene						
N						2512
k						0.807
d						0.733
r						0.889

Butyl – Butyl acetate; Ethyl – Ethyl acetate; m/p-Xyl – m/p-Xylene; o-Xyl – o-Xylene.

The ratios of the minimum concentration C_{\min} and the mean concentration C_{mean} are between 16 and 71. Only for ethyl acetate is the ratio 390. As for α -pinene only one odour threshold concentration could be found, a quotient of 30 (the mean value of the other species with the exception of ethyl acetate) is calculated for this species resulting in a C_{mean} of $3000 \mu\text{g m}^{-3}$.

Further on a time series of the odour emission OD (OU s^{-1}) was calculated. By using the mass equivalent M_{\min} out of the lowest odour threshold C_{\min} the maximum odour emission OD_{\max} was assessed. By using the mass equivalent M_{mean} out of the mean odour threshold C_{mean} the mean odour emission OD_{mean} was calculated

$$\text{OD}_{\max} = \sum_{i=1}^7 \frac{Q_i}{M_{\min,i}}$$

and

$$\text{OD}_{\text{mean}} = \sum_{i=1}^7 \frac{Q_i}{M_{\text{mean},i}}$$

The two resulting odour emission rates OD_{\max} and OD_{mean} were analysed analogously to the seven species. The calculated emission rate of odour represents a mean value for 30 min.

3.3.1. Statistical analysis of the odour emission rate

Each single species contributes to the odour emission rate in an additive way. The intermittence factor IF of the odour emission was determined with 1 (in Table 3 it can be seen that at least 1 species was observed for all half-hour values), which means that for all half-hour mean values an odour emission was observed.

In Fig. 6 the cumulative frequency of the relative contribution of each single species is shown for the two odour emission rates OD_{\max} and OD_{mean} . The graphs show that not all species have the same relevance for the odour emission of this plant. For the maximum odour emission rate ethyl acetate has the highest contribution, followed by butyl acetate and toluene. The share of ethyl acetate lies between 18% and 90%, whereas for example benzene lies between 0% and 20%. For the mean odour emission OD_{mean} the species with the highest impact is butyl acetate.

The extreme values, quantiles as well as mean values and standard deviations are presented in Table 7. The maximum values

Table 6

Chemical characterisation and odour threshold concentrations of the seven species used to calculate the odour emission of the plant.

	Species						
	Butyl acetate	Benzene	Ethyl acetate	Toluene	m/p-Xylene	o-Xylene	α -Pinene
Molecular formula	$\text{C}_6\text{H}_{12}\text{O}_2$	C_6H_6	$\text{C}_4\text{H}_8\text{O}_2$	C_7H_8	C_8H_{10}	C_8H_{10}	$\text{C}_{10}\text{H}_{16}$
Molar mass (g mol^{-1})	116.16	78.11	88.11	92.11	106.17	106.17	136.24
1 ppm = $x \mu\text{g m}^{-3}$	4716	3171	3577	3740	4310	4310	5531
Chemical Abstract Number (CAS)	123-86-	71-43-2	141-78-6	108-88-3	1330-20-7	1330-20-7	
Odour threshold concentration ($\mu\text{g m}^{-3}$)							
C_{\min}	30	507	21	80	216	216	100
C_{mean}	495	13,406	8191	5684	3497	3929	3000
Ratio C_{\min}/C_{mean}	17	26	390	71	16	18	30

are about a factor of 40 and 90 above the 0.99-quantile. Therefore these values are outliers and can be discarded.

4. Discussion

The advantage of analysing the emissions of a plant instead of the measured ambient concentrations is obvious. Ambient concentration measurements are a complex function of a number of factors including wind velocity, stability of the atmosphere, and source characteristics. These influences can be reduced by analysing the emission rate instead of the ambient concentrations. Environmental authorities are doing a lot of ambient concentration measurements to monitor the environmental status. In many cases these data are only representative of the site where they are surveyed. If meteorological data are available for a site, it is possible to reconstruct the emission rate of a certain pollution source.

