A Simulation of the Eddy Accumulation Method for Measuring Pollutant Fluxes

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ABSTRACT

"Eddy accumulation" is a variation of standard eddy correlation techniques for determining eddy fluxes by sampling air in two separate systems depending on whether the vertical velocity is positive or negative. In concept, the corresponding eddy flux is determined directly from measurements of the pollutant concentration (or accumulation) difference between the two sampling systems. In practice, the method has not yet been demonstrated for a slowly-depositing pollutant.

A numerical simulation of the eddy accumulation technique has been used to test the sensitivity of the method to errors arising from various sources, including sensor orientation, sampling limitations and chemical resolution. These tests were conducted using artificial pollutant concentration signals derived from real meteorological data (obtained above a forest canopy), in order to avoid the possibility of injecting unwanted errors by employing a poor quality pollutant signal. To detect a pollutant deposition velocity of 0.1 cm s^{-1}, it appears necessary to maintain linear sampling characteristics over a dynamic range corresponding to two orders of magnitude of vertical wind speed (the limits are approximately 0.05 σ_w and $5\sigma_w$ in any given condition, where σ_w is the standard deviation of the vertical velocity w), to maintain sampling zero offsets to less than $0.02\sigma_w$ of equivalent vertical velocity and to resolve chemical concentration differences amounting to about 0.4% in typical conditions.

1. Introduction

Heightened interest in the dry deposition of air pollutants has led to renewed discussion and development of the "eddy-accumulation"[1] or "integrated eddy correlation" method of flux measurement. This technique has been contemplated and tested for several decades and remains a matter of special attraction whenever sensors lack the rapid response characteristics required for true eddy correlation. In essence, the method involves the collection of two independent samples of air, one during updrafts and the other during downdrafts. A fast-response vertical wind sensor drives a sampling system having a similar rapid response characteristic, so that the sampling speed is proportional to the magnitude of the vertical velocity. Air is directed to two separate sample "accumulators," one each for updrafts and downdrafts.

Figure 1 outlines two typical configurations. Given a (perfectly sensed) vertical velocity signal $V = Aw$, where w is the instantaneous vertical wind speed and A is a calibration constant, the output of a perfect sampling system would be a sample flow rate $F = BV = ABw$, where B is the calibration coefficient of the pumping system. Here, A would have dimensions such as V, (m s^{-1}) and B, (m^3 s^{-1})/V; thus the flow rate F would be in m^3 s^{-1}. The two sampling systems would accumulate air for a period T, at the end of which the sampled volumes would be

$$\left.\begin{aligned} \mathrm{Vol}_\uparrow &= \int_0^T F\,dt, \quad w > 0 \\ \mathrm{Vol}_\downarrow &= \int_0^T F\,dt, \quad w < 0 \end{aligned}\right\}. \qquad (1)$$

By conservation of mass, $\mathrm{Vol}_\uparrow = \mathrm{Vol}_\downarrow$ over a long sampling time (30–60 min) and over flat, homogeneous terrain, if $F = 0$ when $w = 0$. The amount of pollutant contained in each sampling system is

$$\left.\begin{aligned} \mathrm{Acc}_\uparrow &= \int_0^T F \times C\,dt = AB \int_0^T w \times C\,dt, \quad w > 0 \\ &\text{and similarly,} \\ \mathrm{Acc}_\downarrow &= -AB \int_0^T w \times C\,dt, \quad w < 0 \end{aligned}\right\}. \qquad (2)$$

From (2), it is clear that we can express the conventional eddy flux EF as

$$\mathrm{EF} = T^{-1} \int_0^T w \times C\,dt = (TAB)^{-1} \times (\mathrm{Acc}_\uparrow - \mathrm{Acc}_\downarrow), \qquad (3)$$

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[1] The term "eddy accumulation" seems to have been popularized in an EPA workshop report: Hicks, B. B., M. L. Wesely and J. L. Durham, 1980: Critique of methods to measure dry deposition. Workshop summary, available from NTIS as PB81-126443 (69 pp).

