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ESTIMATION OF THE RATE OF GASEOUS MASS TRANSFER FROM A SURFACE SOURCE PLOT TO THE ATMOSPHERE

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Abstract—Using the predictions of a trajectory-simulation model of turbulent dispersion it is shown that the rate of gaseous mass transfer from a small (radius $R \leqslant 50$ m) disc-shaped source plot to the atmosphere may be calculated from measurements of mean cup windspeed $\bar{s}$ and mean concentration $\bar{c}$ at a single height ZINST, where ZINST is a function of roughness length z_0 and source radius R. This is an inexpensive and simple alternative to the use of a large (~ 300 m fetch) plot and eddy-correlation or profile measurements to determine the source strength.

1. INTRODUCTION

A problem which frequently confronts the agricultural meteorologist, the agricultural engineer, and the agronomist is estimation of the rate of loss of material from the ground to the atmosphere. Recently Denmead *et al.* (1974) and Beauchamp *et al.* (1978) have used micrometeorological methods to experimentally determine the rate of loss of nitrogen to the atmosphere (from grazed alfalfa pasture and from sludge applied to a bare field, respectively) and to relate the deduced source strength to other environmental variables. This paper proposes a very inexpensive and simple technique for the determination of surface source strength.

It is possible to estimate the loss from the surface $\overline{F}_z(O)$ from a knowledge of the vertical flux density $\overline{F}_z(z)$ at a plane z in the atmospheric surface layer above the source, obtained either directly, by the eddy correlation method, or indirectly, by profile methods. If there is no divergence in the horizontal of the horizontal flux and conditions are steady then

$$\overline{F}_z(O) = \overline{F}_z(z).$$

That this is so may be deduced by consideration of the rates of gain and loss from an imaginary box whose bottom is the ground, and whose top is formed by a plane at z.

The requirement of uniform horizontal flux implies that the experimental situation must be horizontally homogeneous—the measurement of $\overline{F}_z(z)$ must be made with a large upstream fetch of uniform conditions—uniform source strength, roughness length, wind field and turbulence. In practice a uniform fetch of the order of 300 m is necessary. If the profile or Bowen ratio method is used one must make assumptions such as equivalence of the eddy diffusivities for different additives, or equivalence of eddy diffusivities and eddy viscosity.

These difficulties may be avoided by the following radically different approach to the problem which has already been employed (Beauchamp *et al.*, 1978) but is described here for completeness.

Let the source be a disc of radius R over which the source strength $\overline{F}_z(O)$ is spatially uniform. Let the windspeed at (x, y, z, t) along directions (x, y, z) be (u_1, v_1, w_1), and define the instantaneous cup windspeed by $s_1 = \sqrt{u_1^2 + v_1^2}$. We are interested in the vertical profile of horizontal flux at the axis of the disc. Let us call this system 1 (see Fig. 1a). If there is no correlation between the instantaneous wind direction and the horizontal and vertical speeds, then we may consider all wind directions to be equivalent and to be equally effective in moving material from a given elementary annulus of the source (lying between r and $r + dr$) to the collector. We assume that the spatial and temporal correlation of the wind direction is sufficient that the effect of the changing wind direction is simply to position the observer at the origin at the same distance downwind of a changing segment of the source. Under this assumption trajectories from source to collector exhibit little lateral meandering, and system 1 is equivalent to system 2, which is defined as follows.

In system 2 the wind field is two-dimensional (u_2, O, w_2) with $u_2 = s_1 = \sqrt{u_1^2 + v_1^2}$ and with all statistics of w_2 identical to those of w_1. The vertical profiles of

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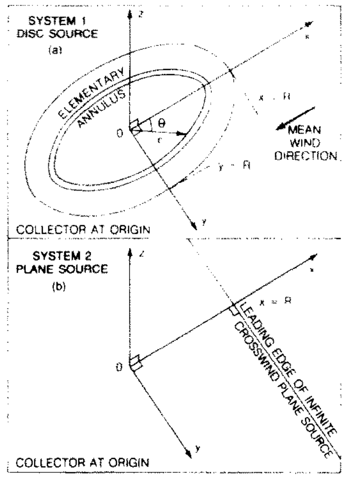

