Horizontal Coherence Decay Near Large Mesoscale Variations in Topography

STEVEN G. PERRY,[1] JOHN M. NORMAN,[1,3] HANS A. PANOFSKY[1]
AND J. DAVID MARTSOLF[2]

Pennsylvania State University, University Park, PA 16801

(Manuscript received 8 December 1977, in final form 24 May 1978)

ABSTRACT

A surface layer experiment is described which includes measurements of turbulent velocities at 2 m above the surface with an array of newly developed drag anemometers. The experiment site is located in central Pennsylvania where mesoscale topographic irregularities exist. The presence of a low mountain ridge near the site affects the estimated lateral scale of turbulence and the fluctuations of the lateral velocity component. A good correlation has been found between the variance spectrum of the lateral (or crosswind) velocity component and an estimate of the lateral Eulerian integral scale of the longitudinal velocity component. This can provide future estimates of the lateral scale from turbulent velocity measurements at a single location.

A model for the decay of horizontal coherence which accounts for the stability, roughness and instrument separation has been suggested in a previous paper by Panofsky and Mizuno. The present data compare favorably with this model. The effect of stability on coherence decay is found to have a definite site dependence.

1. Introduction

Many surface layer turbulence measurements have been made in the past at sites with very long homogeneous fetch [e.g., O'Neill, NE (Haugen, 1959)]. In this study, conducted in central Pennsylvania amidst the ridges of the Allegheny Mountains, similar turbulence measurements have been made at a site where the local fetch is uniform but the nearby topography includes a low mountain ridge. The effects of this ridge on the lateral scale of turbulence (more accurately the lateral Eulerian integral scale) and horizontal coherence decay will be considered.

Measurements of horizontal coherence are of interest because of a model proposed by Panofsky and Mizuno (1975) in an effort to account for the decay of horizontal coherence (with increasing instrument separation) under a wide variety of meteorological conditions. This model was suggested by the behavior of previous coherence measurements at O'Neill. A comparison of the model with the present data and that of O'Neill will be discussed.

2. Experimental design

The site for this experiment is located on The Pennsylvania State University Agricultural Experiment Station in Rock Springs, 8 mi southwest of State College. It is situated in a broad, flat valley bordered by ridges of the Allegheny Mountains. To the southwest and northeast, the terrain is relatively flat for several kilometers, with variations in topography generally less than 3 or 4 m. To the north are rolling grass-covered hills with scattered trees and houses approximately 0.5 km from the site. To the south and southeast are grassy fields for several hundred meters giving way to trees and eventually a mountain ridge, 220 m above the site, less than a kilometer away. The orientation of the ridge is approximately southwest to northeast (236° to 56°). The prevailing wind direction in the area is from the southwest so that often the upwind fetch is quite long over reasonably homogeneous terrain. It is the crosswind mesoscale features which make this site different from previous experimental sites where similar measurements have been obtained. The immediate area containing the instrument array either contained corn stubble ($z_0 \approx 1.0$ cm), was plowed field ($z_0 \approx 0.40$ cm), or in some of the winter runs, was snow covered ($z_0 \approx 0.1$ cm). The roughness lengths z_0 were determined from mean wind profile measurements.

The experiment was designed to measure the three orthogonal velocity components at seven locations in a movable array under various conditions of atmospheric stability and wind direction.

The T-shaped anemometer array consisted of five masts aligned approximately along the mean wind at spacings of 5, 10, 20 and 40 m, and two masts aligned perpendicularly to the mean wind at 10 and 35 m from the central tower. A drag anemometer was mounted

---

[1] Department of Meteorology.

[2] Department of Horticulture.

[3] Present affiliation: Department of Agronomy, University of Nebraska, Lincoln 68583.

0022-4928/78/1884-1889$05.00

TABLE 1. Results from Rock Springs, Pennsylvania (1976–77).