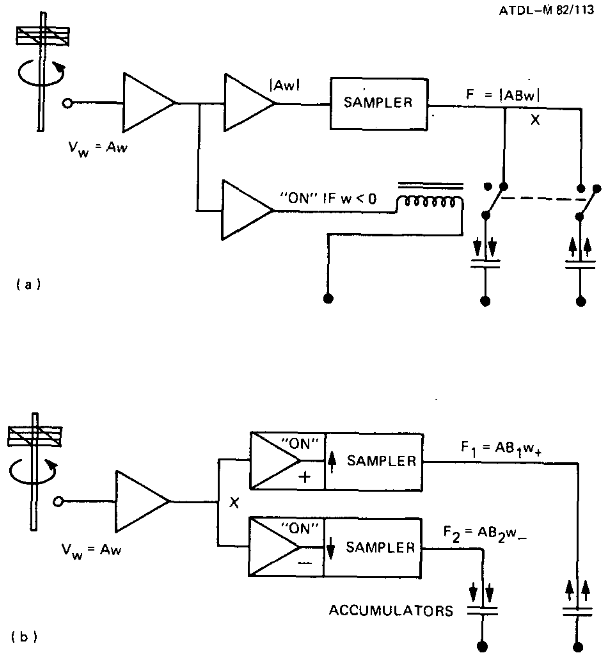

FIG. 1. A schematic representation of two alternative configurations of eddy accumulation apparatus. The x marks the points at which air is switched between updraft and downdraft sampling systems.

which is the form adopted by most analyses using this kind of method. Note that the mathematical question which arises with the case $w = 0$ presents no physical or conceptual difficulties and can be disregarded without loss of generality. Note, also, that (3) applies for the case of perfect sensors operating in a perfect system. The intent of the discussion that follows is to test the sensitivity of the method to imperfections such as will certainly arise in any real-world application. The complexity of the problems facing those who attempt to design eddy accumulation apparatus is such that analytic answers to design questions are generally not available. In order to obtain realistic guidelines, the matter has been investigated by a computer simulation employing actual turbulence information.

2. The computer model

Figure 2 is a diagrammatic representation of the numerical procedure developed to simulate the eddy accumulation technique. The model is of the system outlined in Fig. 1a, this appearing at the outset as the most likely approach to be profitable since it avoids the necessity for perfect matching of independent sampling system performance characteristics. Clearly, this is one of the matters that can be addressed theoretically, by introducing different "updraft" and "downdraft" values for the sampling calibration factor B in (2) and (3). For the present, a system employing one sampling system will be considered. The features are assumed to be as follows:

1) An anemometer provides a signal which is linearly related to the vertical wind speed, but with a zero offset C_1. This offset is intended to simulate the feature that perfect anemometer orientation is impossible in practice, and in any case, the presence of the sensor itself imparts a streamline departure which is hard to detect but which is sometimes significant (e.g., of the order of 10 cm s^{-1} for a truly "vertical" propeller anemometer, see Hicks, 1972).

2) The signal is processed by a perfect amplifier, which drives a sampling system that is linear in response between a starting speed (corresponding to $w = C_2$) and a maximum flow rate ($w = C_3$). The sampling system has a response time C_4 and is assumed to have perfect resolution.

3) Air is switched between updraft and downdraft integration systems with perfect detection of $w = 0$.

4) The displacement volume C_5 in the sampling system ahead of the switching valve, is assumed to be finite, since, if this is too large, significant lags and phase-shifts will be introduced. The effect of a fixed displacement volume can be minimized by increasing the sampling flow rate (i.e., by increasing B), but clearly B cannot be increased without a limit.

5) For purposes of these calculations, flow rates and related factors have been selected to provide manageable sample volumes, of the order of 1 m^3 after integrating for 1 h. This does not impose any limitations on the generality of the results, but it might be necessary to adjust the results to simulate other circumstances.

