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Field Testing Two Flux Footprint Models

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Abstract. A field study was undertaken to investigate the accuracy of two micrometeorological flux footprint models when calculating the gas emission rate from a 10 x 10 m synthetic surface area source, based on the vertical flux of gas measured 15 to 50 m downwind of the source. Calculations were made with an easy-to-use tool based on the Kormann-Meixner analytical model and with a more sophisticated Lagrangian stochastic dispersion model. A total of 323 10 minute observation periods were measured over 9 days. On average, each of the two models calculated the emission rate to within 10 % of the actual release rate. No clear differences were observed between the two models in terms of overall accuracy.

1 Introduction

Micrometeorological techniques such as eddy-covariance and flux-gradient measure a vertical flux of gas in the atmosphere, which can be used to deduce the surface flux from an underlying area of interest. If the underlying surface is expansive and horizontally homogenous, the measured atmospheric flux and the surface flux can be considered equivalent (Dyer, 1963). However, if the area of interest has a limited spatial extent, or is located some distance from the atmospheric measurement, the relationship between the two fluxes can be complex, as the measured flux may be capturing a dynamic mixture of surface fluxes from both inside and outside the area of interest. In these cases, flux footprint modelling can be used to quantify the relationship between the measured atmospheric flux and the surface flux from the area of interest.

The analytical flux footprint model of Kormann and Meixner (2001), hereafter referred to as the KM model, is widely used to evaluate and interpret flux measurements taken over spatially limited surface sources. The KM model relies on a simplified representation of atmospheric transport (Schmid, 2002) in order to create an easy-to-compute footprint. It has been used to help quantify ammonia fluxes from fertilized plots (Spirig et al., 2010), interpret methane fluxes from heterogeneous peatland areas (Budishchev et al., 2014), and to reject periods where the footprint extends beyond the source of interest (Stevens et al., 2012). Other footprint models use a more realistic treatment of atmospheric transport (e.g., Kljun et al., 2002; Sogachev and Lloyd, 2004). Using a state-of-the-art Lagrangian stochastic (LS) footprint model, Wilson (2015) found a clear separation between the LS and KM footprints, depending on atmospheric stability and the distance from the measurement location. While more rigorous footprint models are clearly more defensible, the simpler KM model has the advantage of rapid analysis and the existence of software tools that make its application more accessible to non-specialists (Neftel et al., 2008).

This field study compares the accuracy of the KM footprint model with a more rigorous LS model. The motivation for this study was the question of whether the accuracy of the LS model was sufficiently better than the KM model, so as to justify the more complex LS application in interpreting the results from field studies. In this experiment we released gas at a known rate from a small synthetic area source and measured the vertical gas flux at a downwind location using the eddy-covariance technique. The KM and LS models were then used to calculate the source emission rate based on the measured atmospheric flux. The accuracy of those calculations is examined in this report.

2 Methods

2.1 Gas Release

The experiment took place on an extensive flat agricultural field at the University of Alberta’s Breton Research Farm, in Alberta, Canada (53° 07′ N, 114° 28′ W). Measurements were made after autumn harvest, and the surface was rye (*Secale cereale* L.) stubble having an average height of 3 cm. No obstructions to the wind were present within 250 m of the measurement site.

A synthetic source of carbon dioxide (CO_2) gas was constructed using 10 lengths of ½" (12.7 mm) diameter PVC pipe, each 10 m long. The 10 pipes were loosely positioned to create a nominal 10 x 10 m square source area. Compressed CO_2 gas (99.9 % purity) passed through a mass flow controller (Aalborg Instruments and Controls, Inc. Orangeburg, NY, USA) to a manifold (17 L) having outlets for each of the 10 pipes. Gas outlets of 1/16" (1.6 mm) diameter were placed every 50 cm along each pipe. We assumed equal flow rates from each outlet due to the high head loss across each outlet relative to the manifold pressure (e.g., Flesch et al., 2004).

The vertical CO_2 flux downwind of the synthetic source was measured using the eddy-covariance (EC) technique. The instrumentation included a fast-response CO_2/H_2O analyser (Li-7500DS, Licor Biosciences, Lincoln, NE, USA) and a sonic anemometer (CSAT-3, Campbell Scientific, Logan, UT, USA) placed at a height of 1.97 m above ground. The 10 Hz concentration and wind measurements were processed using the EddyPro® open source software (version 6.2.1 LI-COR Biosciences, Lincoln, NE, USA) to obtain 10 minute (min) average fluxes of CO_2. The software was run in express mode applying a double coordinate wind rotation, Webb-Pearman-Leuning correction terms for density fluctuations (Webb et al., 1980), and spectral corrections for inadequate high and low frequency response of the sensors (Moncrieff et al., 1997, 2004). Quality checks for steady state conditions and integral turbulence characteristics (Mauder and Foken, 2004) were used to exclude error-prone periods.