Date	Time (EST)	$\bar{U}$ (m s^{-1})	Wind direction (deg)	α* (deg)	L_y (m)	Ri	σ_v (m s^{-1})	σ_w (m s^{-1})	z_0 (cm)	Temperature (°C)	Ground cover
2/07/76	1805–1833	3.66	242	2	105	0.01	0.57	0.17	0.10	−12	20 cm snow
	1922–1936	5.59	232	−8	74	0.01	0.69	0.30	0.10	−12	20 cm snow
	2025–2045	6.28	219	−21	80	0.01	1.21	0.38	0.10	−12	20 cm snow
2/12/76	1226–1300	4.03	217	−3	320	0.03	1.17	0.45	0.15	−1	5 cm snow
	1354–1422	3.57	231	11	145	0.06	1.37	0.34	0.15	−1	5 cm snow
3/20/76	1333–1450	6.45	218	−2	76	0.01	1.85	**	0.20	21	bare
	1503–1530	6.81	202	−18	138	0.02	2.52	**	0.20	21	bare
3/23/76	1720–1738	3.78	264	14	106	0.02	0.67	**	0.71	11	bare
	1810–1832	1.36	244	−7	86	0.22	0.16	**	0.75	9	bare
3/26/76	1231–1259	4.05	233	13	240	−0.06	1.83	0.36	0.14	18	bare
	1402–1435	4.76	218	−2	204	−0.04	1.60	0.38	0.15	20	bare
	1556–1624	3.72	215	−5	200	−0.00	1.26	0.31	0.16	21	bare
2/28/77	1738–1800	5.01	275	15	25	0.00	0.76	0.43	1.30	−1	corn stubble
3/17/77	1309–1331	5.56	293	13	56	−0.09	1.60	0.46	1.23	2	corn stubble
3/23/77	1805–1830	5.94	301	21	33	0.03	1.15	0.52	0.51	5	corn stubble
	1957–2019	3.89	294	14	23	0.07	0.64	0.34	0.43	4	corn stubble

* Angle between direction of instrument separation and mean wind.
** Data unavailable.

on each mast such that the drag elements were positioned 2 m above the surface. At the center, or pivot point, of the array was a rigid 6 m triangular tower that served as a support for one of the seven drag anemometers, sensitive cup anemometers at four levels for velocity profile information, an aspirated, shielded 10-junction thermopile at two levels for temperature profile data, and a sensitive wind vane for continuous wind direction monitoring. The central anemometer served both axes of the array.

The turbulent velocity measurements were made with seven fast-response drag anemometers which were designed, constructed and tested at The Pennsylvania State University (Norman *et al.*, 1976). Each anemometer is temperature compensated through a range from −15 to 28°C, has a resonant frequency of 20 Hz (viscously damped), contains an electrical filter with a cutoff frequency of 5 Hz, has orthogonality between velocity components within 0.2°, and has a measuring range from 0.5 to 14 m s^{-1}. Also each of the drag components has been calibrated over its full range in a wind tunnel.

The drag anemometer has been compared with a sonic anemometer[4] and, when great care was taken in the alignment of the drag elements, the spectra and cross spectra measured by the two instruments were almost indistinguishable. In addition, a comparison of means and variance (for all three velocity components) from the drag anemometer and a pressure sphere anemometer indicates agreement within a few percent (Norman *et al.*, 1976). The output from each velocity component of the drag anemometers was sampled at a rate of 20 samples per second (31.5 samples per second in a few cases) for periods ranging from about 15 to 75 min. The electrical signals from all the instruments in the field were digitized on site and recorded on magnetic tapes under the control of a NOVA 2/10 minicomputer.

Table 1 summarizes the important measurements and details at Rock Springs during the periods for which analyses are described in this paper.

3. Lateral Eulerian integral scale

Very important to the understanding of the structure of atmospheric turbulence are turbulent length scales. In a model for the decay of horizontal coherence Panofsky and Mizuno (1975) use the lateral Eulerian integral scale L_y as a measure of the average lateral dimension of large horizontal eddies. To test this hypothesis, three anemometers at Rock Springs were positioned in a line perpendicular to the mean wind direction. The lateral integral scale was estimated assuming an exponential fall-off of the correlation between the longitudinal velocity components separated at crosswind distances up to 35 m. Compared to lateral scales, obtained from previous measurements at O'Neill, those measured at Rock Springs were considerably larger. Lateral scales estimated from O'Neill ranged from 1 m up to 43 m with the increase occurring with increasing instability. Those obtained at Rock Springs ranged from 23 m up to 320 m with no obvious dependence on stability. The apparent source of the contrasting results was the nearby mountain ridge at the Rock Springs site. The terrain at the O'Neill site has a uniform fetch of 800 m with minor variations beyond, but at Rock Springs a ridge of the Allegheny Mountains (<1 km away) rises 220 m above the site. This ridge is a significant obstacle to the large-scale flow.