The emission rate of the thermal treatment plant was calculated by a Gaussian dispersion model. In the light of the general availability of more sophisticated models, such as Lagrangian or Eulerian models or even CFD codes, the use of the Gaussian model in the present case has to be justified. The main reason of using the Austrian regulatory Gaussian model lies in the simple standard meteorological information available. This also justifies the use of discrete stability classes to characterise the turbulence state of the

Table 5

Overview of the odour threshold concentrations ($\mu\text{g m}^{-3}$) of the seven species.

Reference	Species						
	Butyl acetate	Benzene	Ethyl acetate	Toluene	m/p-Xylene	o-Xylene	α -Pinene
Brauer (1997)	850		65×10^3	6000	2700 – m; 9100 – p	23.6×10^3	
GIRL Brandenburg	30	16,200	22,000	7600			
HAZ MAP occupational exposure to hazardous agents	$283\text{--}34.9 \times 10^3$ (0.06–7.4)	$4757\text{--}15.9 \times 10^3$ (1.5–5)	$22.9 \times 10^3\text{--}179 \times 10^3$ (6.4–50)	$598\text{--}138 \times 10^3$ (0.16–37)	$345\text{--}172 \times 10^3$ (0.08–40)	$345\text{--}172 \times 10^3$ (0.08–40)	
Nagata (1990)	77 (0.016)	8562 (2.7)	3112 (0.87)	1234 (0.33)	m – 1767 (0.41); p – 250 (0.058)	1638 (0.38)	100 (0.018)
Center for Disease Control and Prevention		$4757\text{--}15.9 \times 10^3$ (1.5–5)		3740 (1)	4310 (1)	4310 (1)	
Office of the Environmental Health Hazard Office		2775		5980 (1.6)	4310 (1)	4310 (1)	
Smith (2002)		$507\text{--}1015 \times 10^3$ (0.16–320)	21–2454 (0.006–0.686)	10,800 (2.9) EPA 636 (0.17) CHRIS	m – 4741 (1.1) EPA o,m,p – 216 (0.05) CHRIS		
		4757 (1.5) EPA $2474\text{--}507 \times 10^3$ (0.78–160) AIHA		$636\text{--}150 \times 10^3$ (0.17–40.0) AAR	$862\text{--}17,242$ (0.2–4) AAR		
		$507\text{--}1015 \times 10^3$ (0.16–320) AAR 14.9×10^3 (4.7) CHRIS		$80\text{--}258 \times 10^3$ (0.021–69) AIHA	o,m,p – 349–23,276 (0.081–5.4) AIHA		

If a value was given in ppm this value is shown in brackets.