Fig. 1. (a), System 1. Schematic of a disc source at ground. The source is composed of elementary segments, labelled by r, θ of area $\mathrm{d}r \cdot r\mathrm{d}\theta$. It is assumed that there is no correlation between the instantaneous wind direction and the instantaneous horizontal and vertical wind speeds. The concentration profile is measured at the origin. (b), System 2. Schematic of a ground level plane source of infinite crosswind (y) extent and extending upwind from the origin to $x = R$. The windspeed in the y direction is zero (two-dimensional dispersion). The concentration profile is measured at the origin.

concentration and horizontal flux are observed a distance R downwind of the leading edge of a uniform plane source, again with spatially uniform source strength $\overline{F}_z(O)$, of infinite crosswind (y) extent (see Fig. 1b).

In system 2 all material emitted from the surface in a strip of width Δy running upstream from collector to leading edge must eventually pass the collector in a vertical strip of width Δy and of infinite vertical length. Whence the time average rate of emission from the surface strip equals the time average rate of passage through the vertical strip. Denoting a time average by an overbar, this equality may be expressed as

$$\overline{F}_z(O)R\Delta y = \Delta y \int_0^\infty \overline{F}_x(z)\,\mathrm{d}z.$$

The time average horizontal flux density at any level z is

$$\overline{F}_x = \overline{u}_2\overline{c}_2 + \overline{u_2 c_2} + \overline{u_2' c_2'},$$

where c is the admixture concentration and the prime denotes the instantaneous departure from the average value. Therefore

$$\overline{F}_z(O) = \frac{1}{R}\int_{z_0}^{\infty} \overline{u_2 c_2}\,\mathrm{d}z. \qquad (1)$$

The lower limit has been set at z_0, below which there is no horizontal motion. Assuming that $\overline{u_2' c_2'} \ll \overline{u}_2\overline{c}_2$ we may write

$$\overline{F}_z(O) \simeq \frac{1}{R}\int_{z_0}^{\infty} \overline{u}_2\overline{c}_2. \qquad (2)$$

Because system 2 is equivalent to system 1, (2) is also valid in system 1, with u_2 replaced by s_1 and c_2 by c_1. Therefore, according to the above reasoning, the surface flux to the atmosphere from a uniform disc source may be deduced by measuring the time average profiles of cup windspeed and concentration along the vertical at the axis of the disc and performing an integration on their product. If there is a non-zero background concentration $c_\infty(z)$ due to material (of the same species) other than that emitted by the source this must be subtracted from the measured profile before the integration is performed.

There are several advantages to this method. A long fetch of source is not necessary. There is no requirement for high frequency-response instruments or for concentration gradient measurements. Cup windspeed and (usually) mean concentration are relatively simple measurements. Troublesome assumptions about equivalence of diffusivities for different species are avoided—in fact the concept of eddy diffusivity is bypassed, since no need arises to relate fluxes to gradients.

The assumptions inherent in applying equation (2) to system 2 should be restated. They are:

(1) That the source strength is spatially uniform. If this is not the case one may correctly write

$$\langle \overline{F}_z(O)\rangle = \frac{1}{R}\int_0^R \overline{F}_z(O)\,\mathrm{d}x = \frac{1}{R}\int_{z_0}^{\infty} \overline{F}_x\,\mathrm{d}z,$$

where the angular bracket implies a spatial average. However it is stressed that the predictions given in section 3 assume a spatially uniform source.

(2) That $\overline{u_2' c_2'} \ll \overline{u}_2\overline{c}_2$. If it were feasible to measure the total horizontal flux $\overline{u_2 c_2}$ this approximation would be unnecessary and one could employ equation (1) to determine the source strength. However measurement of $\overline{u}_2$ and $\overline{c}_2$ is a simpler proposition. We cannot give a quantitative argument as to the validity of ignoring the turbulent horizontal flux but feel that it is likely to be of secondary importance except perhaps very near ground where the turbulence intensity is large.

In stating that system 1 is equivalent to system 2 (which is a two-dimensional system) a further assumption arises, which essentially states that the frequency distribution of travel times for material released from a source element defined by r, θ, $\mathrm{d}r$, $\mathrm{d}\theta$ and passing the axis between z and $z + \mathrm{d}z$ is independent of the angle θ. This assumption is made in order to allow the application of a two-dimensional model of turbulent dispersion (a model of system 2) in order to make predictions of the vertical profile of horizontal flux in system 1.