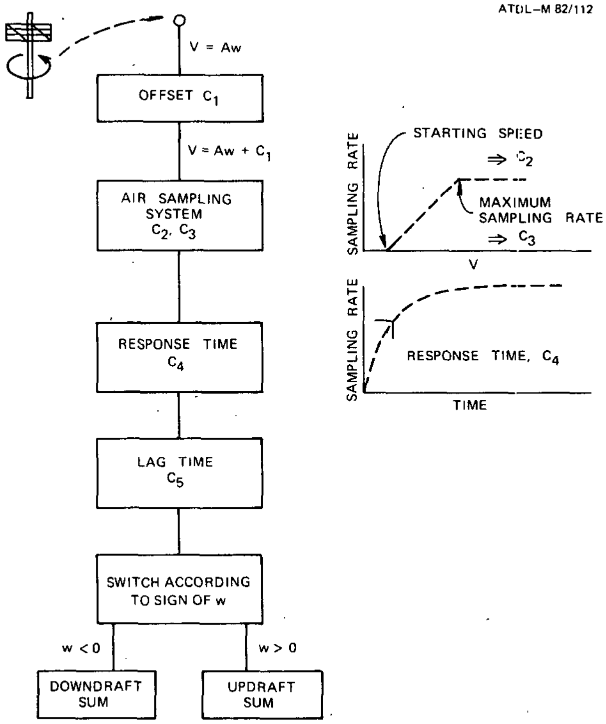

FIG. 2. Flow diagram of the computer simulation of the eddy accumulation alternative of Fig. 1a.

3. Turbulence data base

To obtain data that are suitable for the present tests, it is necessary to utilize signals representing actual turbulence. Since no suitable pollutant signal was available (this being the reason for the interest in eddy accumulation in the first place), a high quality surrogate signal has been manufactured from velocity data. It should be pointed out that the data used here were obtained in high winds in slightly unstable but near-neutral atmospheric stability. The results obtained are correspondingly limited in their generality; in more strongly unstable conditions, correlation coefficients between actual pollutant signals and the vertical velocity would be somewhat greater than is imposed on the present use of velocity data only. However, the error involved is of relatively little concern, since the purpose here is to derive guidelines suitable for designing equipment rather than to give a precise measure of the errors that will arise in practice.

Strong, high-quality turbulence signals were obtained from a u-v-w orthogonal array of propeller anemometers mounted ~6 m above the treetops of a deciduous forest canopy at the ATDL Walker Branch Watershed field site, near Oak Ridge, Tennessee. To provide the best possible information for testing analysis procedures, data were computer-processed using the procedure of Horst (1973). Axes were first rotated about the vertical to obtain a signal representative of the longitudinal wind component u. Subsequently, coordinates were rotated about the transverse (v) axis to force the average vertical velocity to zero. After these two transformations were completed, it was found that the average product vw was several orders of magnitude less than the longitudinal (Reynolds stress) product uw; hence, the third rotation about the longitudinal (u) axis to force vw to zero was unnecessary (see Wesely, 1974).

High wind speed conditions were selected to provide the strongest possible signals. The data used were recorded at 1 s intervals on digital magnetic tape, over a 1 h period. The response time of the anemometers is estimated to have been about 0.2 s for u and v components and 0.3–0.4 s for w. The average wind speed was 5.95 m s^{-1}. Conditions were slightly unstable, i.e., $z/L \approx -0.003$).

4. Simulation results

As cardinal values, we use the results of a conventional eddy-correlation analysis using these same data, yielding 113 cm s^{-1} for the friction velocity $[u_* = (-\overline{u'w'})^{1/2}]$ and 595 cm s^{-1} for the average velocity $\bar{u}$. Hence, the "deposition velocity" for these raw data is $u_*^2/\bar{u} = 21.3$ cm s^{-1}.

