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Comparing emissions from a cattle pen as measured by two micrometeorological techniques[☆]

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ABSTRACT

Accurate measurement of ammonia (NH_3) emissions from livestock pens is challenging. Two micrometeorological techniques, the integrated horizontal flux (IHF) and the backward Lagrangian stochastic (bLS) dispersion techniques were used to measure NH_3 emissions from an isolated cattle pen (20 × 20 m) in Victoria, Australia. The bLS technique is simple and insensitive to the presence of animals, but typically gives discontinuous measurements due to the need for target wind directions and wind conditions above accepted thresholds. In contrast, the IHF technique as implemented here gives near-continuous measurements with no restriction on wind directions. However, IHF needs more complex field measurements, and there are ambiguities when applied to an animal pen due to the presence of animals. Over the 29 days of our experiment, we collected 124 coincidental bLS and IHF emission measurements from the pen (30–min each). We found no statistical difference in the bLS and IHF calculations when the IHF turbulent flux correction factor (TF_{cor}) was set to 15%. Our results confirm that the IHF and bLS techniques, using independent sensors and having very different equipment layouts, gives nearly equivalent results. This suggests the choice of the two methods in future experiments can focus on their different strengths and weaknesses.

1. Introduction

Accurate quantification of gaseous emissions from livestock is challenging. While respiration chamber (McLean and Tobin, 1987) and SF_6 tracer (Johnson et al., 1994) techniques are widely used to measure enteric emission, and soil chambers (Denmead, 1979) are used for manure emissions, micrometeorological techniques have several advantages over these approaches. In particular, they do not interfere with the surface environment and they have the potential for continuous measurements over large surface footprints.

The integrated horizontal flux (IHF) (Denmead, 1995; Denmead et al., 1977; Harper et al., 2004) and the backward Lagrangian stochastic (bLS) dispersion techniques (Denmead et al., 2013; Flesch et al., 2007; Harper et al., 2011; Todd et al., 2011) are two micrometeorological techniques that have been used to measure emissions from cattle (both enteric and manure sources). The IHF technique is simple in principle, and works best for small and symmetrically shaped source areas (Laubach et al., 2012). The IHF technique measures the horizontal flux of gas past a tower and this flux is attributed to the emission rate from an upwind source area. Laubach et al. (2013) demonstrated the accuracy of the mass budget method (also called IHF technique) for measuring manure emissions from grazing cattle. In contrast, the bLS technique is based on a theoretical calculation of the dispersion of gas from a well-defined source area, so that with a measurement of a downwind concentration increase one can calculate the source emission rate. The bLS technique is flexible in handling complex source shapes, arbitrary measurement locations, and minimizes the needed field equipment, but it requires conditions where the dispersion model is accurate. Uncertainties in the bLS technique arise from factors such as atmospheric stability and both bLS and IHF techniques are affected by source area inhomogeneity. The objectives of this study are: 1) measure NH_3 emissions from an isolated feedlot cattle pen using IHF and bLS techniques; 2) assess the agreement between these two micrometeorological approaches by comparing the measured concurrent NH_3 emissions over the study period.

2. Materials and methods

This study was conducted 200 km north of Melbourne near Dookie (36.3° S, 145.7° E), Victoria, Australia. The experimental site was a flat short-grass field with a poorly drained clay soil. An

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isolated cattle pen (20 × 20 m) was constructed to mimic the environment of a cattle feedlot (e.g., bared soil surface, the stocking density of 17 m^2/cattle) (Fig. 1). The pen contained twenty-four Angus steers (*Bos taurus*, 6 months old, initial average live weight of 260 ± 24 kg) fed twice a day with a diet of 50% grain and 50% hay (13.5% crude protein, 12 MJ/kg dry matter (DM), 10.9 kg DM, and 255 g N/day). Ammonia emission measurements began on 4 September when cattle were introduced to the pen and ended in the morning on 2 October 2014 when cattle departed the fenced pen. The cattle were weighed and the accumulated manure were collected and recorded at the end of the measurement period. The prevailing winds during the experimental period were northeast and southwest, with the wind speeds of 0.3–6.1 m/s at a height of 3 m. The average minimum/maximum temperature ranged from 8 to 32 °C.

2.1. The bLS calculations

The bLS inverse-dispersion technique uses an atmospheric dispersion model (WindTrax) to calculate the relationship between the emission rate (Q_{bLS}) from the pen and the increase in gas concentration downwind of the pen (Eq. (1)):

$$Q_{bLS} = (C_{down} - C_{up})/(C/Q)_{sim} \tag{1}$$

where $(C/Q)_{sim}$ is a dispersion coefficient calculated by the WindTrax dispersion model. The $(C/Q)_{sim}$ calculation is based on wind and turbulence information in the form of the Obukhov stability length (L), the surface roughness (z_0), the friction velocity (u_*), wind direction (β), and wind statistics (σ_u/u_*, σ_v/u_*, σ_w/u_*), as described in Flesch et al. (2004).

