7.1 ATMOSPHERIC DISPERSION OF ODORS AND GASES FROM ANIMAL WASTES

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1. INTRODUCTION

The rapid development of intensive livestock production systems using confined rearing methods, often close to residential areas, is causing severe environmental problems through the creation of concentrated sources of malodorous animal wastes. Odor problems arise again when the wastes are disposed of by application to agricultural fields. There are at least two needs: predicting concentrations for given source strengths, geometries and weather conditions, needed for planning and hazard assessment, and inferring source strengths from concentrations, needed for regulatory and control purposes.

More or less standard meteorological methods exist for predicting concentrations of odors or gases generated by large areal sources, and line and point sources, e.g., Pasquill and Smith (1983). These will not be examined here. A more serious problem in the context of residential development is dispersion from small, irregularly-shaped sources, like lagoons, slurries, piles and barns. The problem of predicting odor intensities and gas concentrations generated by such sources is addressed in the final section of this paper in discussion of a newly developed backward Lagrangian stochastic dispersion technique.

Most of this overview is concerned with measuring the strengths of small emitting sources, but it sidesteps what is perhaps the main problem in the field: how to quantify odor intensity. It assumes that the concentrations of odorous gases can be measured directly or estimated from the concentrations of some tracer gas dispersing with them. Usually, however, olfactory response is subjective and is due to a mixture of compounds including ammonia (NH_3), hydrogen sulfide (H_2S) and >100 volatile organic compounds. Setting of air quality standards by regulatory authorities, prediction of odor dispersion and attempts to mitigate odor emissions all require objective measurements of odor intensity. Much work is now under way on this topic, e.g., Hobbs et al., (1995), Zahn et al., (2001).

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2. INFERRING SOURCE STRENGTHS

Here, we consider the problem of inferring source strengths from concentration measurements. If the odor can be identified and measured on-line, the methods outlined below can be applied directly. NH_3 and H_2S are two such examples. It will often be the case, however, that odor concentrations are very small and /or difficult to measure on-line and we need to rely on a ratio technique. The source strength of a tracer gas dispersing with the odor, that has the same spatial source distribution and time dependence, is measured and the odor flux is calculated from the product of the tracer gas flux and the ratio of odor concentration to tracer concentration at the same separation from the source. determined periodically. Again, NH_3 and H_2S are likely tracers. Others could be carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). It can be shown that downwind of a change in surface flux, the change in concentration of the emitted scalar from its upwind concentration is directly proportional to the downwind flux. Assuming that odor and tracer are subject to the same atmospheric transport mechanisms and that both are non-reactive,

$$F_0 = (\delta\rho_o / \delta\rho_t) F_t \qquad (1)$$

where F_o and F_t are the fluxes of odor and tracer, respectively, and δc_o and δc_t are the corresponding concentration changes. Figure 1 (from a landfill study described by Denmead et al., 1998) provides confirmation of this. Figure 1a shows changes in the concentrations of methane (CH_4) and carbon dioxide (CO_2) at a height of 0.5m over a distance of 100m downwind of the leading edge of a landfill. The slope of the line (1.03) is the ratio of the two δs. Figure 1b shows the corresponding fluxes of the two gases. The slope of the line (1.04) is virtually the same as the ratio of the δs, confirming the validity of Eq.(1).

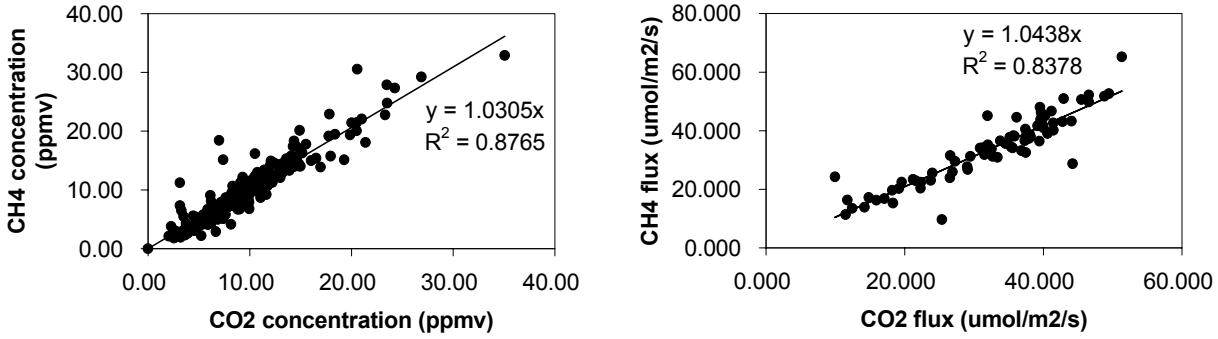

Figure 1 (left) Enrichment in the concentrations of methane and carbon dioxide, measured at 0.5m above ground, over a downwind distance of 100m in a landfill. (right) Simultaneous fluxes of CH_4 and CO_2 from surface of the landfill, after Denmead et al. (1998).