The vertical profile of horizontal flux at the centre of a source disc has been investigated using a two-dimensional trajectory-simulation (TS) model which has been demonstrated to be in good agreement with observations. It was found that for a given z_0 and radius R there exists a height ZINST at which the value of the normalised horizontal flux $\overline{sc}/\overline{F}_z(O)$, which is independent of u_*, is only slightly dependent on the value of the Monin–Obukhov length L. Therefore a measurement of $\overline{sc}$ ($\approx \overline{s}\overline{c}$ by assumption) at a single height ZINST (which must be chosen in accordance with the values of z_0 and R) in combination with the theoretical value of $\overline{sc}/\overline{F}_z(O)$ at ZINST is sufficient to determine $\overline{F}_z(O)$.

The advantage of reducing the experimental input required to deduce the source strength for system 1 from knowledge of the complete vertical profile of horizontal flux (with satisfactory resolution) to a knowledge at a single height is primarily that of simplicity, with an associated reduction in cost. To determine the complete profile it would be necessary to measure concentration up to large heights in unstable conditions, while the higher measurements would be unnecessary in stable conditions when the requirement is for closer spacing of measurements near ground. One would therefore be faced with the need for a large number of sensors (with associated hardware and manpower costs) or alternatively the need to alter the positions of sensors according to stability.

The following work will briefly describe the trajectory-simulation model, and clarify the assumptions underlying its use. Examples of the vertical profile of horizontal flux will be given for particular choices of z_0, R, showing the sensitivity of the profile to stability, L, and demonstrating how ZINST is chosen.

For $R = 20$ m, 50 m and over a range of z_0 from 0.05 cm to 5 cm, graphs will be given which present ZINST (z_0, R) and the predicted value of $\overline{sc}/\overline{F}_z(O)$ at each ZINST (z_0, R) for $L = \infty$ and $L = \pm 5$ m. For all L such that $|L| \geqslant 5$ m the value of $\overline{sc}/\overline{F}_z(O)$ lies between these limits. An example of the application of these graphs is given. The effect of uncertainty in the estimation of z_0 is tabulated in terms of its effect on the accuracy of the determined source strength.

2. THE TRAJECTORY-SIMULATION MODEL

Because the aim of this paper is not to convey the details of the trajectory-simulation model but to present a particular set of predictions, the method will be described only briefly. Full details are contained in papers by Wilson *et al.* (1981a,b,c).

The trajectory-simulation model has herein been applied to the motion of neutrally-buoyant particles for which the surface may be regarded as a spatially and temporally uniform source. The turbulence is assumed to be horizontally homogeneous.

The wind profile in the atmospheric surface layer is described by

$$\frac{kz}{u_*}\frac{d\overline{s}}{dz} = \phi_m\left(\frac{z}{L}\right),$$

where $L = -u_*^3/(k \cdot g/T_0 \cdot A/\rho c_p)$. ϕ_m is the Monin–Obukhov universal function for momentum, u_* is the friction velocity, k is von Karman's constant (0.4 used herein), g the acceleration due to gravity, T_0 a reference temperature, A the sensible heat flux (positive in unstable stratification), ρ the density of the air and c_p the specific heat at constant pressure. In unstable stratification ($L < 0$) $\phi_m = \left(1 - 16\frac{z}{L}\right)^{-1/4}$ (Dyer and Hicks, 1970). Integration gives

$$\overline{s}(z) = \frac{u_*}{k}\left[2 \arctan \phi_m^{-1} + \ln\left(\frac{\phi_m^{-1} - 1}{\phi_m^{-1} + 1}\right) - f(z_0)\right]$$

where

$$f(z_0) = 2 \arctan \phi_{mo}^{-1} + \ln\left(\frac{\phi_{mo}^{-1} - 1}{\phi_{mo}^{-1} + 1}\right)$$

and

$$\phi_{mo} = \phi_m\left(\frac{z_0}{L}\right).$$

In stable stratification $\phi_m = 1 + 4.7\,z/L$, (Businger *et al.*, 1971), which gives

$$\overline{s}(z) = \frac{u_*}{k}\left[\ln\frac{z}{z_0} + 4.7\frac{z - z_0}{L}\right].$$

In the simulation of a particle trajectory we have not included any turbulent fluctuation in the horizontal windspeed—horizontal movement occurs at a steady height-dependent velocity given by the appropriate formula above. For travel times which are long with respect to the local timescale the effect of s' tends to be averaged out, so that neglect of s' should cause only small errors in the horizontal flux predicted by the model—for this reason we have written the prediction as $\overline{sc}$ rather than $\overline{s}\,\overline{c}$.