---

[4] Unpublished results from an experiment at Risø, Roskilde, Denmark, August, 1974

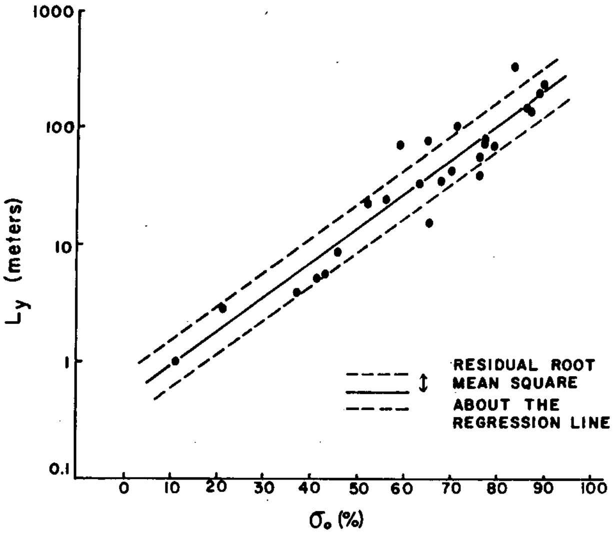

FIG. 1. Lateral integral scale L_y estimated from Rock Springs and O'Neill, measurements, as a function of the fraction of variance σ_0 of the lateral velocity component for $nz/u < 0.025$.

The relative size of the lateral scales at Rock Springs (as well as the fluctuations in the lateral velocity) was larger, in general, if the wind direction was nearly perpendicular to the ridge than in the cases where the mean wind direction was such that the air flowed down the relatively uniform valley before reaching the site.

At present the only method for estimating the lateral integral scale from measurements is by means of instrument arrays of several anemometers spaced perpendicularly to the mean wind direction. This process could be avoided and the lateral scale would be a more useful quantity if measurements at a single location were sufficient. Therefore, a relation was sought between the lateral scale and a quantity that could be obtained at one location.

Since the variance spectrum of the motions in a particular direction is often related to the length scale of those motions, the variance spectrum of the lateral velocity component was given special attention. A good linear relation was found between the logarithm of the lateral scale and the fraction of the variance (area under the spectrum) below $f=0.025$ ($f=nz/U$, where z is the measurement height, n the frequency and U the mean wind speed). The selection of $f=0.025$ was not arbitrary. In most of the spectra considered there was a relative minimum at approximately this nondimensional frequency. In cases of small L_y (O'Neill data) there is a large percentage of the variance above $f=0.025$. In cases where large L_y are observed, as was generally the case at Rock Springs, most of the variance is below the value of $f=0.025$.

The linear relationship which results by plotting $\ln(L_y)$ as a function of the fraction of variance below 0.025 (Fig. 1) is

$$\ln(L_y)=b_0+b_1\sigma_0, \qquad (1)$$

where σ_0 is the fractional variance, $b_0=-0.69\pm0.27$, and $b_1=0.067\pm0.004$ (±0.27 and ±0.004 are the standard errors of b_0 and b_1, respectively). The small scatter about the regression line shows that (1) should yield fairly accurate estimates of L_y. Therefore, estimates of lateral scale are made possible by turbulent velocity measurements at a single location.

Eq. (1) is presumably not the best relationship because horizontal velocity spectra depend on z_i rather than z (Kaimal, 1978). Unfortunately, measurements of z_i were not available at the time the present experiment was performed. Also the regression line should be asymptotic at the extremes of variance (0% and 100%), to make complete physical sense, but Eq. (1) still applies well in the practical range of $10\% < \sigma_0 < 95\%$.