A similar argument can be made for the build-up in gas concentrations that occur in calm, stably-stratified, near-surface air at night, i.e., in the nocturnal boundary layer (NBL). The emission rate of the odor or targetgas can be inferred from the ratio of the simultaneous rate of increase of its concentration, measured at a convenient level in the NBL, to that of a tracer gas with a similar surface source distribution, whose rate of emission is known. Kelliher et al. (2002) used this approach to calculate emission rates of nitrous oxide from grazed pastures. They used CO_2 as the tracer gas. This NBL approach has much promise for linking odors and source strengths. Odor concentrations in the NBL will be much higher than by day, hence easier to quantify, and there are several likely tracer gases whose rates of emission can be measured e.g. CO_2, NH_3, H_2S, CH_4 and N_2O itself.

2.1 *Semi-infinite plane source*

For a large flat uniform source, such as a field where manure has been spread, standard micrometeorological flux measurement techniques apply. The flux of gas from the surface can be calculated from energy balance, aerodynamic, eddy correlation, or eddy accumulation approaches. Those techniques are well known and need no explanation here.

2.2 *Semi-infinite line source or semi-infinite strip*

Often, emissions from volatile wastes spread on the ground are short-lived and the problem is to define the time-course of the emission. Then, it may be more convenient to work with a smaller emitting area created by one or a few runs of an applicator than to wait for hectare sized areas to be created. In this case, we will be seeking solutions of the 2-dimensional atmospheric equation:

$$u\frac{\partial \rho}{\partial x} = \frac{\partial}{\partial z}\left(K\frac{\partial \rho}{\partial z}\right) \qquad (2)$$

where u denotes wind speed, ρ concentration, x horizontal distance downwind, z height and K the eddy diffusivity for the gas in question. It is difficult to obtain exact mathematical solutions for Eq. (2) for the usual logarithmic wind profile and a diffusivity that varies linearly with height, and numerical techniques are often employed. However, the use of power law profiles for the height dependence of u and K does lead to analytical solutions. Calder (1949) has presented solutions linking concentrations and source strengths for line sources, and Philip (1959) has done the same for semi-infinite strips.

2.3 *Small surface sources*

These are the sources of most concern and they can be the most difficult to handle because they may require 3-dimensional solutions. They include small plots, feedlots, effluent lagoons, slurry tanks and manure piles. At distances far enough from the source, they can be treated as point sources and their dispersion analysed by classical diffusion methods e.g., Pasquill and Smith (1983). Often, however, the concern is with concentrations close to the source, where conventional micrometeorological methods for linking concentrations and source strengths don't apply. Problems of this kind have engendered much innovation in the last few years, notably through the development of mass balance techniques and Lagrangian descriptions of atmospheric dispersion processes.

2.3.1 *Mass balance techniques*

Developed originally for inferring trace gas fluxes from small regularly-shaped agronomist's plots, mass balance methods of varying complexity can be applied to virtually any geometry, e.g., Wilson

et al. (1982), Denmead et al. (1998). Their basis is simple, depending only on the conservation of mass. The simplest situation to consider is a 2-dimensional one where the fetch *X* is fixed or calculable. Then, the net horizontal flux on the downwind edge of the emitting area can be equated with the surface flux within it, so that

$$\overline{F} = (1/X)\int_0^Z \overline{U}\left(\overline{\rho_x} - \overline{\rho_0}\right)dz \qquad (3)$$

where $\overline{F}$ denotes the average flux density within the area, ρ_X and ρ_0 are the gas concentrations on the downwind and upwind boundaries, and *Z* is the the height of the air layer affected by the emission. This approach, dubbed the integrated horizontal flux (IHF) technique by Wilson et al. (1982), is independent of atmospheric stability and requires no particular form for the wind profile. It has been used in many contexts relevant to the theme of this session, e.g., by Khan et al. (1997) to measure CH_4 emissions from stored cattle slurry and by Brown et al. (2002) to measure emissions of N_2O from a manure pile. A further simplification of the approach stems from the demonstration by Wilson et al. (1982) that for a given fetch and surface roughness, there is one particular height where the stable, neutral and unstable horizontal flux profiles intersect. Horizontal fluxes measured at that height are always in the same ratio to $\overline{F}$, regardless of atmospheric stability, so that measurements of *U* and ρ at only that height are all that is necessary to calculate $\overline{F}$. Wilson et al. (1982) call that height ZINST and provide nomograms for deducing both ZINST and the ratio of the horizontal flux there to $\overline{F}$. In order to keep the fetch, hence ZINST, constant, experimental plots should be circular with *U* and ρ measured at the plot centre. Pain et al. (1991) describe an application of the technique in which odor emissions were calculated from measurements of *U* and odor intensity at ZINST. The approach via ZINST is labelled the theoretical profile shape (TPS) method.