It is highly improbable that any pollutant would be deposited with a deposition velocity as high as 21.3 cm s^{-1}; values in the range 0.1–1.0 cm s^{-1} are far more likely. Consequently, the anemometry data have been modified to simulate the case of less rapidly transferred pollutants by the simple expedient of adding a constant to the surrogate pollutant signal (actually, the longitudinal wind speed in this test). Several different values of the additive constant have been employed to simulate pollutant concentration turbulent fluctuations for cases in which the deposition velocity is as low as 0.125 cm s^{-1}. It should be reemphasized that we have intentionally avoided using a pollutant record obtained by some fast-response pollution concentration sensor for these tests, since to do so would necessarily introduce some uncertainty in the results, corresponding to inadequacies of the fast-response pollutant sensor.

The use of a momentum analogy imposes some limitations on the generality of the results obtained, but this is not seen as a severe drawback. In particular, an assumption of cospectral similarity is implied. In fact, it is known that velocity cospectra are somewhat different from temperature and humidity, even over relatively smooth and flat surfaces. We must expect that pollutant cospectra will also differ, especially in the case of a forested surface such as that of this study. Thus, the results that follow and the conclusions that are drawn cannot be considered to be precise evaluations of real pollutant-flux situations, but rather as estimates, guidelines and indicators of factors that are potential sources of error.

Figures 3 and 4 show the influence of a limited dynamic range of the sampling system, in otherwise perfect apparatus. The effect of a sampling threshold (or starting speed C_2 in Fig. 2) is shown in Fig. 3; good results are obtained if the threshold is less than 10 cm s^{-1} of equivalent vertical velocity. The point

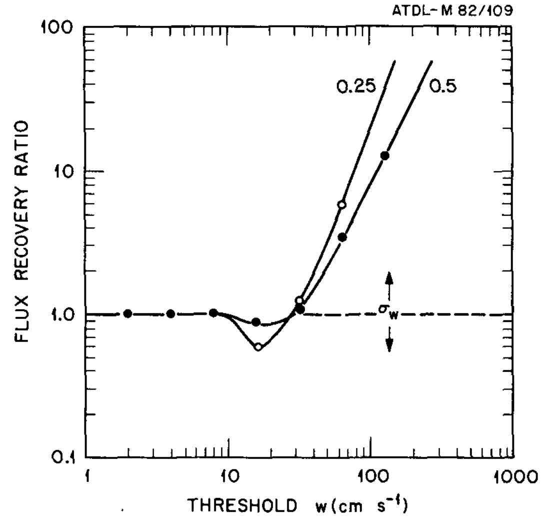

FIG. 3. The effect of an inadequate sampling threshold (equivalent to air anemometer starting speed) on the ratio of apparent to actual flux yielded by an eddy accumulation technique, for the cases of pollutants with deposition velocities 0.25 and 0.5 cm s^{-1}. In the conditions of this test, σ_w was about 125 cm s^{-1} and the results should probably be scaled accordingly.

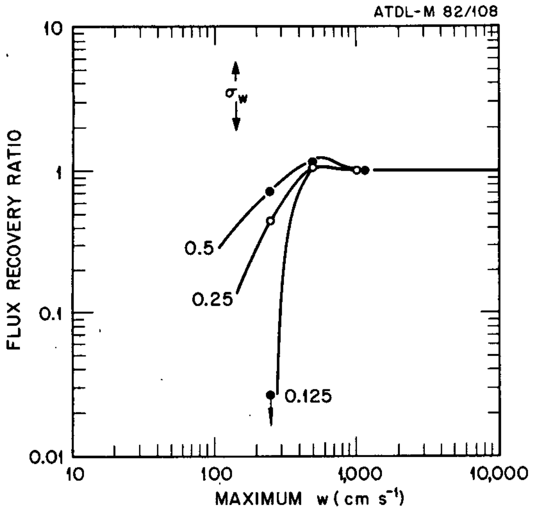

FIG. 4. The effect of an inadequate maximum sampling speed on the flux recovery ratio (measured/actual, as in Fig. 3), for pollutants with deposition velocities of 0.125, 0.25 and 0.5 cm s^{-1}. Note that σ_w was about 125 cm s^{-1} for this set of data.