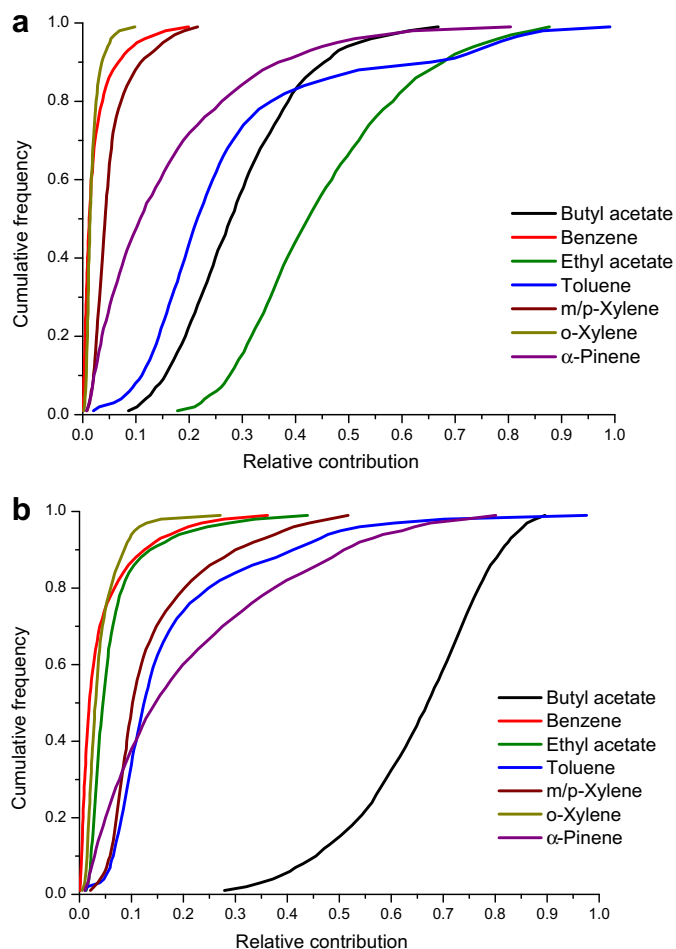


Fig. 6. Relative contribution of the single species to the maximum odour emission OD_{max} (a) and the mean odour emission OD_{mean} (b).

boundary layer. The use of more complex models will give better results only if the appropriate meteorological input is also provided. Three-dimensional ultrasonic anemometers e.g. deliver a direct measurement of the turbulent state via the sensible heat flux and the Monin-Obukhov length and can be used as input for some models like the Lagrangian model LASAT (Janicke, 2007). Such measurements were however not available at Arnoldstein. Other reasons to use the Gaussian model include the preliminary nature of the inverse modelling technique, the regulatory character of the model in Austria (at least in the near future) and other uncertainties in odour studies of which the use of the Gaussian model is not the largest one. In future, however, with the intended increased availability of data provided by ultrasonic anemometers, Sodar/RASS systems and ceilometers to derive the mixing height, the use of more advanced dispersion models will increase. This will lead to a more accurate calculation of C/Q by the aid of more direct meteorological input to the models.

A variety of meteorological selection criteria exist to assess the magnitude and quality of the re-calculated emissions, but only the wind direction is taken into account, reduced to a narrow sector of 30° between 235° and 265° . In these cases, the plume centreline is close to the measuring site. Other meteorological selection criteria like wind velocity and the stability of the atmosphere are not taken into account. Low wind speeds as well as very stable and very unstable conditions can deteriorate the accuracy of C/Q . According to Flesch et al. (2004) the single best indicator is the friction velocity u^* with a threshold between 0.15 m s^{-1} and 0.20 m s^{-1}

Table 7

Descriptive statistics (quantiles, arithmetic mean MW_{log} , and standard deviation SD_{log}) of the two logarithmically transformed odour emission rates OD_{max} and OD_{mean} (OU s^{-1}) for the wind sector 235° – 265° .

Quantile	Odour emission rate OD_{log} (OU s^{-1})	
	OD_{max}	OD_{mean}
Maximum	7.445	6.149
0.99	5.835	4.179
0.98	5.658	4.022
0.95	5.320	3.722
0.90	5.049	3.439
0.85	4.848	3.236
0.80	4.677	3.066
0.75	4.550	2.919
0.70	4.400	2.781
0.65	4.288	2.664
0.60	4.172	2.554
0.55	4.076	2.446
0.50	3.971	2.331
0.45	3.862	2.215
0.40	3.755	2.097
0.35	3.632	1.966
0.30	3.504	1.841
0.25	3.348	1.701
0.20	3.205	1.550
0.15	3.047	1.396
0.10	2.851	1.193
0.05	2.539	0.881
0.02	2.210	0.570
0.01	1.977	0.324
Minimum	1.097	−0.755
MW_{log}	3.952	2.314
SD_{log}	0.852	0.866

