FLOW-DISTORTION EFFECTS ON SCALAR FLUX MEASUREMENTS IN THE SURFACE LAYER: IMPLICATIONS FOR SENSOR DESIGN

J. C. WYNGAARD

National Center for Atmospheric Research, Boulder, CO 80307, U.S.A.*

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Abstract. Scalar fluxes measured through the eddy-correlation technique are prone to two types of errors caused by the sensor-induced flow distortion: those due to crosstalk from the horizontal flux, and those due to amplification or attenuation due to flow blocking. We show that the crosstalk error can be eliminated by designing the sensor array to be vertically symmetric about its horizontal midplane. In such an array, the flow-blocking effect causes the scalar flux to be overestimated, but this error can be made negligible by designing an array with minimal stagnation loss in streamwise speed at the flux-measurement point.

1. Introduction

While there is a long history of research into the effects of flow distortion on mean wind measurements (see, for example, Cermak and Horn, 1968; Izumi and Barad, 1970), much less attention has been paid to the effects on turbulence statistics. This situation began to change in 1980, however, in part due to Wieringa's (1980) assertion that certain of the turbulence data from the 1968 Kansas experiments (Businger *et al.*, 1971; Haugen *et al.*, 1971) had significant errors due to the flow distortion caused by the tower structure. In disputing this, Wyngaard *et al.* (1982) showed that Wieringa's technique for calculating the effects of flow distortion on turbulence was only approximate; they argued that it substantially overestimated the errors. All agreed (Wieringa, 1982) that further analysis of the Kansas data was not likely to shed new light. Nonetheless, Wieringa succeeded in focusing attention on a long-neglected problem in micrometeorology.

Stimulated by Wieringa's study, I presented a simple theory (Wyngaard, 1981) for the effects of flow distortion on turbulence when the scale of the distorting body is small compared to the integral scale of the turbulence. This is almost always the case with distortion by sensors measuring turbulence statistics in the energy-containing range in the surface layer. That first paper concentrated on velocity variance and covariance measurements ahead of a sphere and a cylinder; it also showed that flow-distortion effects on turbulence could not be reliably removed by treating them as 'tilt' errors, as was done by Wieringa (1980). A second study (Wyngaard *et al.*, 1985) extended these results to axisymmetric bodies.

Researchers are now using the eddy-correlation technique to measure vertical fluxes of scalars other than temperature, including O_3 (Wesely *et al.*, 1978), NO_2 (Wesely *et al.*,

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1982), CO_2 and water vapor (Ohtaki and Matsui, 1982), aerosols (Fairall, 1984), and NO (Delany *et al.*, 1986). Efforts are underway to develop fast-response sensors for other trace constituents as well. These eddy-correlation devices are typically less than aerodynamically 'clean', however, and the resulting flow distortion has concerned a number of researchers. Current practice is to remove flow-distortion errors in turbulence statistics through use of 'tilt corrections' (e.g., Dyer *et al.*, 1982), although recent lively discussion (Wyngaard *et al.*, 1982; Wieringa, 1982; Dyer, 1982) reveals an emerging consensus that this is *ad hoc* and that flow-distortion corrections should be more fundamentally based.

In concluding their discussion on flow distortion effects in an international turbulence comparison experiment, Dyer *et al.* (1982) write "... it seems abundantly clear that in some cases the sensors themselves would have introduced significant distortion of the flow to an extent that may not be readily predictable, and considerable care must be taken in the basic design of turbulence sensors." In order to provide guidelines for that design process, I will show what flow-distortion theory suggests about the optimum geometry of instruments for the measurement of scalar fluxes near the surface.

2. Scalar Flux Measurement Errors

We denote the fluctuations in scalar mixing ratio and vertical velocity by c and u_3, respectively, and assume that they are measured by sensors located sufficiently close together and of sufficiently small path length or averaging volume. In general, this means the separation and path length are small compared to the height above the surface; we discuss more specific criteria later. We assume that the tower structure and booms have negligible effects on the flow at the sensors. Nevertheless, the measured u_3 signal will be somewhat in error because of the flow distortion caused by the sensors themselves, and this causes an error in the measured scalar flux.

In analyzing this problem, we assume that the sensor housings and mounting apparatus are small compared to the integral length scale of the u_3 field. Since this integral scale is of the order of the height above the surface (Kaimal *et al.*, 1972), this amounts to requiring that the instrument scale is an order of magnitude smaller than the measurement height. This makes the underlying flow-distortion theory simpler and also allows us to ignore the vertical variations of the mean wind and mean concentration (Wyngaard, 1981).

