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ATTENUATION OF SCALAR FLUXES MEASURED WITH VERTICALLY–DISPLACED SENSORS

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1. INTRODUCTION

Turbulent scalar fluxes are determined by correlating vertical velocity measurements, commonly made on towers with a sonic anemometer, with scalar density measurements made with an appropriate fast response sensor, e.g. an open–path optical–absorption hygrometer in the case of water vapor fluxes. In order to avoid flow distortion errors in the velocity measurements, in–situ scalar sensors must be displaced from the measurement volume of the sonic anemometer. Unfortunately this causes a decorrelation of the velocity and scalar density measurements and a reduction in the measured flux. As noted by Kristensen et al. (1997, hereafter KMOW), it is expected that the attenuation of the measured flux will be "an increasing function of the ratio of the sensor displacement and the scale of the turbulence". In the surface layer, the integral scale of the vertical velocity component increases with height, and therefore the flux attenuation will increase with the ratio of sensor displacement to the measurement height. The measured flux can be corrected simply by dividing it by the estimated fractional attenuation of the measured flux.

Horst (2006) previously discussed scalar flux attenuation caused by horizontal sensor displacements, and here we extend that investigation to vertical sensor displacements. KMOW examined this topic using a pair of vertically-displaced sonic anemometers, each able to measure both vertical velocity w and the scalar variable T_c, sonic virtual temperature derived from the speed of sound (e.g. Kaimal and Gaynor, 1991). The flux for displaced sensors is $F(z,z') = \langle w'(z)\,T_c'(z')\rangle$, where z is the height of the anemometer and z' is the height of the scalar sensor. Assuming a constant flux layer, the flux for collocated sensors is $F_o = \langle w'(z)\,T_c'(z)\rangle = \langle w'(z')\,T_c'(z')\rangle$. It is assumed that, by scalar similarity, the observed reduction in the virtual heat flux can be applied equally as well to other scalar fluxes (Hill, 1989).

KMOW plot their data as $F(z,z')/F_o$ versus z/z',

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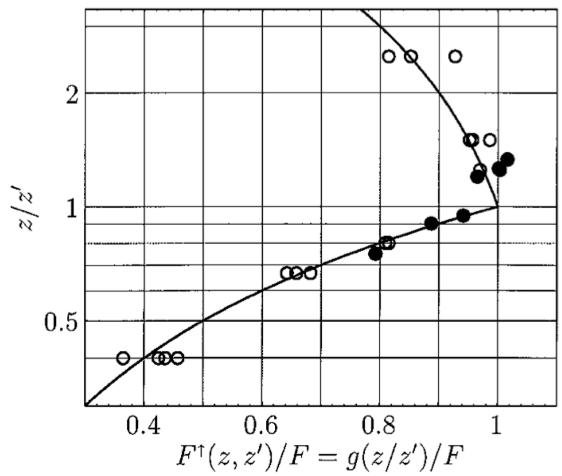

Figure 1: Kristensen et al. (1997) plot of flux attenuation $F(z,z')/F_o$ as a function of the height ratio z/z'.

Figure 1, and find the unexpected result that the flux attenuation is considerably less when the scalar sensor is below the anemometer, $z/z' > 1$, than for the opposite configuration. Their data cover the range $0.4 < z/z' < 2.5$ and are fit reasonably well by

$$F(z,z')/F_o = \begin{cases} 1-1.0[1-(z/z')], & z < z'; \\ 1-0.1[(z/z')-1], & z > z'. \end{cases} \qquad (1)$$

KMOW explain theoretically how the asymmetry is caused by the dependence of the vertical scalar gradient on height, but their theoretical development does not lend itself to a quantitative prediction of flux attenuation and hence they are limited to the empirical Equation (1).

The KMOW flux attenuation data exhibit minimal dependence on stability. This seems at variance with the stated expectation that the measured flux attenuation should be an increasing function of the ratio of sensor displacement and the scale of the turbulence. However, the height range of the KMOW data is 1–2.5 m and 90% of the their data fall in the range -0.1 m^{-1} < L^{-1} < 0.2 m^{-1} (Jakob Mann, personal communication),