The Q_{bLS} calculations are based on concentrations measured with an open-path Fourier transform infrared (OP-FTIR) spectroscopic concentration sensor (Bai, 2010). The OP-FTIR measures the average concentrations between the sensor and a distant retro reflector. The OP-FTIR system was set up approximately 40 m south of the cattle pen (1.40 m above ground level), and two retro reflectors were located to the east and west of the spectrometer, with a path length of 90 m between spectrometer and each retro reflector. The OP-FTIR spectrometer was coupled with a motorised tripod head (University of Wollongong, NSW, Australia), which enabled the spectrometer to be aimed at the two retro reflectors automatically. These configurations were designed to measure pen emissions during NNE-NNW winds (Fig. 1). Line-average concentrations of NH_3 in each path were measured sequentially at 2.5-min intervals, with a precision of 0.4 ppb in a 100 m path length. A three-dimensional (3-D) sonic anemometer (CSAT3, Campbell Scientific, Logan, USA) was located 123 m south of the experimental site at a height $z_{son} = 3.0$ m, and the wind components as well as ambient temperature and pressure were measured at a frequency of 10 Hz. Fifteen-minute intervals of u_*, L, z_0, β and wind statistics (σ_u/u_*, σ_v/u_*, σ_w/u_*) were calculated. Concentrations of NH_3 were processed into 15-min averages and merged with wind variables using SAS software (SAS 9.3, SAS Institute Inc. Cary, NC, USA).

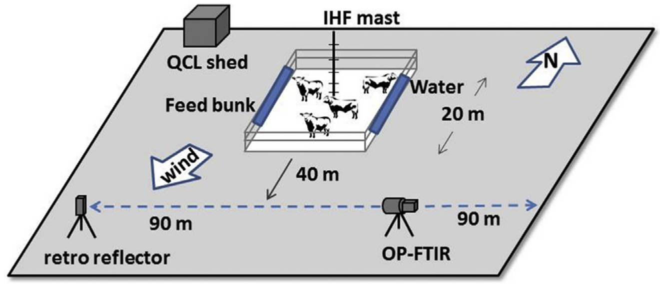

Fig. 1. Schematic of study site showing the experimental cattle pen and instruments. Integrated horizontal flux (IHF) mast is set up in the middle of cattle pen. Quantum cascade laser (QCL) shed is located 30 m north of pen, and 3-dimensional (3-D) sonic weather station is located 123 m south of pen. Figure is not in scale.

The concentration rise over background and the needed wind parameters were input into the WindTrax model (Thunder Beach Scientific, Canada). Following the data filtering procedure described by Flesch et al. (2014), we excluded observations when: the wind was light ($u_* < 0.05$ m/s), atmospheric stratification was extremely stable or unstable ($|L| < 5$ m), the surface roughness was unreasonable given the surface conditions ($z_0 > 0.5$ m), or the wind direction meant that the OP-FTIR was not in the downwind plume (southerly components or parallel to the measurement path, “touchdown” coverage < 30% of pen surface). The low u_* threshold (lower than that in many previous bLS studies) was chosen to increase the number of usable observations. Flesch et al. (2014) noted that a low u_* threshold will increase the number of erroneous outliers, but these will be offset by a large increase in good data. Measured OP-FTIR concentrations corresponding to poor spectra were also rejected (large variation in RMSresid, spec. max <0.15. The RMSresid is used to diagnose the noise level of fitted spectrum to real spectrum and identify the agreement between measured and calculated spectrums using MALT software, and the spec. max provides the signal intensity (Griffith, 1996)).

2.2. IHF calculations

The IHF technique is based on a measurement of the horizontal flux of gas past a measurement tower located in the centre of the source, as given by the height integration of the product of the average horizontal wind speed (U) and the gas concentration (C). Here U and C were measured at five heights ($z = 0.25$, 0.5, 1.0, 2.0, and 4.0 m) above the centre of the animal pen. The emission rate from the pen is calculated as the height integrated horizontal flux using a trapezoidal rule divided by the pen fetch x (the upwind distance from the tower to the edge of the pen using equation (Eq. (2) and (3)):

$$\mathrm{QIHF} = (1/\mathrm{x})\ [1/(1+\mathrm{TFcor})]\left[\frac{1}{2}(z_5 - z_4)(s_5 + s_4) + \cdots + \frac{1}{2}(z_2 - z_1)(s_2 + s_1) + \frac{1}{2}(z_1)(s_1)\right] \tag{2}$$

$$s(z) = u(z)\ \left(C_{pen}(z) - C_{up}\right) \tag{3}$$

In the above calculation we assume the unmeasured turbulent component of the horizontal flux is 15% of the mean flux (Denmead et al., 1998), and set the turbulent flux correction factor $TF_{cor} = 0.15$. In an IHF calculation, the emitted gas plume should ideally lie below our top measurement height ($z = 4$ m). However, we observed the concentration at this top height was often greater than the upwind value, indicating the plume extended above 4 m. We thus modified Eq. (2) and extended the “integration” height to $z = 6$ m, assuming the concentration at 6 m is C_{up}.

A quantum cascade laser (QCL) provided the NH_3 gas concentration measurements needed for the IHF calculations (Aerodyne Research, Inc. Billerica, MA, USA). The QCL measures NH_3 based on the absorption spectrum at mid-infrared wavenumber of 967 cm^{-1} at frequency of measurement of 1 Hz. This sensor has a reported precision of 0.04 ppb at 1 s and an accuracy of 0.1 ppb. The QCL sensor was kept in an air-conditioned shed (room temperature < 25 °C) located 30 m north of the cattle pen.

A 4-m high sampling mast was set up at the centre of