Under these conditions in the surface layer, the flow distortion not only attenuates or amplifies the vertical velocity, but also contaminates it with the horizontal velocity fluctuations. Thus, we can write the vertical velocity fluctuation measured in the region of flow distortion as (Wyngaard, 1981)

$$u_3^m = (1 + d_{33})\,u_3 + d_{31}u_1 + d_{32}u_2\,. \tag{1}$$

The d_{ij} are small coefficients that approach zero in the distortion-free region far from the body. Under the given assumptions, they can be calculated from the solution for potential flow approaching the body at an arbitrary angle (Wyngaard, 1981). Here d_{33}

represents attenuation or amplification, depending on its sign, while the off-diagonal coefficients d_{31} and d_{32} represent crosstalk and have an equally simple physical interpretation. As a unidirectional approach flow nears a three-dimensional body, the blocking effect induces velocity components in the other two directions. The same effect occurs for large-scale turbulent eddies, and in this way u_1 and u_2 fluctuations induce u_3 fluctuations near the body, as indicated in (1).

Equation (1) assumes that u_3 is measured at a point, but in practice it is usually averaged over a path or a volume, depending on the type of anemometer. This creates no mathematical difficulty, however; by assumption, the only spatial dependence in (1) is in the d_{ij}, so we can formally average (1) over the sensing volume and interpret the d_{ij} as spatially averaged quantities.

We assume that the scalar sensor is of the open-path variety without devices such as aspirating pumps that can lead to wind-gust contamination of the scalar fluctuations. Particle measurements, for example, are subject to such errors (Wesely and Hicks, 1979; Fairall, 1984). Since the local Peclet number of the flux-carrying scalar fluctuations is large, we can neglect the effects of molecular diffusion during the travel time near the sensor. Thus, to a good approximation the total time derivative of the scalar vanishes, and it suffers no changes due to flow distortion:

$$c^m = c\,. \tag{2}$$

While this indicates that the amplitude of scalar fluctuations is unchanged by flow distortion, their spatial scale clearly can be changed. These deformation effects can be very important when measuring scalar fine structure (Wyngaard, 1986) but should be of no consequence for flux measurements provided that the flux-carrying eddy scale is large compared to the probe, as we have assumed.

Multiplying (1) and (2) and averaging gives an expression for the measured flux:

$$\overline{u_3^m c^m} = (1 + d_{33})\,\overline{u_3 c} + d_{31}\overline{u_1 c} + d_{32}\overline{u_2 c}\,. \tag{3}$$

If we choose u_1 to be in the mean wind direction, then by lateral symmetry we would expect that $\overline{u_2 c} = 0$ under horizontally homogeneous conditions; this is confirmed by observations of temperature fluxes (Zubkovskii and Tsvang, 1966). However, the streamwise flux $\overline{u_1 c}$ does not vanish. This was apparently first demonstrated experimentally for temperature by Shiotani (1955) and confirmed by Zubkovskii and Tsvang (1966). Wyngaard *et al.* (1971) extended these results for temperature to a wide range of stabilities, and showed that the horizontal scalar flux is produced through the interaction of turbulence with the vertical gradients of the mean scalar concentration and mean wind and is of opposite sign to the vertical flux.

Although the Wyngaard *et al.* (1971) analysis was for fluxes of temperature, their findings should hold equally well for any conservative scalar in the surface layer, and so I present their results as $\overline{u_1 c}/\overline{u_3 c}$ in Figure 1. Note that in stable and near-neutral conditions $\overline{u_1 c}/\overline{u_3 c} \sim -3$, so that (3) yields

$$\overline{u_3^m c^m}/\overline{u_3 c} \simeq 1 + d_{33} - 3d_{31}\,. \tag{4}$$

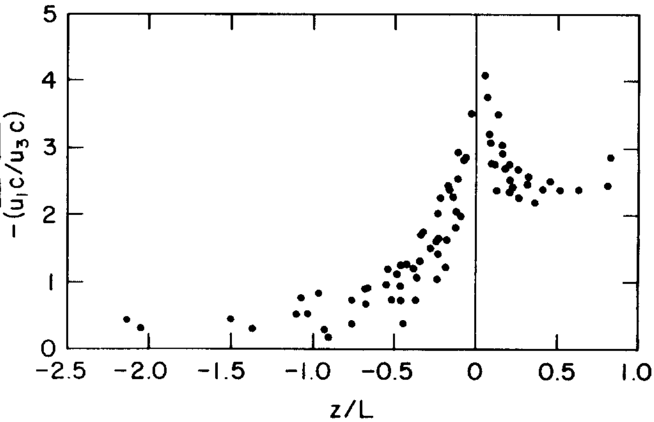

Fig. 1. The ratio of streamwise and vertical components of scalar flux in the surface layer, as measured for temperature in the 1968 Kansas experiments. Data taken at 5.66, 11.3, and 22.6 m and plotted against the stability index z/L. From Wyngaard *et al.* (1971).

