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Comparison of a backward-Lagrangian stochastic and vertical radial plume mapping methods for estimating animal waste lagoon emissions

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ABSTRACT

The long-term measurement of emissions from defined open area sources is needed to properly inventories annual emissions and assess regulatory compliance. Comparisons between the NH_3 emissions calculated using the Vertical Radial Plume Mapping (VRPM) method and a backward Lagrangian Stochastic (bLS) method were made using NH_3 concentration and wind measurements from eight livestock farms between 2006 and 2009. Concentration measurements were made along twenty optical paths using open-path tunable diode laser absorption spectroscopy. Wind measurements were made at three heights using three-dimensional sonic anemometers. Two concentration measurement configurations were evaluated: when the area source was surrounded by concentration measurements ('fenced') and when the concentration measurements were made perpendicular to the area source. The mean ammonia (NH_3) emissions from the eight farms ranged from 0.3 g s^{-1} to 2 g s^{-1} with the bLS-calculated NH_3 emissions on average 0.06 g s^{-1} (8%) lower than the VRPM-calculated NH_3 emissions in the perpendicular configuration and 0.04 g s^{-1} (5%) lower than the VRPM-calculated emissions in the 'fenced' configuration. There was great variability in the comparison farm to farm due to the wide range of atmospheric, measurement, and farm configurations. Variability in the mean difference between the two methods from farm to farm was less than the difference in calculated bLS emissions resulting from the measured turbulence from the source or the surrounding landscape. The overall mean difference between the bLS and VRPM emissions methods under optimal conditions was −0.05 g NH_3 s^{-1} (−5%). The variability in the VRPM NH_3 emissions (1.4 g^2 s^{-2}) was significantly different (F = 1.2) from the bLS NH_3 emissions (1.6 g^2 s^{-2}).

1. Introduction

The evaluation of emissions of various pollutants from specific sources is important to the inventory, assessment and regulation of pollution nationwide. Emissions from point sources are generally relatively easy to measure. However, the emissions from discrete open sources are often very difficult to measure due to their size and their complex interaction with the atmospheric boundary layer and, consequently, the error of estimation is significant. The determination of emissions from open area sources requires measurement of gas concentrations and a measurement of the transport of the gas such as wind speed or turbulence. Two models currently in use are the Gaussian plume fit Vertical Radial Plume Mapping: VRPM model (Arcadis Inc., Denver, CO) and the backward Lagrangian Stochastic (bLS) model (WindTrax; Thunder Beach Scientific, Nianamo, Canada, http://www.thunderbeachscientific.com).

The application of the VRPM model for various open area sources has been evaluated by a range of studies beginning around 1999 and codified by the US Environmental Protection Agency Other Test Method 10 (OTM-10). The VRPM emissions model, an integrated horizontal flux (IHF) method, calculates the emission from a defined source utilizing a measured wind speed profile and measured path-integrated gas concentrations (PICs). The VRPM method is an integrated horizontal flux method in its simplest configuration and a mass balance method when using measurement planes completely around the source (termed 'fence configuration'). The method utilizes multiple non-intersecting optical path(s) (OP) in vertical measurement planes upwind and downwind from an emission source. Multiple vertical scanning planes downwind of the source are used to directly measure the gaseous flux from defined sources under variable winds. The VRPM method assumes a bivariate Gaussian function to describe the distribution of mass across the vertical plane, and the parameters of the mass-equivalent bivariate Gaussian function(s) are reconstructed from the measured PIC

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values. These reconstructed parameters are then used to calculate the concentration values across the vertical (y–z) measurement domain at 2 m × 2 m resolution according to Hashmonay et al. (2008). The mean wind speed component perpendicular to the vertical plane at each height z is computed by linear interpolation between the three wind sensors with the mean wind speed from the top sensor up to the domain ceiling at 25 m set to the wind speed at the top sensor. The mean flux of pollutants for a time period through the vertical plane j of horizontal extent a is then determined by:

$$Q_j = \sum_{y=0}^{a}\sum_{z=0}^{25} \bar{u_z}\bar{c_{y,z}} \tag{1}$$

where c is the gas concentration. The measured fluxes for each vertical plane are then used to estimate the emission rate of the upwind source being characterized. Tracer release studies evaluating the accuracy of the VRPM method showed model accuracies using five OP and relatively stringent quality assurance criteria that varied widely: 21% ± 14% underestimated (Hashmonay et al., 2001), 6% underestimated (Hashmonay et al., 2008), 19% ± 33% underestimated (Thoma et al., 2010), 10% ± 16% overestimated (Ro et al., 2009), and 46% ± 26% overestimated (Ro et al., 2011). Studies indicate that variability in the wind flow across the measurement plane within an averaging period contribute to the underestimation of the emissions under highly unstable atmospheric conditions. Under conditions of poorly defined surface plume position, the method overestimates by 38% with a variability of ±28% (Ro et al., 2011).