between approximately the 10 and 30 cm s^{-1} thresholds indicates a slight reduction of the apparent flux and higher thresholds give clearly unsatisfactory overestimates of the eddy flux (presumably because of the rejection of all except the most intense, very efficient eddies and the redefinition of mean values using this modified "data" record). Fig. 4 shows that the sampling system should accommodate velocity fluctuations as large as ~10 m s^{-1}, with an uncertain behavior resulting if the limit is in the range 4–10 m s^{-1}, but with obvious problems if it is below 4 m s^{-1}. It appears, therefore, that the dynamic range of the sampling system should not be less than two orders of magnitude. In practice, it is probable that the required sampling range will scale as σ_w, which was about 125 cm s^{-1} in the case used for illustration here. Thus, the dynamic range of the sampling system should be sufficient to assure linearity between extremes corresponding to about 0.05 and 5σ_w. Since σ_w cannot be predicted with accuracy, and since σ_w can vary over a wide range during the course of a normal day, practical applications will require a much greater dynamic range than the two orders of magnitude indicated by the case study above.

It is of passing interest to note that no significant loss of flux occurs when vertical velocity signals $\lesssim 0.05\sigma_w$ are disregarded. Thus, it is not critical that the anemometer and sampling system maintain perfect performance through zero. This is a reassuring confirmation of the experimental finding that eddy correlation calculations of fluxes are not particularly sensitive to sensor imperfections near $w = 0$, which in turn is part of the justification for the common use of propeller anemometers even though they have obvious performances deficiencies when used to measure flow nearly normal to their axis of rotation.

Two other features of Figs. 3 and 4 are worthy of mention. First, the adverse effects of inadequate sampling characteristics are greatest for slowly "depositing" pollutants. Second, an experiment using a sampling system of severely limited dynamic range may indeed yield an answer that appears correct, as a fortuitous consequence of overestimation corresponding to an inadequate threshold and underestimation caused by a maximum sampling rate that is too low.

Figure 5 illustrates the influence of a sampling (or anemometer) offset (C_1). For $v_d > 1$ cm s^{-1}, the eddy accumulation analysis procedure is fairly insensitive to offsets less than a few centimeters per second; however, when the offset is more than about 4 cm s^{-1}, large errors can result. It should be noted, in this context, that a vertical velocity offset of 4 cm s^{-1} corresponds to a vertical alignment error of approximately 0.4° in the conditions of this study.

Clearly, a large anemometer or sampling-system offset will result in different sample volumes of air in the separate updraft and downdraft "accumulators." In this context, it is necessary to differentiate between sampling systems that measure the concentration of material directly (either by using a real-time concentration monitor and averaging its output or by employing an after-the-event measurement of the average concentration) and those that accumulate the pollutant in question from the two airstreams (e.g., by using filters to collect particles). In the former case, there is a built-in protection against errors resulting from zero offsets, since concentrations are measured directly and only small offset errors will be imposed on the averages

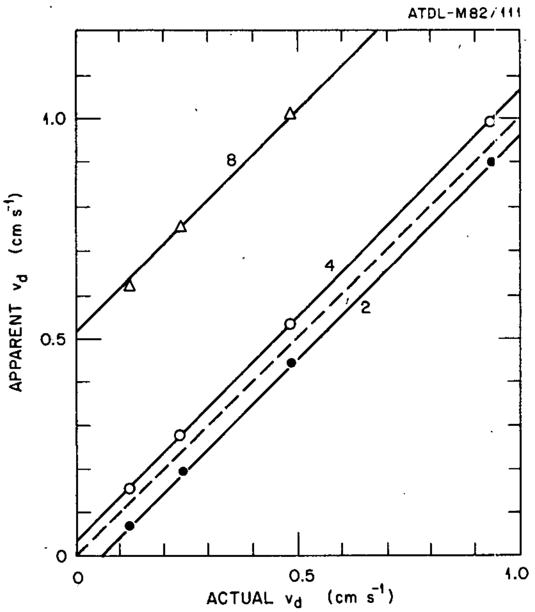

FIG. 5. The effect of an anemometer (or sampling system) zero offset on the apparent deposition velocity, assuming no capability to apply appropriate corrections based on volumetric measurements. Offsets of 2, 4 and 8 cm s^{-1} are illustrated.