Denmead et al. (1998) describe a more elaborate, 3-dimensional mass balance approach in which vertical profiles of gas concentration are measured on N, S, E and W boundaries of a square of side *X* around the emitting area. When multiplied by the profile of wind speed, these yield profiles of the horizontal flux of the gas across each boundary. The difference between the integrated horizontal fluxes on downwind and upwind boundaries represents production in the emitting area. If we denote the rate of production by F_0, the vector wind speeds by *U(N-S)* and *V(W-E)* and gas densities by ρ_g, then

$$F_0 = X\int_0^Z \left[\overline{U}\left(\left\langle\overline{\rho}_{g_{S,z}}\right\rangle - \left\langle\overline{\rho}_{g_{N,z}}\right\rangle\right) + \overline{V}\left(\left\langle\overline{\rho}_{g_{E,z}}\right\rangle - \left\langle\rho_{g_{W,z}}\right\rangle\right)\right]dz \qquad (4)$$

In Eq. (4), *Z* is the height of the layer affected by the emission and is of order 0.1*X*, the overbars denote time means and the angular brackets spatial means. Harper et al. (1999) have used the technique to measure CH_4 production by cattle in small fields. The advent of open-path lasers and Fourier Transform Infrared Spectrometers that can measure spatially averaged concentrations of potential tracer gases such as NH_3, H_2S, CO_2, CH_4 and N_2O over distances of hundreds of meters promises to extend the usefulness of this approach considerably. Because of the long measuring path of these instruments, the problem can be reduced to measuring concentrations on only the upwind and downwind boundaries. The technique should prove particularly useful for measuring odor and gas emissions from lagoons, manure piles and buildings.

2.3.2 *Langrangian dispersion*

Flesch et al. (1995) describe a backward-time Lagrangian stochastic dispersion model (the bLs model) that calculates trajectories of air parcels backward in time from a sensor location to a specified source. It uses a large number of simulated releases to calculate the probability that parcels departing from the sensor will touch down within the source area thus permitting calculation of the contribution of the source to the horizontal flux of the emitted gas at the sensor. The input requirements are source geometry, surface roughness, atmospheric stability and the height and distance downwind of the sensor. The output is the ratio of the horizontal flux at the sensor to the mean emission rate within the source area. This allows emissions from sources of any geometry to be linked to concentrations at any location downwind. Thus, the model can be used for both measurement of source strengths and prediction of concentrations.

Figure 2 (from unpublished work of O.T. Denmead, D. Chen and J.R. Freney, 1998) provides examples of the use of the model. In this instance, both the bLs and the TPS methods were used to estimate NH_3 emissions from a fertilized field. The fertilized area was a circle of 95m radius. Measurements of wind speed, NH_3 concentration and atmospheric stability were made on a tower at the centre of the circle. NH_3 emission rates were calculated by an aerodynamic technique from the

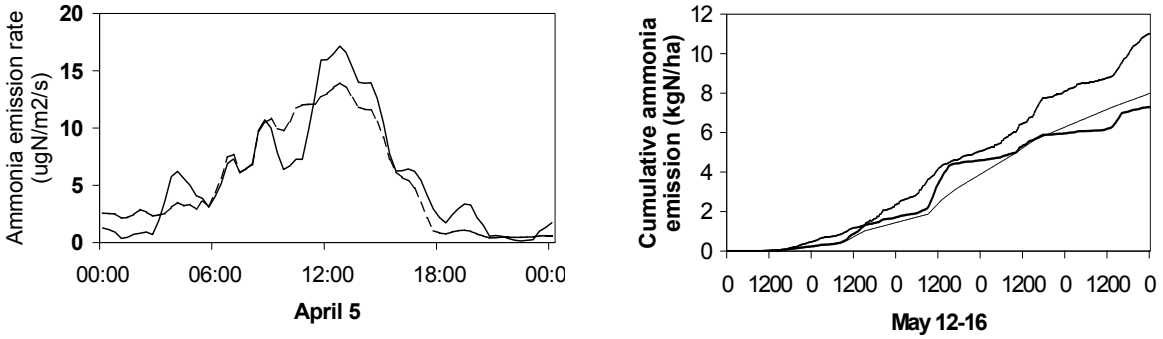

Figure 2. a (on left). Comparison of bLs-measured ammonia fluxes (dashed line) with those from an aerodynamic technique (solid line). b (on right). Comparison of cumulated bLs- and TPS-estimated fluxes, over 5 days, (solid line and light dashed line, respectively) with those calculated from an aerodynamic technique (heavy dashed line).

measurements at 0.26 and 1.1m, by the bLs method from the measurements at 1.1m, and by the TPS method from measurements at 2.9m. Figure 2a compares surface fluxes calculated by the aerodynamic and bLs methods over a 24h period, and Fig. 2b compares the cumulative fluxes measured by the 3 approaches. In both instances, the simplified 1-level measurement techniques provided very good agreement with the more complicated 2–level aerodynamic approach. Though not as simple in application as the TPS approach, the bLs model will be a very valuable tool in investigating dispersion from small irregularly shaped source areas because of its ability to predict both fluxes and concentrations.

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