4. Coherence

Interest in coherence (which can be thought of as a correlation between two time series in frequency space) has recently increased among those concerned with the three-dimensional structure of atmospheric turbulence. In terms of turbulence structure, coherence between velocity components separated in space can be described as a measure of eddy velocity persistence. Mathematically, however, coherence (sometimes known as squared coherence) is expressed, according to Lumley (1970), as a measure of the square of the correlation between the Fourier component of two time series with their phases adjusted to obtain maximum correlation. It is given by

$$\mathrm{coh}(n)=[\mathrm{Co}^2(n)+Q^2(n)]/[S_1(n)S_2(n)], \qquad (2)$$

where n is frequency, $S_1(n)$ and $S_2(n)$ are estimates of the spectral density of the two time series, $\mathrm{Co}(n)$ is the cospectrum and $Q(n)$ the quadrature spectrum. Coherence values range from zero, for no correlation, to one for perfect correlation.

An empirical expression for coherence decay was first given by Davenport (1961) in the form

$$\mathrm{coh}(n)=\exp(-an\Delta z/U), \qquad (3)$$

where a is the decay parameter, Δz the vertical instrument separation and U the mean wind speed. Pielke and Panofsky (1970) generalized Eq. (3) to include horizontal separation and obtained

$$\mathrm{coh}(n)=\exp(-a\Delta f), \qquad (4)$$

where Δf is a nondimensional frequency defined as $n\Delta x_i/U$ (Δx_i is the instrument separation in the ith direction). This study limits itself to the longitudinal instrument separation (i.e., Δx_1 along the mean wind direction) and streamwise wind component.

5. A model for the decay parameter

Several previous studies have been done on the empirical properties of the decay parameter a in relation to atmospheric stability, α (the angle between the axis of instrument separation and the mean wind direction), surface roughness and instrument separation (Berman, 1972; Ropelewski *et al.*, 1973; Powell, 1974; Panofsky *et al.*, 1974). Variations in a with instrument separation have been detected by Panofsky and Mizuno (1975) in presently available data from O'Neill (Haugen, 1959). Three runs were used during which the angle α was less than 10°. For stable and neutral conditions the decay parameter increased as Δx, the instrument separation, increased, but for unstable conditions a does not appear to depend significantly on Δx. An empirical relationship between a and separation was suggested as a result of these findings to be

$$a=a_0(1+b\Delta x). \tag{5}$$

Powell's (1974) observations at Hanford, Washington, agree with these conclusions, also suggesting an increase of a with increasing separation for stable and neutral cases.

Assuming the relationship between a and Δx to be of the form shown in (5), Panofsky and Mizuno (1975), with results from Ropelewski *et al.* (1973), suggested that the intercept a_0 is solely dependent on the intensity of turbulence σ_w/U (σ_w is the standard deviation of the vertical velocity), and that the loss of coherence when instrument separation is not considered is simply a function of terrain roughness and stability. To explain the behavior of a for varying instrument separations Panofsky and Mizuno proposed that b [in (5)], which accounts for the loss of coherence due to wind direction fluctuations about the longitudinal axis of the instrument array, is proportional to $\sigma_v t/L_y$, where σ_v is the standard deviation of the lateral velocity and L_y is the lateral Eulerian integral scale of the longitudinal velocity component. This quantity measures the ratio of typical lateral distances traveled in time t to the lateral integral scale. The complete model then becomes

$$a=(c\sigma_w/U)(1+C\sigma_v\Delta x/L_y), \tag{6}$$

where c and C are nondimensional coefficients.

Eq. (6) implies that the decay parameter becomes negligible (i.e., slight coherence decay) if σ_w is small, regardless of the fluctuations in the wind direction. This behavior is of doubtful physical reality. Therefore, a more satisfying expression for a which is comparable to the Panofsky and Mizuno formulation is

$$a=(c\sigma_w/U)+(C\sigma_v\Delta x/UL_y), \tag{7}$$

in which the intensity of turbulence and the wind fluctuation effects are additive. It is the expression for a [Eq. (7)] that will be considered with the present data from this study as well as those from O'Neill.

6. Some results

As seen from (3) the decay parameter a is the slope of a graph of $\ln[\mathrm{coh}(n)]$ as a function of Δf for a *given instrument separation*. Such graphs were constructed and a values were estimated for each of the data sets from Rock Springs (Fig. 2). A different value of a is found for each separation. The confidence in coherence estimates decreases as the numerical values become very small. Therefore, the linear fits to the semi-log plots of coherence and Δf were obtained subjectively where values of coherence less than 0.1 were given very little weight. The decay parameter is then plotted as a function of Δx and a linear fit is obtained in each case (Fig. 3), as had previously been done with the O'Neill data. Error bars on the data points represent the maximum uncertainty in a with the subjective fit.