A turbulent velocity w_L having the correct root-mean-square value (σ_w, the velocity "scale") and the correct Lagrangian timescale (τ_L, a measure of the persistence of the vertical velocity) is applied to move the particle along the vertical axis. It is assumed that

$$\sigma_w = 1.25\,u_*\left(1 + 4.1\frac{z}{-L}\right)^{1/3} \quad \text{for } L < 0$$

$$\sigma_w = 1.25\,u_* \quad 0 < L \leqslant +\infty \text{ (see Haugen, 1973).}$$

The Lagrangian timescale is chosen as

$$\tau_L(z) = 0.5\,z\left(1 - 6\frac{z}{L}\right)^{1/4}/\sigma_w(z), \quad \text{for } L < 0$$

$$\tau_L(z) = \left[0.5z\Big/\left(1 + 5\frac{z}{L}\right)\right]\Big/\sigma_w, \quad \text{for } L > 0$$

$$\tau_L(z) = 0.5z/\sigma_w, \quad \text{for } L = \infty.$$

This choice led to good agreement between predictions and the observations of Project Prairie Grass (SO_2 diffusion from a point source in the surface layer), (see Wilson *et al.*, 1981c). The trajectories were calculated in a transformed system in which the turbulence is homogeneous. This method is fully described by Wilson *et al.* (1981a) and the sole difference here is that the vertical velocity in the transformed (z_*) system was formed from a Markov chain rather than by sampling filtered Gaussian noise.

The source was always at z_0 and extended for a distance R upstream of the collection point. The only other detail which must be mentioned is that in unstable stratification a bias velocity

$$\bar{w}_L = \sigma_w(z)\, \tau_L(z) \frac{\partial \sigma_w}{\partial z}$$

was added to the turbulent velocity. This has been found to be necessary as a means of modifying the turbulent velocity distribution to correctly simulate motion when σ_w is height-dependent (Wilson *et al.*, 1981b).

Before presenting the predictions of the trajectory-simulation model it is worthwhile to restate the assumptions involved in its application to real problems.

(1) That one may neglect the effect of s', the instantaneous departure of the horizontal windspeed from its time average value without introducing serious error in the predicted horizontal flux density.

(2) That the important statistics pertaining to the turbulent vertical velocity which must be correctly incorporated in a simulation are σ_w, τ_L, and the spectrum used need not exactly duplicate the real world spectrum. This assumption is certainly valid in homogeneous turbulence (see Taylor, 1921; Pasquill, 1974).

(3) That if the given choice for τ_L leads to good agreement with the Project Prairie Grass data [for which all other inputs to the simulation were specified by the data set] it is a correct choice and is applicable to motion in any other horizontally homogeneous surface layer.

(4) That the chosen wind profile and velocity scale profile will closely represent reality.

(5) That a spatially and temporally uniform source strength is a satisfactory approximation.

3. ESTIMATION OF SOURCE STRENGTH FROM MEASUREMENTS OF WINDSPEED AND CONCENTRATION AT A SINGLE HEIGHT

Consider a source disc of radius 50 m at ground and let the roughness length be 1 cm. Specification of the friction velocity is unnecessary because it does not (on its own) affect the profile of horizontal flux. The trajectory-simulation method predicts that the vertical profile of horizontal flux normalised by source strength is a function only of L (for fixed z_0 and experimental geometry). Figure 2 presents the profile of normalised horizontal flux for neutral ($L = \infty$), very unstable ($L = -5$m), and very stable ($L = +5$m) stratification. In the top corner of the figure, on an expanded scale, are values of the profiles for other values of L at the level at which the profiles for $L = +5$m and $L = -5$m intersect. Let us call this level (where the intersection occurs) ZINST (z_0, R). Then ZINST (1, 5000) = 191 (all lengths in cm).