Gas releases took place over 9 days, with the center of the synthetic source positioned (Fig. 1) at one of three nominal distances from the EC system (i.e., fetches of 15, 30, and 50 m). Placement of the source relative to the EC system depended on the expected wind direction. Because CO_2 is naturally emitted from the landscape it was important that the synthetic CO_2 release rate be sufficiently high so as to create a measured atmospheric flux that was many times larger than that due to the natural landscape flux. Nicolini et al. (2017) found a CO_2 release rate of 22 L min^{-1} was sufficient to distinguish the release signal from background levels. Our situation was helped in that the experiment took place during the dormant autumn season when landscape CO_2 fluxes were small. Gas was released at rates between 30 and 90 L min^{-1}, with larger rates used for the larger fetches. Prior to any release interval, and immediately after each hour of gas release, a 30 min period of background CO_2 flux was measured. These background fluxes (which were consistently small) were subtracted from the EC-measured fluxes prior to undertaking the footprint analyses.

Our study consisted of more than 300 10 min flux measurement periods, and included periods of gas release, background flux measurements, and transitions when gas was released but a steady state plume may not have been established over the field site (we assumed this occurred 10 min after gas was turned on). There was a total of 125 valid gas release periods. From this total we excluded 66 periods from our analysis based on two broad factors:

- 19 periods were excluded for having wind conditions associated with unreliability in the EC measurements or the dispersion model calculations: light winds with a friction velocity $u^* < 0.05$ m s^{-1}, or an inferred roughness length $z_0 > 0.25$ m. A low u^* filtering criterion is often used in an EC analysis (e.g., Rannik et al., 2004) and in dispersion model calculations (e.g., Flesch et al., 2014). The z_0 filtering criterion indicates an unrealistic wind profile given the bare soil conditions of our site, and the likelihood of inaccurate dispersion model calculations based on the wind profile.
- 47 periods were excluded when the EC measurement location was not obviously in the source plume. This included periods when the EC measured CO_2 flux was less than zero, when the wind direction deviated more than 30 degrees from the line between the EC site and the source center, or when the LS footprint model (described below) indicated the plume may not have reached the EC measurement site (i.e., fewer than 1,000 of 1,000,000 backward trajectories released from the EC site reached the source).

These various quality control criteria eliminated over half of the gas release periods, leaving a total of 59 periods for the footprint analysis. The final data are summarized in the supplemental material accompanying this report.

2.2 Flux Footprint Models

2.2.1 Kormann and Meixner (KM) Model

The KM model is based on an analytical solution to the steady-state advection-diffusion equation, assuming simplified power-law profiles for windspeed and eddy diffusivity, and a crosswind diffusion component (Kormann and Meixner, 2001). We used the ART Footprint tool software (Neftel et al., 2008), which is based on the KM model, to calculate the synthetic-source emission rate (Q_{KM}, g C m^{-2} s^{-1}) based on the measured EC flux. The calculation uses the spatial outline of the source polygon, the EC measurement height (z_{EC}), the horizontal wind speed at z_{EC}, the friction velocity (u_*), the standard deviation of the lateral wind velocity (σ_v), and the Obukhov length (L). The wind variables were measured with the 3-D sonic anemometer (part of the EC system). In this study, the ratio of the KM-predicted synthetic emission rate to the actual release rate (Q_{KM} / Q) is the fundamental metric for model testing. A perfectly accurate prediction is $Q_{KM} / Q = 1$.

2.2.2 Lagrangian Stochastic (LS) Model

A state-of-the-art LS model was also used to calculate the emission rate from the synthetic source (Q_{LS}, g C m^{-2} s^{-1}) based on the measured EC flux. The predicted EC flux resulting from the synthetic emissions was calculated from the trajectories of thousands of model "particles" travelling upwind from the EC measurement point (backward in time). We follow the calculation procedure outlined in Flesch (1996) using the LS model detailed in Flesch et al. (2004). The model uses the wind velocity fluctuations in the three directional components (σ_u, σ_v, σ_w), the friction velocity (u_*), the Obukhov stability length (L), the average wind direction, and the surface roughness length (z_0). These properties were calculated from the 3-D sonic anemometer measurements. The LS calculations were made using 1,000,000 particles for each 10 min observation interval. A perfectly accurate LS model prediction will give $Q_{LS} / Q = 1$.

3 Results and Discussion

The overall average of the footprint calculations, expressed as the ratio of the model derived emission rate to the actual emission rate, are encouragingly close to 1 for both models: $Q_{KM} / Q = 0.97$ (0.08) and $Q_{LS} / Q = 1.08$ (0.11), with the standard error given within the parentheses. These averages are neither statistically different from 1.0 nor from one another (paired t-tests with $Ps > 0.05$). The period-to-period variability in the Q / Q ratios was relatively high, with an overall coefficient of variation (CV) near 1.0. This was variability was expected. The 10 x10 m source area is a small portion of the entire flux footprint. As opposed to larger areas, this small area will amplify the differences and the inaccuracies of the models, and also increase uncertainty (e.g., a larger source means increasing the spatial integration of the footprint function, which acts to increasingly constrain the numerical results, reducing model differences).