The VRPM method typically uses mean wind profiles measured by cup anemometers. Within a turbulent environment, the instantaneous wind speeds and concentrations can be described by two components: a mean value and a deviation from the mean. Using the definitions of the two components, the flux across the vertical plane can be stated as:

$$Q_j = \sum_{y=0}^{a}\sum_{z=0}^{H} \left(\bar{u_z}\bar{c_{y,z}} + \overline{u'_z c'_{y,z}}\right) \tag{2}$$

where $\overline{u'_z c'_{y,z}}$ is the turbulent diffusive flux in the direction perpendicular to the plane. The cup anemometers used in the previously mentioned tracer studies do not measure the higher frequency turbulence due to the inertia of the sensor. However, if the mean wind profile is derived from sensors with a high frequency response such as sonic anemometers, there is a mismatch between the relatively slow response sensor measuring the gas concentrations and the fast response of the wind sensor. Consequently, the product of the mean values of each sensor do not represent the mean of the product of the individual measurements with differing time responses. The mismatch of sensors results in the measured mean advective flux including a turbulent diffusive flux (Eq. (2)) and the method inherently will overestimate the true mass flux (Denmead, 2008). The overestimate for homogeneous conditions was estimated at 5% to 20% (Denmead, 2008) with this error dependent on the degree of sensor mismatch and the spectral distribution of the turbulence.

More recently (since 2004), the WindTrax^{TM} bLS model has been evaluated but has not been codified by the USEPA. The backward-Lagrangian Stochastic (bLS) model calculates the emission from a defined source utilizing the measured turbulence statistics and the measured PIC. The model quantifies the relationship between a measured PIC and the average surface flux density across the source area ($F_{c,0}$) assuming the relationship is only a function of flow characteristics (Flesch et al., 2004). The relationship between a PIC and $F_{c,0}$ is based on simulated flight paths of air parcels backwards from the OP until each parcel intersects the ground (a 'touchdown'). The velocity vector of each air parcel is varied over each modeling timestep as a function of turbulence statistics for u, v, and w. The location of each parcel is calculated over a large number of timesteps. At some time, all parcels will impact the surface but not necessarily in the domain. The location of the impact and the vertical velocity at impact with the surface (w_0) are recorded and the parcel rebounds from the surface. If the parcel impacts the surface within the source domain area, then it contributes to the flux, while if it does not impact the surface within the source domain, the parcel does not contribute to the flux. The model calculates "touchdown catalogs" of x, y, and w_0 for each concentration measurement point j along the m OP ($m > 1$). The number of impacts within the source domain, weighted by w_0, divided by the number of parcels released from P equidistant points along each OP (here 30) provides the ratio a_i for each PIC. The program then calculates the best fit emission rate (Q) for each i PIC by solving the set of equations

$$\begin{aligned} a_i\,Q + PIC_{bg} &= PIC_i \\ a_m\,Q + PIC_{bg} &= PIC_m \end{aligned} \tag{3}$$

Using the standard Singular Value Decomposition algorithm where m is the number of OP and i designates the OP. Depending on the turbulence and source/sensor geometry, all sensors might measure some part of the source emission, and none are sure to provide the correct background concentration (PIC_{bg}) at any given time. The model calculated the C_{bg} since the number of measured PIC values (here 12 OP) was at least one greater than the number of unknown emission rates (one lagoon/basin).

Accuracy estimates for the bLS method from tracer studies vary with the number of OP used, the quality assurance criteria applied, and the positioning of the OP relative to the source. Studies using one OP and less stringent quality assurance criteria indicated a 2% ± 36% overestimate (Flesch et al., 2004) and a 36% ± 42% underestimate (Ro et al., 2011). Tracer studies evaluating the bLS method with more stringent quality assurance criteria showed higher model accuracies: 2% ± 24% underestimated using one OP and 7% ± 17% underestimated using three OP (Ro et al., 2011). These more stringent quality assurance criteria reduced the useful measurements by 78%.

Given the tracer-based bias of the VRPM method of +46% to −21% with a variability of 24% and tracer-based bias of the bLS method of +2% to −36% bias with a variability of about 30%, the comparability of the two methods is uncertain. Clearly the specific terrain, configuration of sensors, and atmospheric conditions strongly influenced the results. The purpose for this study is to compare and qualify the bLS emission measurement method relative to the codified VRPM emission measurement method for the measurement of emissions from lagoons and basins.

2. Methods

The measurement of emissions required the measurement of gas concentration and wind. The NH_3 PIC was measured using tunable diode laser spectrometers (TDLAS; GasFinder2®, Boreal Laser, Ltd, Edmonton, Canada). Two scanning, open path, monostatic TDLAS instruments were mounted on opposite corners of each monitored lagoon or basin with sides of length L (Fig. 1). Each instrument scanned five retro-reflectors on each of two adjacent sides of the lagoon or basin. Three OP extended from the TDLAS at 1 m above berm level (abl) and up to 10 m away from the lagoon/basin edge to retro reflectors at 0.3 L, 0.7 L, and 1.1 L located 1 m abl. In addition, two OP extended from the TDLAS at 1 m abl to retro-reflectors at 7 m above ground level (agl) and 15 m agl on a tower located at approximately 1.1 L (Fig. 1). This resulted in five OP down each of the four sides of the lagoon/basin. Assuming a lagoon with no elevation of the berm, the resulting mean scan path height associated with the highest retro-reflector (15 m agl) across the width of the lagoon is 7.5 m agl, This height is approximately the vertical standard deviation of a Gaussian plume under the slightly-unstable Pasquill stability class C (Hanna et al., 1982).