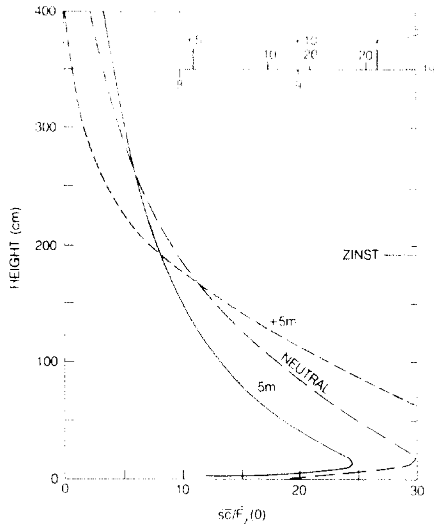

Fig. 2. Predictions of the trajectory-simulation model for the vertical profile of dimensionless normalised horizontal flux $\overline{sc}/\bar{F}_z(O)$ at the centre of a surface disc of radius $R = 50$ m. Roughness length $z_0 = 1$ cm. ———, $L = -500$cm; – – – – – –, $L = +500$cm and —·—, $L = \infty$. The height of intersection of the curves for $L = +500$cm and $L = -500$cm is labelled ZINST. At the top right of the diagram is an expanded scale showing the predicted values of the normalised horizontal flux at z = ZINST for other values of L (given in meters).

The expanded scale shows that at ZINST (1, 5000) all profiles with $|L| \geqslant 5$ m lie between the curves for neutral conditions and $L = \pm 5$ m. The spread between these limits, expressed as a % of the neutral value, is about 16 %. Thus without knowledge of u_* or L (which will usually have a magnitude exceeding 5 m), with a measurement of $\bar{s}$ and $\bar{c}$ at a single height, ZINST, we may deduce the source strength to within about 8 %. The experienced observer, having the ability to roughly guess whether $|L|$ lies near infinity or near 5 m, may do better. For many purposes, an accuracy of 8 % is adequate, and as the graphs to be presented will show, the uncertainty will often be less than this (decreasing with decreasing fetch because particles are then confined closer to the surface where buoyancy has little effect on the motion, and with decreasing roughness length, because the windspeed is accordingly higher, decreasing travel times and again confining material closer to the surface).

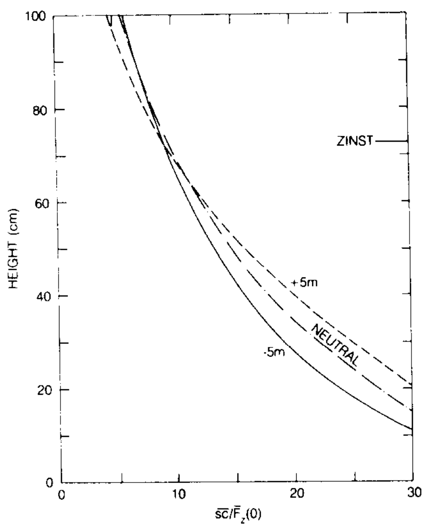

Fig. 3. Predictions of the trajectory-simulation model for the vertical profile of dimensionless normalised horizontal flux $\overline{sc}/\overline{F}_z(O)$ at the centre of a surface disc of radius $R = 20$ m. Roughness length $z_0 = 0.2$ cm. ———, $L = -500$ cm; – – – – – – –, $L = +500$ cm and —·—, $L = \infty$.

As a further example, Fig. 3 presents the normalised vertical profiles of horizontal flux for the case with $R = 20$ m, $z_0 = 0.2$ cm. Again, at ZINST(0.2, 2000), defined by the intersection of curves for $L = +5$ m and $L = -5$ m, all profiles with $|L| \geqslant 5$ m lie between the limits of the neutral profile and the $L = \pm 5$ m intersection. The source strength can in this case be deduced from a single measurement of $\overline{s}$ and $\overline{c}$ to within 4%. (Note that this figure of 4% for the uncertainty does not include errors due to deviation of the experimental situation from the ideal embodied in the assumptions of the TS model).