(McBain and Desjardins, 2005) to avoid low wind velocities below 1.5 m s^{-1} . Gao et al. (2009) suggest a combination of the friction velocity $u^* < 0.15 \text{ m s}^{-1}$ and the Monin-Obukhov length $|L| < 10 \text{ m}$ to avoid very stable and very unstable conditions. Flesch et al. (2009b) exclude a roughness length $z_0 > 1 \text{ m}$, to eliminate unrealistic wind profiles. As no ultrasonic anemometer measurements are available at Arnoldstein, the on-site dependence of u^* or L on the wind speed cannot be determined. This is a serious issue as more than half of all measured wind speeds at Arnoldstein are below 1 m s^{-1} . However, this possible uncertainty in emission estimates is probably overcome by the fact that the lowest wind velocity which is used for the recalculation by the Gaussian dispersion model is set to 1 m s^{-1} . This wind velocity is close to the suggested limit value of 1.5 m s^{-1} . The narrow wind sector avoids the uncertainty of the plume edge on the measuring site, which is caused by a high Q/C ratio (Flesch et al., 2005). Further on, this data selection increases the measured ambient concentrations which reduces the uncertainty of the model calculation (Flesch et al., 2007).

For the assessment of the odour emission flux, it is necessary to know the most important chemical compounds which contribute to the odour sensation of this source. In the industrial context it can be assumed that the composition will not change a lot. Nevertheless, it is important to find out the dominant chemical species. By an analysis of the outlet air these compounds can be determined. For the thermal waste recycling plant in Arnoldstein, seven compounds were identified: butyl acetate, benzene, ethyl acetate, toluene, m/p-xylene, o-xylene, and α -pinene. The high correlation coefficient r (Table 4) between the odourous species is a good evidence that the selected species originate from the same source. Even if benzene is an omnipresent species due to the emission by traffic, the high correlation for the selected wind directions (235° – 265°) is a good indication that the measured ambient concentrations originate predominantly from the thermal treatment plant for waste. This means that in this narrow wind sector the emission source was

“seen” by the measuring site which is according to Flesch et al. (2005, 2009a) important to increase the accuracy of the calculation. To calculate the odour emission rate we have to consider that the selected odourous species undergo no deposition or scavenging for the travel time we are interested in. A similar assessment of odour was done by Saral et al. (2009) for a municipal solid land fill using 22 VOC species and H₂S. Kabir and Kim (2010) used seven VOCs, among other species toluene and xylene to characterise the odourant emission of a large industrial complex. Muezzinoglu and Dincer (2005) used this method for a petrochemical complex in Louiseville, to compare odour complaints and ambient concentration measurements of about 20 species.

The odour threshold concentration of the seven species and the derived mass equivalent to cause an odour sensation is in the range of n-butanol (European reference odour mass EROM = 123 µg) which is used as reference species to calibrate olfactometric measurements (EN 13725, 2003). The uncertainties of the odour threshold concentrations of the seven species (Tables 5 and 6) described by the ratio of the minimum concentration and the mean concentration show values between 16 (m/p-xylene) and 390 for ethyl acetate. These values have to be compared to the accepted range of sensitivity of the panellists for olfactometric measurements according to the European standard (EN 13725, 2003), which lies between 62 and 246 µg (factor 4).

The two calculated odour emission rates result from the two selected mass equivalents M_{\min} and M_{mean} . The mean values of the two odour emission rates are 8950 and 206 OU s⁻¹, respectively, which is a discrepancy of a factor of 43. This is caused by the wide variation of the odour thresholds of the seven species. The higher value is in the upper range of emission rates of modern thermal treatment plants for waste, which, dependant on the capacity of the plant, lie in the range 1400–9000 OU s⁻¹.

If only a limited number of species are used to calculate the odour emission rate the result depends on the completeness of the selected species as components of the odour emission. If a species other than the selected ones contributes substantially to the odour emission, an underestimation of the odour emission rate can be expected.