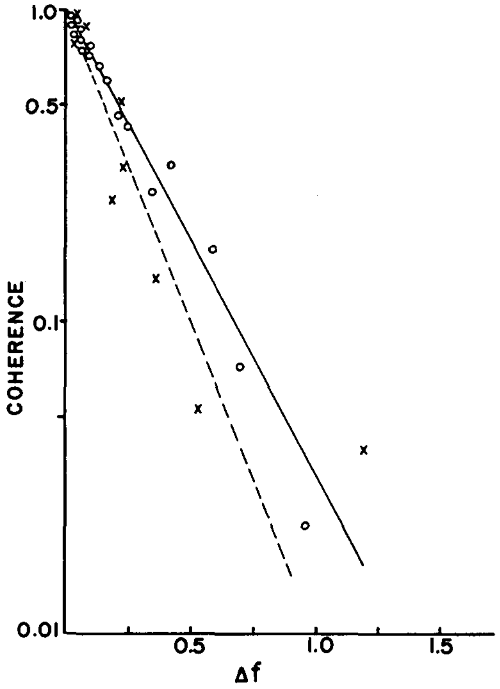

Fig. 2. Sample of the observed exponential decay of horizontal coherence at Rock Springs for near-neutral stability. The solid line represents a subjective fit to the decay over a 5 m instrument separation, the dashed line over a 60 m instrument separation.

An increase of a with increasing Δx for stable and neutral cases was found at O'Neill, but little dependence of a on Δx was found for the unstable case. In contrast, the Rock Springs results indicate a generally weak dependence of a on Δx for all Richardson numbers ranging from -0.09 to $+0.22$. Table 2 shows a comparison between various quantities from O'Neill and Rock Springs. The only glaring differences are the mesoscale terrain features and the lateral integral scales.

The unusually large lateral scales found at Rock Springs retard the decay of coherence from instrument separation by reducing the second term in the expression for the decay factor given by (7).

Probably the more important term of (7) is the second which indicates this instrument separation effect on coherence decay. Fig. 4 shows a plot of the slopes of the relation between a and Δx as a function