The reader may be surprised that at ZINST all profiles with $|L| \geqslant 5$ m lie within the limits given. It must be admitted that for $z_0 > 2$ cm this is not strictly so; there was found to be a very small deviation to values larger than the neutral case as $|L|$ was decreased from ∞, and that as $|L|$ further decreased, a return to a value within the specified limits occurred. However these excursions were very small, and since it would require a large amount of computing to exactly delineate the effect, we feel justified in considering it to be of secondary importance.

Figures 4 and 5 summarise the predictions of the trajectory-simulation method for $R = 20$ m and $R = 50$ m with $z_0 = 0.05$, 0.1, 0.2, 0.5, 0.75, 1, 2, 5 cm; space does not allow the presentation of the complete profiles of normalised horizontal flux for all these combinations of (R, z_0).

There is a statistical uncertainty in each of the generated profiles of horizontal flux which decreases in proportion to the reciprocal of the square root of the number of particles released. In the profiles summarised here, the uncertainty has been reduced to a very low level, but some smoothing of the profiles was still necessary. This is probably the cause of the small irregularities seen in Figs 4 and 5.

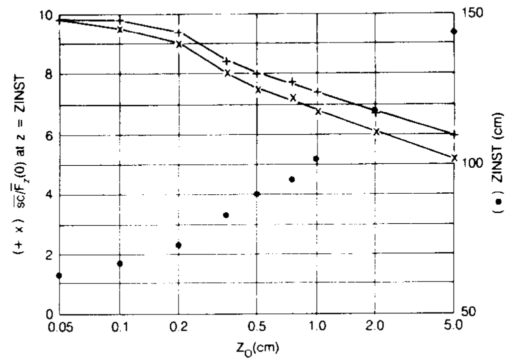

Fig. 4. Predictions of the dimensionless normalised horizontal flux $\overline{sc}/\overline{F}_z(O)$ at height ZINST (z_0, 2000) for a disc source of radius $R = 2000$ cm. •, values of ZINST vs z_0; +, values of normalised flux at ZINST for $L = \infty$ and ×, values of normalised flux at ZINST for $L = +500$, -500 cm.

Figures 4 and 5 are read as follows: for the given R, z_0 read off the value of ZINST (z_0,R). Then read off the upper and lower limits to the value of the normalised horizontal flux at z = ZINST. If you have values of $\overline{s}$ and $\overline{c}$ at ZINST and wish to deduce the source strength, write

$$\frac{(\overline{s}\,\overline{c})^{\text{measured}}}{\overline{F}_z(O)} = \left[\frac{\overline{sc}}{\overline{F}_z(O)}\right]^{\text{given on graph}}$$

then rearrange to obtain $\overline{F}_z(O)$, which will have the dimensions of $(\overline{s}\,\overline{c})^{\text{measured}}$.

Example. Urea has been applied on a disc of radius 50 m. The surface has roughness length 0.1 cm, de-

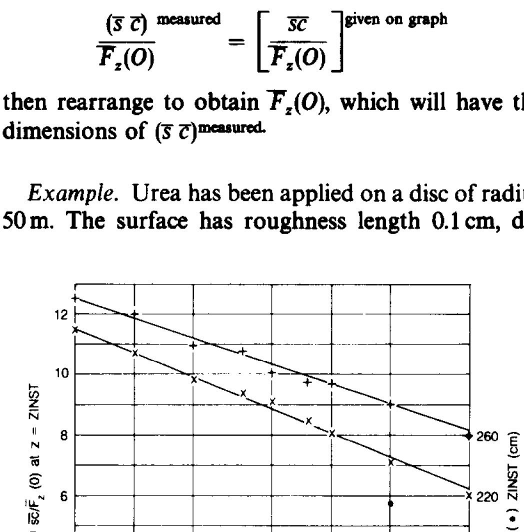

Fig. 5. Predictions of the dimensionless normalised horizontal flux $\overline{sc}/\overline{F}_z(O)$ at height ZINST (z_0, 5000) for a disc source of radius $R = 5000$ cm. •, Values of ZINST vs z_0; +, Values of normalised flux at ZINST for $L = \infty$ and ×, Values of normalised flux at ZINST for $L = +500$, -500 cm.