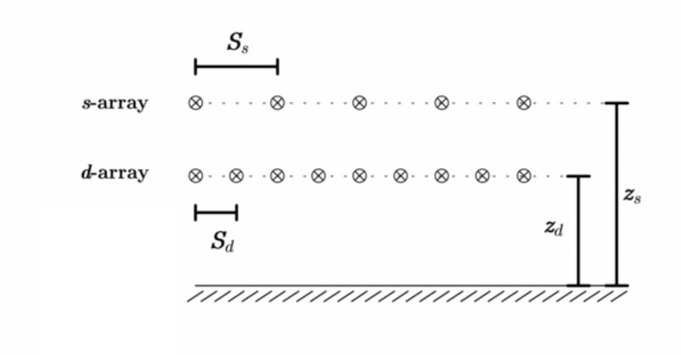

Figure 2: Schematic of the two HATS horizontal sonic arrays at heights $\{z_d, z_s\}$ agl and with crosswind sonic separations $\{S_s, S_d\}$.

suggesting that Equation (1) may correspond to near-neutral stratification. The present paper extends the highly original results of KMOW to a greater range of stability using a data set from the Horizontal Array Turbulence Study (HATS) field project.

2. HATS FIELD OBSERVATIONS

The Horizontal Array Turbulence Study (Horst et al., 2004) collected data from two parallel, horizontal arrays of sonic anemometers oriented in the climatological crosswind direction. The two arrays, labeled s and d, were composed respectively of 5 and 9 equally–spaced sonic anemometers, with one array located directly above the other as shown in Figure 2. Table 1 lists the heights and height ratios of the four HATS configurations. An aerodynamic displacement height h_d of 32 cm and a surface roughness length of 2 cm were calculated from near–neutral wind profiles measured at the site. The HATS range of z/z', corrected for h_d, is 0.48–2.09, similar to that for the KMOW data. The following results were calculated from 49 stationary 25–60 minute periods, which were selected to cover a wide range of stability from each of the four sonic configurations.

Table 1. HATS Transverse Array Dimensions

Configuration	$z_d - h_d$ (m)	$z_s - h_d$ (m)	z/z'
1	3.13	6.58	0.48, 2.10
2	4.01	8.34	0.48, 2.08
3	8.34	4.01	0.48, 2.08
4	3.83	4.83	0.79, 1.26

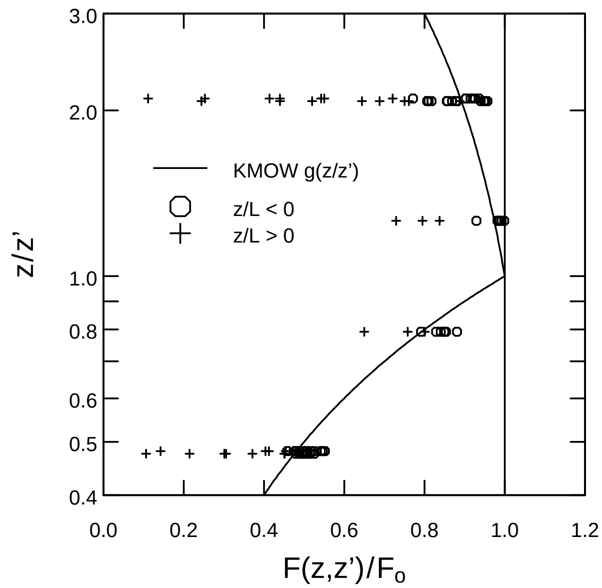

Figure 3: Flux attenuation for vertical sensor displacement as a function of the height ratio z/z'.

3. VERTICAL SENSOR DISPLACEMENTS

Four unique values of z/z' are available from the HATS data, 2.09, 1.26, 0.79, and 0.48, while the measurement height, $z_{agl} - h_d$, ranges from 3.13 m to 8.34 m. Figure 3 shows $F(z,z')/F_o$ as a function of z/z', along with the KMOW formula for $F(z,z')/F_o = g(z/z')$, Equation (1). The HATS data are in qualitative agreement with the KMOW formula and support the KMOW finding that flux attenuation is less for the scalar sensor located below the anemometer than for the opposite configuration.

The HATS data points are plotted separately for stable and unstable stratification. It can be seen that the flux attenuation for stable stratification is generally greater than estimated by the KMOW formula and for unstable stratification is often less than estimated by KMOW, consistent with our suggestion that Equation (1) corresponds to near-neutral stratification.