that are derived. In the latter case, however, it is required that the entire system be aligned so that equal volumes of air are sampled; otherwise, major corrections will be necessary. Suppose that the updraft volume $\mathrm{Vol}_\uparrow$ exceeds the downdraft $\mathrm{Vol}_\downarrow$ by an amount $\Delta\mathrm{Vol}$, as a consequence of some error in orientation of the sensors or in mechanical or electronic alignment of the sampling system. Then the quantities of pollutant accumulated in each "container" can be approximated as

$$\left.\begin{aligned} \mathrm{Acc}_{\uparrow a} &\approx \mathrm{Acc}_\uparrow + \Delta\mathrm{Vol} \times \bar{C}/2 \\ \mathrm{Acc}_{\downarrow a} &\approx \mathrm{Acc}_\downarrow - \Delta\mathrm{Vol} \times \bar{C}/2 \end{aligned}\right\} . \quad (4)$$

The subscripts a can be read as "apparent." The apparent eddy flux EF_a obtained by manipulating the erroneous accumulations of pollutant will be

$$\begin{aligned} \mathrm{EF}_a &= (TAB)^{-1}(\mathrm{Acc}_{\uparrow a} - \mathrm{Acc}_{\downarrow a}) \\ &\approx (TAB)^{-1}(\Delta\mathrm{Vol} \times \bar{C}) + \mathrm{EF}, \quad (5) \end{aligned}$$

and hence the error imposed on the apparent deposition velocity $v_{da} = -\mathrm{EF}_a/\bar{C}$ will be

$$\Delta v_d = v_{da} - v_d \approx (TAB)^{-1}(\Delta\mathrm{Vol}). \quad (6)$$

In essence, the error Δv_d is the average effective updraft error; if there were an average vertical velocity $\bar{w}$ and if all other systems worked perfectly, then the resulting difference in sampled volumes would be

$$\Delta\mathrm{Vol} = TAB \times |\bar{w}|. \quad (7)$$

Some similarity is obvious with standard eddy correlation procedures, for which it is well-known that failure to properly account for mean values when computing eddy fluxes can cause great errors.

It should be noted that only a small error is involved in approximating $\mathrm{Acc}_\uparrow$ and $\mathrm{Acc}_\downarrow$ by $\mathrm{Vol}_\uparrow \times \bar{C}$ and $\mathrm{Vol}_\downarrow \times \bar{C}$, respectively, in (4). Furthermore, this error diminishes with v_d; hence the results of this analysis are quite securely based in the circumstances of major interest here (i.e., pollutant fluxes, typically with $v_d < 1$ cm s^{-1}). It should also be emphasized that accurate first-order corrections can be made for errors resulting from volume-sampling inconsistencies and that most errors of this kind appear to scale as v_d/σ_w. Providing measurements of the volumes are available, Eq. (6) can be used to correct estimates of v_d. To do so requires that the volumes be measured with considerable accuracy. If there were a 1% undetected difference between $\mathrm{Vol}_\uparrow$ and $\mathrm{Vol}_\downarrow$, this would cause an error of about 1% in the amount of pollutant accumulated in the sampling systems, leading to an erroneous contribution to the apparent deposition velocity equivalent to about 1% of σ_w.[2] If the intent of a particular experiment is to resolve v_d to an accuracy of 0.1 cm s^{-1} in the conditions of the test data used here, then it would be necessary to measure the volumes sampled in each sampling system to an accuracy of better than 0.1%. While not impossible, this task is likely to be difficult in field conditions.