termined prior to the experiment. A measurement height z = ZINST(0.1, 5000) = 140 cm is chosen. On an overcast breezy afternoon ($L \approx \infty$) half-hour averages at 140 cm were: cup windspeed = 500 cm s^{-1}, NH_3 concentration = $2.5 \times 10^{-4}\ \mu g\,cm^{-3}$. Therefore

$$\frac{500 \times 2.5 \times 10^{-4}\ \mu g\,cm^{-2}\,s^{-1}}{\bar{F}_z(O)} \simeq 12.0$$

$$\bar{F}_z(O) \simeq 1.04 \times 10^{-2}\ \mu g\,cm^{-2}\,s^{-1}.$$

NH_3 is being emitted at a time average rate of $1.0 \times 10^{-2}\ \mu g\,cm^{-2}\,s^{-1}$. If the same values of windspeed and concentration were observed the next day under clear skies with hot sun and dry ground the estimated source strength should be increased by 10%.

The predictions given in Figs 4 and 5 may be modified for application to experiments over a short crop only if the displacement height, d, defined by fitting the above-crop neutral wind profile to the equation

$$\bar{s} = \frac{u_*}{k} \ln \frac{z-d}{z_o},$$

is sufficiently small that $\sigma_w \tau = 0.5\ (z-d)$ is a good approximation to the length scale above the crop in neutral conditions. Then if motion below d is ignored, and the source placed at $d + z_o$, the predictions given in Figs 4 and 5 may be applied directly with z everywhere interpreted as $z - d$, because the replacement of z with $(z-d)$ in all functions has no effect on the outcome of the simulations other than to displace the entire profile of horizontal flux upward by a distance d. One would choose a measurement height

$$\text{ZINST}'(z_o, R, d) = \text{ZINST}(z_o, R) + d,$$

and use the given value of the normalised horizontal flux. In the example given, had there been a measured displacement height of d = 10 cm (typical for a crop of height 15 − 30 cm) the concentration and windspeed measurements would be at z = 140 + 10 = 150 cm and one would again write

$$\frac{(\bar{c}\,\bar{s})^{\text{measured}}}{\bar{F}_z(O)} \simeq 12.0.$$

It is stressed that this treatment is only valid for a short crop ($d \lesssim 10$ cm). Measurements of the length scale in taller crops (Wilson *et al.*, 1982) have indicated that the length scale varies as $\sigma_w \tau \propto z$ both in and above the crop canopy so that the length scale immediately above the canopy is much larger than that given by $\sigma_w \tau_L = 0.5\ (z-d)$. And in a tall crop there is appreciable horizontal motion within the canopy which should not be ignored—a large proportion of the vertically integrated profile of horizontal flux may be contributed within the crop. Therefore to give information equivalent to Figs 4 and 5 for a tall crop one must first be able to correctly simulate the motion within the canopy where the turbulence statistics are quite distinct from the region above it. To date, this is not possible (see Wilson *et al.*, 1981b).

4. ERROR DUE TO UNCERTAINTY IN z_o

The assumptions underlying this technique have been clearly stated. It is intended now to allow the user to estimate the importance of errors which might arise through imprecise specification of z_o.

Let ZOFALSE be the value of z_o assumed (or measured) in order to choose the measurement height ZEXPT = ZINST(ZOFALSE, R). Let FNORM (z, z_o, R) denote the value of the normalised horizontal flux in neutral conditions for radius R, roughness length z_o, height z. If ZOTRUE is the correct (true) value of z_o, discovered (for the sake of argument) after the experiment has been performed, then

$$E^{R}_{\text{ZOFALSE}}(\text{ZOTRUE}) = \frac{\text{FNORM(ZEXPT, ZOTRUE}, R)}{\text{FNORM(ZEXPT, ZOFALSE}, R)}.$$

Values of this error ratio are given in Table 1, and curves of $E^{5000}_{\text{ZOFALSE}}$(ZOTRUE) for several values of the parameter ZOFALSE are given in Fig. 6.

The error ratio curves for 50 m radius are flattest and have value unity over the widest range for smallest ZOFALSE. This implies that if there is uncertainty as to the value of z_o, the smallest reasonable choice should be used.