The presented method can be applied in multiple ways:

- Retrospective analysis of the emission to monitor the consensus conform operation status of a plant, i.e. if the emissions meet or are below the maximum emission rate approved by the authorizing agency. For this purpose it is important to situate the measuring site for the ambient concentration in the lee of the source considering the prevailing wind direction.
- By situating the measuring site in between the source and the residential area, it is possible to control the impact of the emitted pollution to an area of interest. Due to the monitoring of the ambient concentration and an on-line recalculation of the emission it is possible to report alerts and to use a feedback for control purposes.
- If several sources contribute to the measured ambient concentration (a superposition of various sources) it is possible to discriminate between these sources by means of the inverse dispersion technique. In such cases it is important to situate several measuring stations in such an area.
- Odour surveillance can only be done by field inspection (VDI 3940 Part 1, 2006). Routine on-line ambient odour concentration measurements by an electronic nose are not technically mature compared to the methods used by environmental agencies. Further on, the ambient concentrations are, in many cases, below the detection threshold of such devices. It can be shown that, by using the species which contribute most to

odour sensation, the measurements of these compounds can be used to reconstruct the odour emission rate. This indirect method is an appropriate way to deal with odour in the same way as other chemical compounds.

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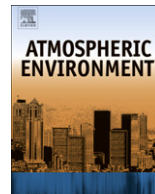
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Corrigendum to “Odour emissions from a waste treatment plant using an inverse dispersion technique [Atmos. Environ. 45, 1639–1647]”

The authors regrets that the x-axis was missing from Fig. 4. A correct version of the figure is now reproduced below.

The scattergrams on the right side show the relationship of the three meteorological parameters to the ratio Q/C ($10^3 \text{ m}^3 \text{ s}^{-1}$). The ratio Q/C ($10^3 \text{ m}^3 \text{ s}^{-1}$) describes the dilution process of the atmosphere.

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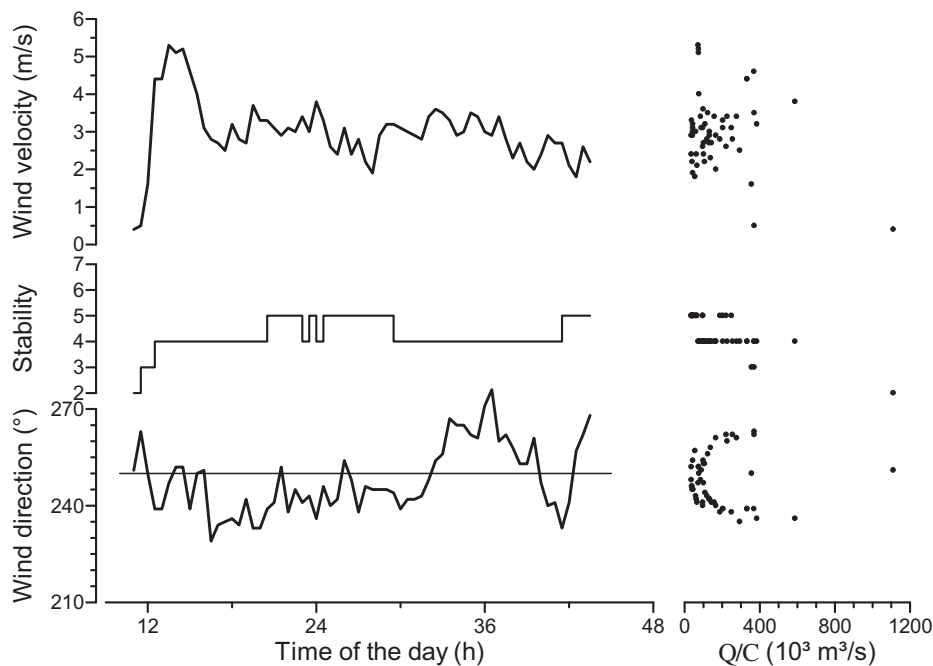


Fig. 4. Selected period (15.2.2006 11:00–16.2.2006 19:30) to demonstrate the time course of the three meteorological parameters which are used as input parameters for the dispersion model: wind velocity (m/s), stability of the atmosphere in classes according to Reuter (1970), and wind direction ($^{\circ}$). The direction from the source to the measuring site is indicated by a thin line.

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