Figure 6 shows the effects of a finite displacement volume (corresponding to a lag time C_5 in Fig. 2) between the sampling intake and the switching mechanism that directs the airstream to the appropriate accumulator. Clearly, it is desirable for the displaced volume to be small, since otherwise some air will be routed to the wrong accumulator and fluxes will be underestimated accordingly. In Fig. 6, it appears that 10% underestimation of pollutant fluxes will occur when the displacement ("lag") volume amounts to about 0.1% of the total volume sampled (for a 1 h sampling period). In any practical application of these techniques, tubing diameters and flow speeds should be arranged to ensure a minimum displaced volume ahead of the switching mechanism (as identified in Fig. 1). It is somewhat surprising that the effects of displacement volumes were found to be largely independent of v_d, although this may be a peculiarity of the data used for this particular study.

5. Chemical resolution requirements

A few simple sums provide estimates of the difference in pollutant concentrations (or accumulated quantities of pollutant) between the updraft and downdraft integration systems. The volume sampled and the various operating parameters (amplifier gains, etc.) are related to the average value of the amplitude of the vertical velocity by

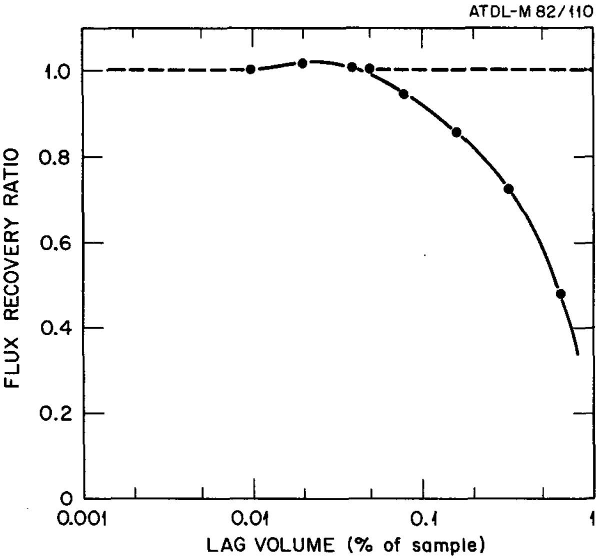

FIG. 6. The effect of a significant lag volume between the sampling port and the switching mechanism that directs air to the alternative sampling systems (i.e., ahead of the point x in Fig. 1).

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[2] This can be demonstrated by considering a Fourier decomposition of the vertical velocity signal. For every frequency, the average absolute value of w is $(2\sqrt{2}/\pi)\sigma_w$. When contributions are combined by adding variances over a Gaussian distribution of w, $|\bar{w}|$ is found to be about $0.8\sigma_w$.

$$\mathrm{Vol}_\uparrow + \mathrm{Vol}_\downarrow = (TAB)|\bar{w}|, \qquad (8)$$

when all of the machinery is operating perfectly. If set up correctly, the updraft and downdraft volumes will be the same and we can combine (8) with (3) to evaluate concentration differences as

$$\mathrm{Conc}_\uparrow - \mathrm{Conc}_\downarrow = (\mathrm{Acc}_\uparrow - \mathrm{Acc}_\downarrow)/(TAB \times |\bar{w}|/2) = 2 \times \mathrm{EF}/|\bar{w}|. \qquad (9)$$

By introducing the deposition velocity and invoking the near equality between $|\bar{w}|$ and σ_w, the following informative expression for the concentration differences is derived:

$$\mathrm{Conc}_\uparrow - \mathrm{Conc}_\downarrow = 2C(v_d/\sigma_w). \qquad (10)$$

(Note that the numerical factor 2 applies if a uniform frequency distribution of $|\bar{w}|$ is assumed. Assumption of a Gaussian distribution leads to a factor of 2.5.)