Let us assume that in the example given in section 3, the value of z_o was in error (ZOFALSE = 0.1) and that in fact z_o = ZOTRUE = 0.5 cm. Looking at Fig. 6 (or Table 1)

$$E^{5000}_{0.1}(0.5) = 1.08 = \frac{\text{FNORM}(140, 0.5, 5000)}{\text{FNORM}(140, 0.1, 5000)}$$

$$\text{FNORM}(140, 0.5, 5000) = \frac{\bar{s}(140)\,\bar{c}(140)}{\bar{F}_z(O)} = 1.08 \times 12.0.$$

The estimate of the source strength for NH_3 must be decreased by 8%.

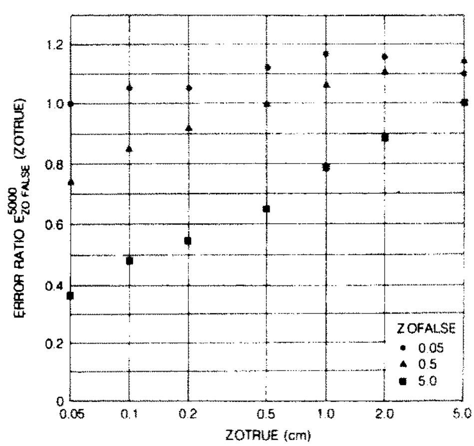

Fig. 6. The error ratio for a disc source of radius R = 5000 cm. The error ratio is defined in the text and may be used to estimate the effect of uncertainty in z_0 on the accuracy of the experimental determination of source strength using Fig. 5.

Table 1a. Values of the error ratio $E^{2000}_{\mathrm{ZOFALSE}}$(ZOTRUE). (Heights in cm, 20 m radius plot)

		ZOTRUE						
ZOFALSE	ZEXP	0.05	0.1	0.2	0.5	1.0	2.0	5.0
0.05	64	1.00	1.11	1.15	1.23	1.27	1.28	1.20
0.1	68	0.91	1.00	1.06	1.16	1.19	1.21	1.14
0.2	74	0.85	0.94	1.00	1.11	1.15	1.19	1.15
0.5	90	0.70	0.81	0.86	1.00	1.09	1.18	1.20
1.0	102	0.59	0.68	0.73	0.95	1.00	1.09	1.18
2.0	118	0.42	0.53	0.63	0.73	0.88	1.00	1.13
5.0	145	0.22	0.32	0.41	0.53	0.68	0.80	1.00

Table 1b. Values of the error ratio $E^{5000}_{\mathrm{ZOFALSE}}$(ZOTRUE)

		ZOTRUE						
ZOFALSE	ZEXP	0.05	0.1	0.2	0.5	1.0	2.0	5.0
0.05	129	1.00	1.06	1.06	1.13	1.17	1.16	1.10
0.1	140	0.92	1.00	1.00	1.08	1.13	1.13	1.08
0.2	156	0.86	0.98	1.00	1.08	1.18	1.16	1.18
0.5	180	0.75	0.85	0.90	1.00	1.12	1.13	1.16
1.0	198	0.62	0.68	0.78	0.90	1.00	1.02	1.08
2.0	215	0.56	0.64	0.75	0.86	0.97	1.00	1.09
5.0	260	0.36	0.48	0.55	0.65	0.79	0.89	1.00

5. CONCLUSION

The use of a disc-shaped source plot to overcome problems associated with estimation of loss from surface to atmosphere has been briefly discussed. The source strength may be obtained by performing an integration along the vertical of the horizontal flux at the axis of the disc.

A two-dimensional model of turbulent dispersion, described in full elsewhere, has been applied to this two-dimensional experimental geometry to generate and tabulate predictions which may be used to reduce the experimental input to a measurement of the horizontal flux at a single height (rather than the measurement of the complete profile). If the dispersion model is accurate, as is believed to be the case, these predictions allow a substantial reduction in the experimental complexity with little or no loss of accuracy. The closer the experimental situation matches that embodied in the assumptions underlying this technique, the more accurate will be the answers. Thus one would expect greatest accuracy when the turbulence is horizontally homogeneous, and the source strength spatially and temporally uniform. However even in cases where there is minor inhomogeneity in roughness length or source strength the method may be applied with the expectation of an answer which is of correct order of magnitude. Such an estimate may be quite satisfactory—for example if it yields the information that loss to the atmosphere is an insignificant term in the overall mass budget.

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