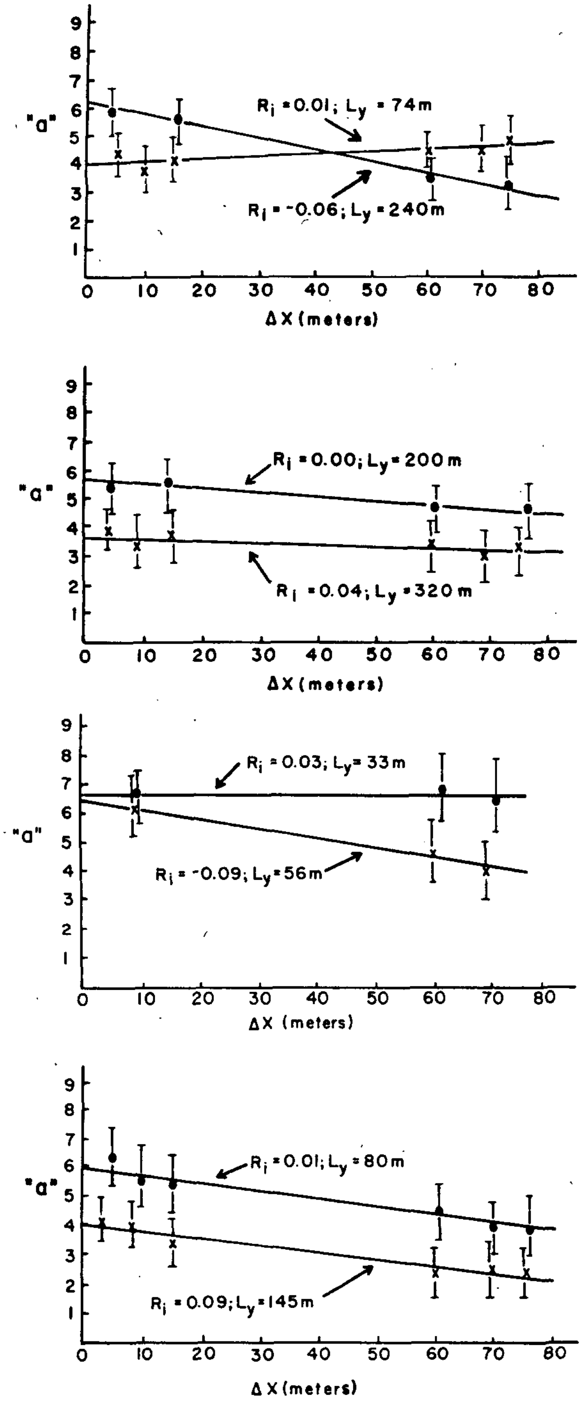

FIG. 3. Decay parameter a as a function of instrument separation Δx for several typical cases at Rock Springs. Bars on the data points represent the maximum uncertainty in a from the subjective fits to the exponential roll off of coherence.

TABLE 2. Comparison between Rock Springs and O'Neill.

Parameter	Rock Springs	O'Neill
Ri	−0.09–+0.22	−0.10–+0.10
z_0 (cm)	0.08–1.30	0.30–1.50
$-\rho\overline{u'w'}$ (dyn cm^{-2})	~1	~1–2
L_y(m)	23–320	1–43
σ_w/U	0.04–0.11	0.02–0.12
Local fetch	<0.2 m variations over 100 m	<0.3 m variations over 100 m
Mesoscale fetch	>200 m variations at 1–3 km	Negligible variations

of σ_v/UL_y as proposed by (7). The line drawn on this figure is a linear fit to only the O'Neill data indicated with crosses. The values of L_y at O'Neill varied such that the calculated values of the proposed slope covered a broad enough range to determine the linear fit. Unfortunately, for this analysis the values of L_y were sufficiently large at Rock Springs that all the new points on Fig. 4 are crowded near the origin. Even though these points do not delineate the relationship determined by the O'Neill values, they do correspond with the fit and reinforce the position of the line near the origin. If the theory is assumed correct, then the constant C in (7), evaluated from the data shown in Fig. 4, is 6.3±0.7. There is one difference between the second term in (7) and the observed data. Eq. (7) would have predicted a zero intercept where the data show a small negative value. The theory does not explain this discrepancy.

If the first term in (7) is considered alone by assuming the instrument separation as zero, the variation in a (or in this case a_0) should depend only on the intensity of turbulence. Fig. 5 is a plot of a_0 as a function of turbulence intensity σ_w/U. If (7) were correct Fig. 5 should show a linear relationship with a zero intercept. Unfortunately, this is not obvious when considering the large amount of scatter and the insufficient data at low intensities of turbulence. Assuming, however, that the theory is correct and fitting a line through the data, the

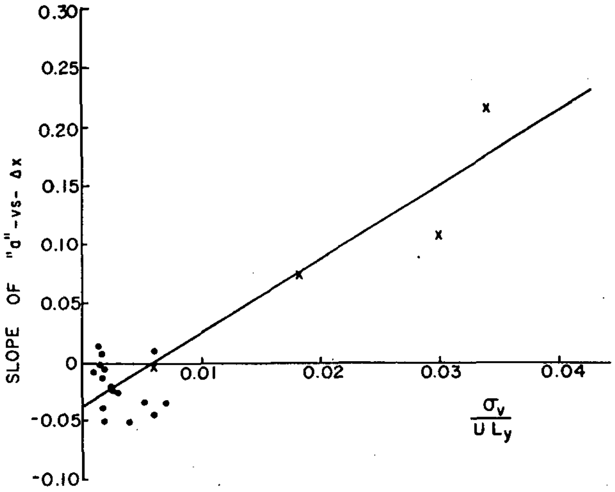

FIG. 4. The slope of the relationship between a and Δx for O'Neill (×) and Rock Springs (●), plotted as a function of the proposed slope σ_v/UL_y in Eq. (7).

