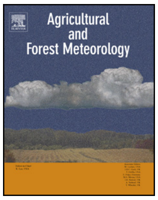
Agricultural and Forest Meteorology 225 (2016) 1–7

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Refining an inverse dispersion method to quantify gas sources on rolling terrain

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ARTICLE INFO

Article history:
Received 18 September 2015
Received in revised form 18 April 2016
Accepted 5 May 2016
Available online 19 May 2016

Keywords:
Agricultural gas emissions
Flux measurements
Greenhouse gas emissions
Inverse dispersion
Wind variation over rolling terrain

ABSTRACT

This paper analyses a trace gas dispersion experiment with multiple point sources and line-averaging laser gas detectors on gently rolling terrain. The objective of the experiment was to establish how well emission rate can be inferred by "inverse dispersion" (ID), using a Lagrangian stochastic wind transport model (WindTrax) that (strictly) is appropriate only in horizontally-homogeneous winds. Measured mean wind speeds at fixed height above ground revealed spatial variation of order ±10% over the site. However the results of the inversion to estimate source strength Q from the concentration field suggest that the unwanted impact of the terrain is adequately compensated by representing detector light paths as curves, approximating their true height above ground. Under that treatment the mean and standard deviation of the ratio Q_{IDM}/Q of inferred to true source strength, over an ensemble of 96 fifteen minute intervals, were respectively $\langle Q_{IDM}/Q \rangle$=1.04 and $\sigma_{Q/Q}=0.15$, with little distinction between outcomes under unstable and stable stratification. We also used the measurements to study the influence (on the accuracy of retrieved source strength) of discretionary elements of inverse dispersion procedure: data quality criteria; optimal placement of detectors relative to the source(s); and the impact of alternative spatial representations of the source, supposing one had but *partial* information in that regard. Because the sources were always rather close to the downwind detector, the quality of the inversions was less sensitive to extremes of stratification than has been reported for other trials. Inversions that treated the actual point sources as an aggregate area source proved acceptable, provided this was placed at or near the height of the (true) point sources. An idealized distribution of elevated point sources can also be satisfactory, but bad inversions may result if placement of the token sources is biased in the cross-plot direction relative to the actual source(s).

1. Introduction

This paper is concerned with the practicability of measuring gas exchange between small surface sources and the atmosphere by inverse dispersion (Wilson et al., 2012), specifically under the circumstance that an assumption of uniformity (horizontal-homogeneity) of the wind field cannot strictly be justified, and/or the spatial distribution of the source or sources is only partially determined. Though this does not restrict the generality of our findings, the context of the paper is the task of measuring agricultural gas emissions from some element of a farm such as a single paddock, or a group of confined animals or a waste lagoon; such types of measurements spurred the work, and the analysis of a trace gas dispersion experiment from point sources over gently rolling terrain will be central to what follows.

It is well known that vertical flux measurements by eddy covariance or by the flux-gradient method are feasible only at sites satisfying certain practical limitations (Denmead, 1995; Foken, 2008; Aubinet et al., 2012). For instance the flow itself needs to be (nominally, and in the statistical sense) horizontally uniform, in order that the needed assumption of a vanishingly small mean vertical velocity be justifiable; and the source needs to be sufficiently extensive as to generate a constant flux layer of the gas in question (equivalently, the flux footprint must not extend off the source). In addition eddy covariance requires the existence of a suitably rapid gas detector, while a flux-gradient method demands that small mean concentration differences along the vertical can be determined with adequate accuracy.

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http://dx.doi.org/10.1016/j.agrformet.2016.05.007
0168-1923/

An inverse dispersion method (IDM) relaxes some of these requirements. Defined briefly, using IDM one measures the mean concentration of the target gas both upwind ("$\bar{c}_u$") and downwind ("$\bar{c}_d$") from the source, along with necessary meteorological information (for example the mean wind direction $\bar{\beta}$, the mean wind speed U at one height ("reference speed"), the Obuhov length L and aerodynamic roughness length z_0), and one invokes an atmospheric dispersion model to infer the emission rate Q necessary to "explain" the observed concentration rise ($\bar{c}_d - \bar{c}_u$). The model provides a *theoretical* value for the dimensionless "conversion number"

$$n = \frac{U(\bar{c}_d - \bar{c}_u)}{Q} \tag{1}$$

that takes into account the meteorological conditions and the known information – which may be complete or partial – regarding the particulars of the source and its placement relative to the detectors. The estimated flux Q_{IDM} is determined from the measured information ("meas") as

$$Q_{IDM} = \frac{[U(\bar{c}_d - \bar{c}_u)]^{meas}}{n} \tag{2}$$

and ideally $Q_{IDM}/Q = 1$ where Q is the true emission rate, in general unknown.

In suitable circumstances IDM is a convenient method with good accuracy. It is not restricted to large sources and, unlike some other possible techniques such as flux chambers, IDM is or can be a non-interfering method in that sensors can be placed out of the way of farm operations. As a rough guide, when IDM is implemented according to established guidelines (Flesch et al., 2004) it is found that individual 15- to 30-min determinations of Q typically scatter around the truth with a standard deviation of about 20% or less, and a bias of no more than about 5%. In the past decade many groups have estimated agricultural gas emissions using WindTrax,[1] which facilitates IDM to compute the theoretical conversion number (n) defined by Eq. (1). For further background please see Wilson et al. (2012).