An independent estimate of the concentration difference can be obtained by considering the eddy flux in more conventional terms, as

$$\mathrm{EF} = r_{wC} \times \sigma_w \times \sigma_C, \qquad (11)$$

which is essentially a definition of the correlation coefficient r_{wC} between vertical velocity and concentration fluctuations. This correlation coefficient is likely to be ~0.4 in unstable (daytime) conditions, so that the concentration standard deviation can be estimated as

$$\sigma_C = \mathrm{EF}/(0.4\sigma_w) = 2.5\, \bar{C}(v_d/\sigma_w), \qquad (12)$$

where $\bar{C}$ is the average pollutant concentration. The similarity with (10) is obvious and estimates of concentration differences derived from the alternative procedures will be much the same provided $|\bar{w}|$ and σ_w are numerically similar. In the case in which it is desired to measure a deposition velocity of 0.1 cm s^{-1}, and for $\sigma_w \approx 50$ cm s^{-1} (a fairly typical value for many daytime situations), it would be necessary to resolve 0.4% differences in concentration or accumulated quantity of pollutant.

Without delving too deeply into the peculiarities of other variations on the eddy correlation theme, it should be pointed out that detection of very small differences in concentration is always a fundamental requirement. In standard covariance applications, such very small concentration differences are detected with fast-response, on-line sensors that typically suffer from drift and high-frequency noise that would be unacceptable for a laboratory or routine monitoring application; drift and noise are not critical issues because they are not correlated with vertical velocity and are hence rejected by the analysis procedure.

A simplified version of eddy accumulation involves the separate determination of average concentrations in updrafts and downdrafts, without imposing the complexity of a sampling system linked to the magnitude of the w signal. In this particular case, the treatment summarized by (10) and (12) provides a first-order approximation of the results that should be anticipated: concentration differences should be expected to differ by 1% or less in most situations of a slowly depositing pollutant and accurate interpretation of the differences would be somewhat more difficult.

6. Discussion and conclusions

Table 1 summarizes the most critical factors indicated by the present examination of eddy accumulation systems. Some of the considerations identified in Fig. 2 are not represented in the tabulation. In every such case, tests have shown relatively little sensitivity, well within the range that can be achieved by standard engineering practices.

Early experimental investigations of the eddy accumulation method demonstrated the technical difficulties involved and attempted to test various configurations, mainly intended to measure the flux of water vapor. These devices were tested in field comparisons with other micrometeorological methods, including gradient techniques and conventional eddy correlation. Desjardins (1977) developed a system which was successfully demonstrated for measuring sensible heat flux (although direct comparisons against independent determinations of the flux were not reported). Application of the technique to other atmospheric quantities has been proposed by many workers, e.g. Hales and Horst, 1974, and interest continues to be relatively enthusiastic. However, Table 1 identifies a number of technical obstacles. In many instances, the severity of the difficulty is directly linked to the

TABLE 1. Technical requirements for practical application of the eddy accumulation method, assuming the desire to resolve deposition velocity to an accuracy of about 0.1 cm s^{-1}. Values given in parentheses are rather uncertain and should be considered as guidelines only.

Sampling system response time	Same as standard eddy correlation, typically <1 s
Sampling threshold (equivalent vertical velocity):	$<0.05\sigma_w$
Maximum sampling rate (equivalent vertical velocity):	$>5\sigma_w$
Sampling system zero offset (equivalent $\lvert\bar{w}\rvert$):	($<0.02\sigma_w$ if concentrations measured directly) ($<0.0005\sigma_w$ if pollutant accumulated and corrections not applied for volume errors)
Accuracy in measuring accumulated volume:	(0.1% if pollutant accumulated)
Displacement ("lag") volume ahead of air stream switching:	<0.1% of total sampled volume
Resolution of chemical analysis:	Difference between updraft and downdraft samples about 2 × v_d/σ_w (expressed as a proportionality)

corresponding deposition velocity. Thus, as an early step in any development program, tests should be conducted using one of the various well-known meteorological quantities that is transferred with a large "deposition velocity" and which can be measured with accuracy by independent means. Of the available quantities, water vapor appears to offer the most advantages. Most conceivable eddy accumulation devices could be modified to measure moisture and determinations of evaporation rates are routine in micrometeorological (and especially agrometeorological) experiments. A satisfactory comparison between eddy accumulation estimates of evaporation rates and evaluations made by gradients, lysimetry, or some other independent method would be a convincing demonstration of the utility of the eddy accumulation technique. As yet, such a demonstration has not been forthcoming.

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