Like KMOW, we are unable to provide a quantitative theoretical model for flux attenuation due to vertical sensor displacements. Rather, we have tried two ad-hoc models to represent the dependence of flux attenuation on atmospheric stability: a linear model and an exponential model. The linear model is a generalization of the near-neutral KMOW model, Equation (1),

$$F(z,z') = F_o[1 - A(z/z', z/L)\, r_z/z'] \quad , \qquad (2)$$

where $r_z = |z - z'|$ and A is assumed to depend on

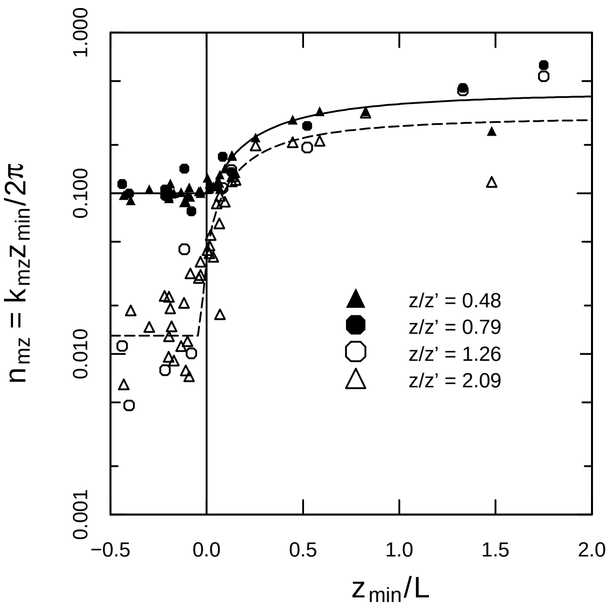

Figure 4: n_{mz} for vertical sensor displacement as a function of z_{min}/L and z/z'.

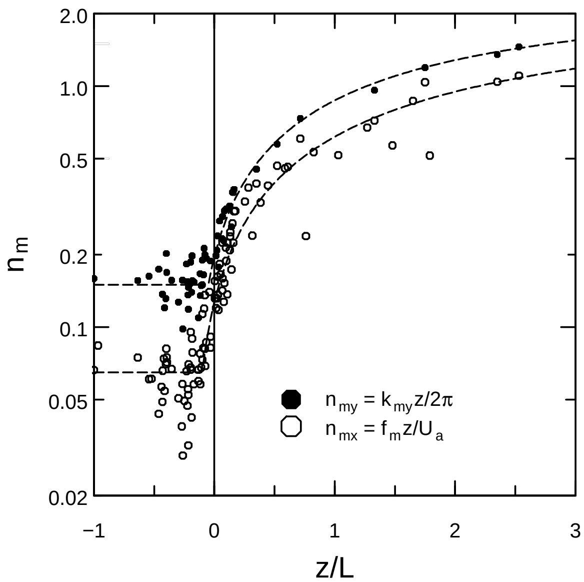

Figure 5: Dimensionless frequency or wavenumber at the maxima of the streamwise and crosswind flux cospectra as a function of z/L.

both z/z' and z/L. The exponential model is similar to an approximate model derived by Horst (2006) for horizontal sensor displacement,

$$F(z,z') = F_o \exp(-k_{mz} r_z) \qquad , \tag{3}$$

where k_{mz} is also assumed to depend on both z/z' and z/L. In the case of a streamwise sensor displacement, k_{mx} is the wave number at the maximum of the frequency-weighted flux cospectrum. We have used the notation k_{mz} in Equation (3) in order to facilitate comparison with corresponding variables for horizontal displacement, but we do not mean to imply that these parameters have the same physical meaning as the corresponding horizontal parameters.

These two models are similar for small values of Ar_z/z' or $k_{mz}r_z$, but the HATS data extend to sufficiently large values of r_z/z' to differentiate between the two models, particularly for $z/z' < 1$. The coefficients A and k_{mz} can be determined for each case of the HATS data from Equations (2) and (3) and plotted as a function of z/L and z/z'. We find that the collapse of the calculated coefficients to universal functions of stability, one for $z/z' < 1$ and another for $z/z' > 1$, is better with the exponential model than with the linear model.