This suggests that the effect of crosstalk is potentially more damaging than that of the attenuation/amplification represented by the d_{33} term in (4).

3. Implications for Sensor Design

The d_{ij} are formally defined (Wyngaard, 1981) through the coefficients in a Taylor series expansion of the distorted flow field about a basic state of uniform mean approach flow of velocity $(U_1, 0, 0)$, The crosstalk coefficient d_{31} in (4) is

$$d_{31}(x) = \left.\frac{\partial \tilde{U}_3(\mathbf{x})}{\partial U_1}\right|_0 , \tag{5}$$

where the tilde represents the distorted flow and U_1 is the free-stream speed. While we can calculate d_{31} for simple bodies and in general we can measure it experimentally, in this case we can also write a simple approximation for it. In the surface layer, we can take the undistorted mean vertical velocity U_3 to be zero, so that for small d_{31} we can approximate (5) by

$$d_{31} \simeq \tilde{U}_3/U_1 \simeq \sin\theta , \tag{6}$$

which is simply the mean deflection angle of the airflow at the measurement point. This allows us to estimate the flux error caused by crosstalk. If we have 5 deg of flow deflection, for example, which seems quite possible in compact, vertically asymmetric arrays, then $d_{31} \sim 0.1$, and (4) indicates that the flux error under near-neutral conditions is about 25%. Note that the flux is overestimated if d_{31} is negative, which occurs for 'top-heavy' geometries, with the reverse true for the 'bottom-heavy' case.

We can now compare the distorted u_3 signal (1) with that caused by a tilt error – that is, by vertical misalignment of an otherwise perfect u_3 sensor. If the tilt angle from true vertical is θ, the measured u_3 signal is

$$u_3^m = u_3 \cos\theta + u_1 \sin\theta\,. \tag{7}$$

In view of (6), the crosstalk contribution of u_1 to u_3^m due to flow distortion (the second term in (1)) is the same as the crosstalk contribution of u_1 to u_3^m due to tilt error (the second term in (7)). The analogy does not extend to the first terms, however. As we shall soon see, the coefficient $(1 + d_{33})$ of the u_3 term in the flow-distortion equation (1) can be greater or less than 1.0, depending on the geometry of the distortion, whereas that coefficient in the tilt equation (7) is simply the cosine of the tilt angle and cannot exceed 1.0 in magnitude. Thus, the use of 'tilt corrections' for flow-distortion effects is incorrect.

The result (6) highlights an important property of d_{31}: it is identically zero on a horizontal plane of symmetry, because on such a plane $\tilde{U}_3$ is zero, by definition. Our first design criterion, then, is that the sensor array (i.e., the combination of c and u_3 sensors) should be symmetric about the horizontal plane passing through the point of measurement of u_3. This will eliminate the crosstalk error.

The need for vertical symmetry in u_3 sensors seems not to have been stressed in the literature. However, Hicks (1972) discussed the updraft caused by the asymmetry of a propeller anemometer mounted with the axis vertical, indicating that the resulting mean flow deflection in one such application was about 1.2 deg. He recommended the use of a vertical shaft extension beyond the plane of the propeller to minimize the asymmetry. More recently, Kaimal (1986) recommended incorporating 'as much vertical symmetry as possible into the probe design'.

Let us assume, therefore, that we design a vertically symmetric array. According to (4), we must now minimize the blocking error represented by d_{33}. To get some insight into this error, let us assume further that the blocking effect of the array is equivalent to that of a sphere. Calculations of d_{33} for a sphere (Wyngaard, 1981) indicate that it is positive within an approach cone of about 70 deg (Wyngaard, 1981) and negative outside. In a symmetric array, we make the u_3 measurement along the centerline, where d_{33} is

$$d_{33} = \frac{a^3}{2r^3} \tag{8}$$

with a the sphere radius and r the distance between the sphere center and the point where u_3 is measured. Thus, we see that for a symmetric array, u_3 is amplified by the flow distortion, leading to an overestimate of scalar flux. This amplification (which is ignored by 'tilt corrections' for flow distortion effects) has been demonstrated in the measurements of Bearman (1972) and Britter *et al.* (1979) ahead of a circular cylinder in turbulent flow.