Below we describe a trace gas dispersion experiment that was executed on rolling terrain, using continuous point sources of equal strength (in aggregate, "Q") and known location (these nominally simulated a herd of cows), and with line-averaged concentrations measured upwind and downwind. We analyse the accuracy of inverse dispersion estimates ("Q_{IDM}") of the true source strength Q in relation to assumptions or adjustments one might hypothetically invoke to compensate for, or minimize the negative impact of: (a) deviation of the wind statistics from Monin–Obukhov similarity theory (MOST) due to topography, and (b) incomplete information or erroneous assumptions about the spatial structure of the source.

2. Theory and methods

In what follows (u, v, w) are the wind velocity components along coordinates (x, y, z), where x is the east–west coordinate increasing towards the east and y the north–south coordinate increasing to the north. Reynolds decomposition splits the local, instantaneous value of u into its mean and fluctuation as $u = \bar{u} + u'$, etc.

2.1. Lagrangian stochastic trajectory model (WindTrax)

A flux measurement by inverse dispersion can be based on any appropriate dispersion model. Lagrangian stochastic (LS) trajectory models compute the $\bar{c} - Q$ relationship (i.e. the conversion number n needed for use in Eq. (2)) by computing an ensemble of N_P representative turbulent trajectories connecting the detector and the source. For simplicity, and as here, it is usually assumed that wind statistics obey MOST, and specialized software (e.g. WindTrax) has been developed to facilitate inverse dispersion using "MO-LS." Numerous groups have applied MO-LS to deduce emissions from various sources, often in an agricultural or waste management context. Examples include emissions of ammonia or methane from barns (Harper et al., 2010), from fields (Sanz et al., 2010), from waste storage ponds (Flesch et al., 2013), from feeder cattle (Todd et al., 2011), from beef cattle (Laubach et al., 2008) and from grazing cattle (McGinn et al., 2011).

WindTrax adopts the LS model given by Thomson (1987) for vertically-inhomogeneous Gaussian turbulence (i.e. the probability density function for velocity is assumed to be Gaussian), a common choice for the atmospheric surface layer. Needed Eulerian quantities are the mean horizontal velocity components ($\bar{u}, \bar{v}$); the turbulent velocity variances ($\sigma_u^2, \sigma_v^2, \sigma_w^2$); the velocity fluctuation covariances ($\overline{u'v'}, \overline{u'w'}, \overline{v'w'}$); the turbulent kinetic energy dissipation rate (ε); and the surface roughness length z_0. With the assumption that MOST applies, measurements from a single sonic anemometer yield this needed information.

In the discussion below, wherever the inversion from observed concentration to inferred gas release rate has treated the source as a collection of *point* sources, $N_P = 5000$ trajectories were calculated forward from each source to the detector (i.e. WindTrax was used in forward mode). If the source was represented as an *area* source, however, backward mode was used with $N_P = 25{,}000$. These choices of N_P ensured that stochastic uncertainty in Q_{IDM} is negligible.

2.2. Site and equipment

In preparation for an inverse dispersion campaign to measure methane emissions from cattle, a tracer dispersion experiment was performed during August 2013 in "plot 22" at the Lacombe Research Centre (Agriculture and Agri-Food Canada, 52.457393 N, 113.765297 W). The topography and instrument layout at the site are indicated by Figs. 1–3; contours in Fig. (3) were derived from digital elevation files covering the township (TWP 40, ranges 27 and 26 west of the 4th meridian) that were purchased from AltaLIS ("LiDAR15 DEM", post spacing 15 m, vertical resolution 0.3 m). The mean roughness length at the site was about 0.08 m. The origin of the coordinate system used for WindTrax simulations coincides with the post in the SW corner of plot 22.

Eight point sources of tracer methane were distributed at known positions, within an overall area of about 20 m × 120 m (Fig. 2), in the gently rolling pasture. The distribution of the sources within a long, narrow area echoed the intended design for the eventual work with cattle, which was to ensure that for almost all mean wind directions $\bar{\beta}$ there should be markedly different upwind and downwind concentrations, despite the inevitable short term fluctuations of wind direction about the mean. The point of the tracer experiment was to evaluate the accuracy with which the inverse dispersion method would estimate the (in this case, known) emission rate Q, without accounting for any disturbance to the surface layer flow over the site: that is, WindTrax would be applied as if the terrain were perfectly flat and uniform, with the trajectory model driven by single point velocity statistics supplied by a sonic anemometer (Campbell Scientific CSAT3, operating at height $z = 1.97$ m), those statistics being height-extrapolated using Monin–Obukhov similarity theory. A set of matched cup anemometers measured the degree of spatial variation of the wind (see Section 2.3), but those data were not used in any way for the inversion of ($\bar{c}_u - \bar{c}_d$) to obtain Q_{IDM}.

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[1] "WindTrax" is a free software package written by B. Crenna that encodes forward and backward Lagrangian stochastic (LS) models into a graphical user interface (GUI), facilitating the application of the inverse dispersion method for small sources. It is applicable on the micrometeorological scale, and assumes the state of the surface layer is described by Monin–Obukhov similarity theory.