When examining the footprint agreements as a function of fetch (Fig. 2), we found the average Q_{KM} / Q is reasonably accurate at the shorter fetches of 15 and 30 m, but less accurate at 50 m. This trend towards underprediction of Q_{KM} / Q at the larger fetch is similar to earlier findings by Tallec et al. (2012) and Felber et al. (2015). Alternatively, the Q_{LS} / Q predictions are very good at the nearer fetch of 15 m and the further fetch of 50 m, but poorer at 30 m. Based on the modelling results of Wilson (2015), we had hypothesized that there would be substantial differences between the two models at the shorter fetch, with the LS model being more accurate due to its better representation of horizontal turbulent transport, which is important for defining the footprint at short fetches. While it is true that the LS model had excellent performance for the short 15 m fetch, our results do not fully support a conclusion that the LS model had better overall performance than the KM model, at least for the limited range of fetches studied in this experiment.

Examination of the emission calculations in terms of atmospheric stability, windspeed, and wind direction did not indicate any clear patterns in terms of affecting the relative accuracy between the two footprint models. In fact, our dataset does not consistently discriminate between the performances of the KM and LS models, despite the theoretical advantages of the LS model. We conclude that any systematic differences between the models in our study were obscured by the substantial period-to-period variability in *Q* / *Q* calculations (i.e., the overall CV for both models is close to 1.0). Detecting such differences would require an even larger sample size than the observations we were able to acquire (n = 323).

4 Conclusions

From an end-user's perspective, our results show that both the KM and LS models returned accurate flux footprint estimates on average (but with large period-to-period variability). Given the high variability of the flux footprint, we conclude that the easy-to-use KM model provides an accurate enough footprint tool that is simple and accessible to non-specialists. This study did not identify a clear benefit to using the more sophisticated LS footprint model.

Data availability

The data used in this analysis are available as supplementary material, or by request to Trevor.Coates@Canada.ca.

Author contributions

TC analyzed the field data and helped write the manuscript. MA design the experiment, and coordinated and collected the field data. TF helped with the experimental design and data analysis, and reviewed the manuscript. GHR helped with the experimental design and reviewed the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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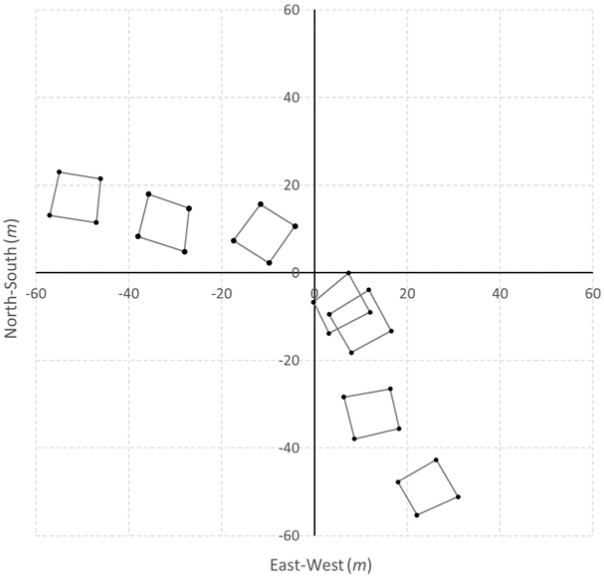

Figure 1: Map of the synthetic source locations used in the study (polygons). The eddy covariance system was located at position (0,0). Grid spacing is 20 m.

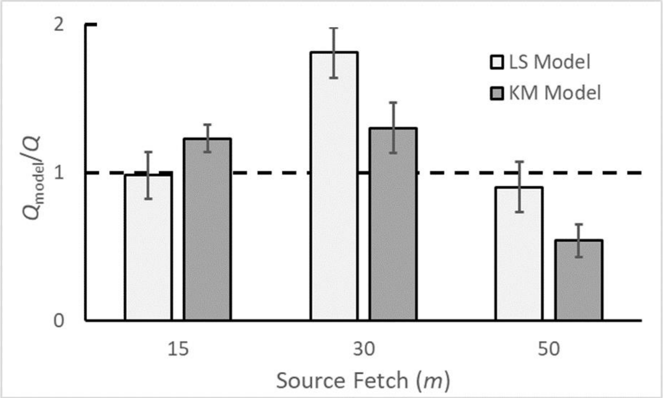

Figure 2: Agreement ratio of the footprint model calculated emission rate (Q_{model}) to actual release rate (Q), grouped by source fetch. Calculations are from the LS and KM models. The error bars represent the standard error of the mean. The horizontal dashed line represents a Q_{model} / Q ratio of one, or a perfect model calculation.