Potential flow theory says that the decrease in streamwise speed along the centerline ahead of the sphere is

$$1 - \frac{\tilde{U}_1}{U_1} = \frac{a^3}{2r^3}\,. \tag{9}$$

If we combine (8) and (9), we can eliminate the sphere radius a and relate d_{33} simply to the mean-flow stagnation effect:

$$d_{33} \simeq 1 - \frac{\tilde{U}_1}{U_1} . \tag{10}$$

This result also holds exactly for a circular cylinder (Bearman, 1972; Wyngaard, 1981) and, judging from the numerical calculations of Wyngaard *et al.* (1985), is a good approximation for an axisymmetric body. Thus, we conclude that a reasonable estimate of the ratio of true and measured scalar fluxes in a symmetric array is, from (4) and (10),

$$\frac{\overline{u_3^m c^m}}{\overline{u_3 c}} \simeq 2 - \frac{\tilde{U}_1}{U_1} . \tag{11}$$

Our estimate of the fractional error in measured scalar flux due to blocking effects is simply the negative of the fractional change in streamwise speed, at the u_3 measurement point, due to stagnation.

Our second design criterion, then, is to minimize the bulk of the array so that u_3 is measured at a point where the stagnation loss in streamwise speed is minimal.

Meeting this criterion will typically require a separation between the u_3 and c sensors. While calculating the effect of this separation on flux measurements is straightforward in principle, in practice it is difficult because we do not have the detailed information on the flux cospectrum needed to evaluate the resulting integrals (Wyngaard, 1986). Spectral modeling can provide useful guidelines here, however (e.g., Kristensen and Fitzjarrald, 1984). One can also evaluate separation effects experimentally, as Koprov and Sokolov (1973) attempted to do. While not complete enough to serve as the basis for design, their results do indicate that flux loss is more sensitive to lateral separation than to vertical separation. Finally, one can also improvise conservative rules of thumb, as have been suggested for sonic anemometry (e.g., Kaimal, 1986). One such rule would be that sensor separation equal to path length would cause no additional flux degradation, providing the path length itself were sufficiently short; a conservative criterion for the latter can, in turn, be developed by considering the spectral response, which can be evaluated numerically (Wyngaard, 1986). This probably can be relaxed for the separation component in the streamwise direction, since to a good approximation this can be corrected for by lagging the upwind sensor signal in time to account for the transit time difference between probes.

Sonic anemometers are often used in scalar-flux sensors because of their excellent dynamic response (Kaimal, 1986). However, they are prone to flow-distortion errors stemming both from the bulk of the sonic array and from the wakes of the acoustic transducers. The latter, called the 'transducer-shadow effect', can cause substantial errors in the spectral response (Wyngaard and Zhang, 1985). The flow-distortion errors due to the array bulk have apparently yet to be investigated systematically, but it is encouraging that recent designs discussed by Wyngaard and Zhang (1985) and Zhang *et al.* (1986) are vertically symmetric and would seem to cause less blockage than earlier units.

4. Conclusions

Scalar fluxes measured through eddy correlation have two types of errors, each stemming from the effects of probe-induced flow distortion on the measured vertical velocity fluctuations. One has the nature of an instrument tilt error, in that it introduces horizontal velocity fluctuations into the measured vertical ones; this crosstalk effect thereby contaminates the vertical flux with the horizontal one. This is potentially a serious source of error because this horizontal flux is not normally negligible; it exceeds the vertical scalar flux by a factor of three in magnitude in the near-neutral surface layer, for example. The other error is due to attenuation or amplification of the vertical velocity due to flow distortion.

The crosstalk error can be eliminated by designing the eddy-correlation array (i.e., the combination of c and u_3 sensors, housings, and mounts) to be vertically symmetric about the horizontal midplane of u_3 and c measurement.

In such an array the flow-blockage effect amplifies the u_3 signal and thereby causes the scalar flux to be overestimated. We show that to a plausible approximation the fractional error in flux is simply the negative of the fractional loss in streamwise speed at the u_3 measurement point and, hence, can be minimized by designing an array with minimum flow obstruction.

The remaining source of error in this 'optimum array' is that due to path averaging and sensor separation. Given the absence of experimental data on the latter, and the lack of the cospectral information needed to evaluate it analytically, we suggest that the lateral separation be limited to distances on the order of the path length. Streamwise separation can be somewhat larger provided that time-lag adjustments be made to account for the transit-time difference between the two sensors.

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