Figure 4 shows the dimensionless 'wave number' $n_{mz} = k_{mz}z_{min}/2\pi$ for the HATS data as a function of z_{min}/L where z_{min} is the smaller of z and z'. (For both models we also tried, with less success, vertical length scales equal to z, z', z_{max} and $(z+z')/2$.) The observations in Figure 4 are approximated with the empirical formulas

$$n_{mz}(z/z' < 1) = \begin{cases} 0.1, & z_{zmin}/L \leq 0.03; \\ 0.43 - 0.33/(0.964 + 1.2z_{zmin}/L)^2, & z_{zmin}/L > 0.03, \end{cases} \tag{4}$$

and

$$n_{mz}(z/z' > 1) = \begin{cases} 0.013, & z_{zmin}/L \leq -0.03; \\ 0.3 - 0.287/(1.051 + 1.7z_{zmin}/L)^2, & z_{zmin}/L > -0.03. \end{cases} \tag{5}$$

Note that $k_{mz}(z/z' > 1)$ is less than $k_{mz}(z/z' < 1)$ for all stability, extending the observation of KMOW that $F(z/z' > 1) > F(z/z' < 1)$ to a broad range of stratification. Comparison of Figure 4 with Figure 5 for horizontal sensor displacements (Horst, 2006) similarly extends to a greater range of stratification the finding of KMOW that flux attenuation with the scalar sensor displaced below the anemometer is less than that for an equal horizontal displacement, particularly for unstable stratification.

Figure 6 compares $F(z,z')/F_o$ as a function of $k_{mz}r_z$ to the exponential model, Equations (3–5). Since the HATS data have only one pair of $F(z,z')/F_o$ and r_z for each case, the values of k_{mz} calculated from Equation (3) identically satisfy the exponential model. Hence we have used the values of k_{mz} calculated from the

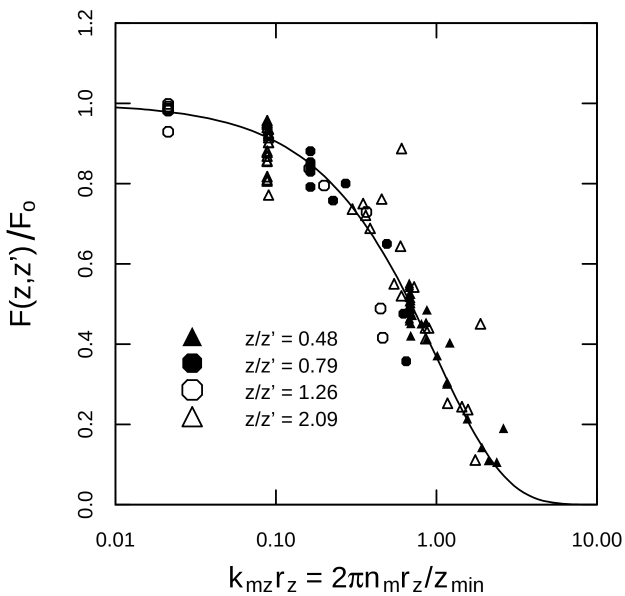

Figure 6: Flux attenuation for vertical sensor displacements as a function of $k_{mz}r_z$.

empirical Equations (4–5) to plot the points in Figure 6. The vertically-aligned points correspond to unstable stratification, or constant values of k_{mz}, for each of the four unique vales of z/z', whereas the scattered points correspond to stable stratification where k_{mz} depends strongly on stability. Note that Figure 6 is consistent with the expectation that flux attenuation increases with the ratio of sensor displacement to measurement height.

4. CONCLUSIONS AND DISCUSSION

The HATS data extend to a broad range of stratification the observation of Kristensen et al. (1997) that flux attenuation is less for the scalar sensor located below the anemometer than for either an equal horizontal displacement or for the scalar sensor located above the anemometer. We find that the flux measured with vertically-displaced sensors decreases more rapidly with increasing displacment for stable stratification than for unstable, as also observed for horizontal displacements, e.g. Figures 4 and 5.

Neither KMOW nor this author have been able to derive a theoretical expression for flux attenuation caused by vertical sensor displacement and, consequently, we are both limited to ad-hoc empirical formulas to describe our observations. The HATS data suggest that the linear KMOW formula for $g(z/z')$, Equation (1), applies best to near-neutral stratification. For a broader range of stratification, we find that an exponential model, Equations (3–5), is better able to organize the observations into one universal relationship for $z/z' > 1$ and another for $z/z' < 1$. Matching the HATS model to the KMOW formula suggests that the latter formula applies for $z_{min}/L \sim -0.025$.

These results were obtained with turbulence data measured within a horizontally–homogeneous surface–flux layer, that is, where the turbulence structure is found to depend only on height above the surface and on the surface fluxes of momentum and buoyancy as described by Monin–Obukhov similarity. The HATS flux attenuation formulas are not valid where the dependence on wavenumber of the scalar–flux cospectrum differs materially from that in the surface–flux layer, as is likely to be true for measurements in advective conditions, in complex terrain, over a wavy water surface, within a canopy, or within the roughness sublayer above the canopy.

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