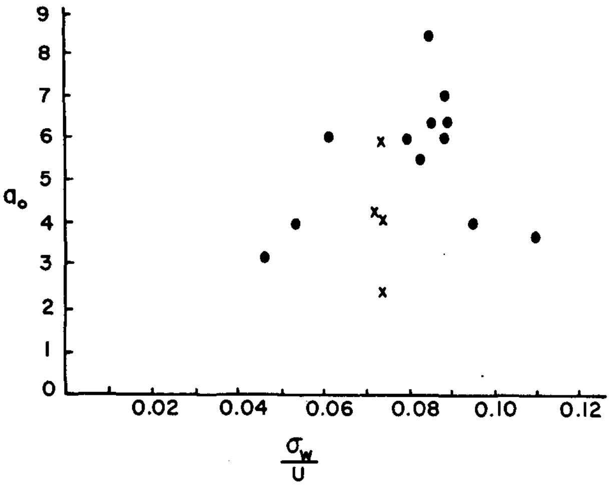

FIG. 5. The intercept a_0 of the relationship between a and Δx for O'Neill (×) and Rock Springs (●), plotted as a function of the intensity of turbulence, σ_w/U, as suggested by Eq. (7).

constant c in (7) is found to be 65±5. It should be said, though, that the present data do not adequately confirm the dependence of coherence decay on turbulence intensity indicated in (7).

7. Summary and conclusions

Surface layer turbulence measurements have been made near a low mountain ridge which show considerably larger values for the lateral scale of turbulence than those obtained from previous measurements. An increase in the variance of the lateral velocity component (at low frequencies) due to the presence of a ridge correlates well with an increase in the size of the lateral Eulerian integral scale. Therefore, the lateral scale can be estimated to a fair degree of accuracy from the turbulent velocity measurements at a single location.

At O'Neill, Nebraska, and Rock Springs, Pennsylvania, for cases of small angles between the anemometer line and the mean wind direction, the proposed expression (7) is a reasonable representation for the coherence decay parameter over a large range of experimental conditions.

Acknowledgments. This study was supported by the Atmospheric Sciences section of the National Science Foundation under Grant DES 74-24105. The authors gratefully acknowledge the assistance of Dr. G. W. Thurtell of the University of Guelph, Guelph, Ontario, and Drs. N. Busch, N. O. Jensen and L. Kristensen of Risø, Roskilde, Denmark, for their indispensable assistance in comparing the prototype drag anemometer to more well-established instruments. We would like to thank the Department of Agronomy of The Pennsylvania State University for providing the land for the field experiment. Finally the authors also acknowledge the assistance of Dr. D. W. Thomson, R. Brower, J. Breon, R. Peters, T. Chin and R. Thompson throughout the preparatory and operational phases of this research.

REFERENCES

Berman, S., 1972: Coherence characteristics of horizontal wind components near the ground. Ph.D. thesis, University of Wisconsin, Madison, 114 pp.

Davenport, A. G., 1961: The spectrum of horizontal gustiness near the ground in high winds. *Quart. J. Roy. Meteor. Soc.*, **87**, 194–211.

Haugen, D. A., Ed., 1959: Project Prairie Grass: A field program in diffusion. Geophys. Res. Pap., No. 59, Vol. 3, AFCRL, Bedford, MA.

Kaimal, J. C., 1978: Horizontal velocity spectra in an unstable surface layer. *J. Atmos. Sci.*, **35**, 18–24.

Lumley, J. L., 1970: *Stochastic Tools in Turbulence.* Academic Press, 194 pp.

Norman, J. M., S. G. Perry and H. A. Panofsky, 1976: Measurement and theory of horizontal coherence at a two-meter height. *Preprints Third Symp. Atmosphere Turbulence Air Quality*, Rayleigh, Amer. Meteor. Soc., 26–31.

Panofsky, H. A., and T. Mizuno, 1975: Horizontal coherence and Pasquill's beta. *Bound.-Layer Meteor.*, **9**, 247–256.

——, D. W. Thomson, D. A. Sullivan and D. E. Moravek, 1974: Two point statistics over Lake Ontario. *Bound.-Layer Meteor.*, **7**, 309–321.

Pielke, R. A., and H. A. Panofsky, 1970: Turbulence characteristics along several towers. *Bound.-Layer Meteor.*, **1**, 115–130.

Powell, D. C., 1974: Analysis of parallel and orthogonal wind components along lines of towers over homogeneous desert. Ph.D. thesis, University of Utah, 226 pp.

Ropelewski, C. F., H. Tennekes and H. A. Panofsky, 1973: Horizontal coherence of wind fluctuations. *Bound.-Layer Meteor.*, **5**, 353–363.