Drag Anemometer Measurements of Turbulence over a Vegetated Surface[1]

T. GRAYSON REDFORD, JR., SHASHI B. VERMA AND NORMAN J. ROSENBERG[2]

Institute of Agriculture and Natural Resources, The University of Nebraska-Lincoln

(Manuscript received 5 June 1980, in final form 1 April 1981)

ABSTRACT

Turbulent fluctuations of vertical wind and fluxes of momentum, sensible heat and latent heat measured with a drag anemometer are compared to like data measured with other instruments. Means of the measured parameters agreed well with energy balance computations of the heat fluxes and profile measurements of the momentum flux. Drag anemometer measurements of turbulent fluxes generally exceeded those obtained with a propeller anemometer, run concurrently. Spectral analysis indicates that the propeller anemometer did not respond well at high frequencies, causing an underestimation of the fluxes and vertical wind fluctuations. The drag anemometer appears to respond well up to 5 Hz.

1. Introduction

Rapid fluctuations of wind speed in three dimensions have been measured by a number of researchers. Close to the ground where the energy containing fluctuations shift to higher frequencies, the requirements for rapid instrument response becomes quite demanding. Operation and calibration of many instruments used for this purpose (e.g., sonic, hot-wire and hot-film anemometers) requires special training. These instruments also are quite expensive. The drag anemometer of Norman *et al.* (1976) is less costly and less difficult to operate.

Here we report results from extensive tests of the drag anemometer conducted during the summer of 1978 at the University of Nebraska Field Laboratory near Mead. Turbulent fluctuations of wind speed and fluxes of momentum, sensible heat and latent heat measured over an alfalfa field with a drag anemometer are compared to concurrent measurements with Gill UVW propeller anemometers. The drag anemometer results are also compared to fluxes calculated from mean profile measurements and energy balance computations. Vertical velocity spectra and momentum flux cospectra derived from the drag anemometer measurements were analyzed and are presented here.

2. Methods

Two drag anemometers and a set of Gill UVW propeller anemometers were used to make simultaneous measurements of three dimensional velocity components over a well-watered alfalfa field during the summer of 1978. Fluctuations in air temperature and water vapor pressure were measured at the same time. Profiles of mean wind speed, air temperature and vapor pressure, net radiation and soil heat flux were measured concurrently. All sensors, except the net radiometers and soil heat flux plates, were located near the center of the north end of the experimental field. The field measures 400 m (N-S) by 110 m (E-W). In order to provide adequate fetch for the tests, measurements were made only when the wind was directed from 135 to 225°. The soil heat flux plates and net radiometers were located near the center of the eastern half of the field. The turbulence sensors were mounted in such a way that they would not interfere with one another. Two drag anemometers were positioned on one mast at 2.4 and 4.5 m above ground (the two drag anemometer units were interchanged several times during the season). The propeller anemometer was mounted 1.5 m horizontally from the upper drag anemometer on a second mast. Height of the alfalfa crop varied from 0.2 to 0.7 m during the periods of measurement. Most measurements were made when plant height was between 0.45 and 0.58 m. All data analyzed were taken during daylight with no precipitation and minimal cloudiness.

a. The drag anemometer

The drag anemometer used in these studies is based on the work of Norman *et al.* (1976). The

---

[1] Published as Paper No. 5993, Journal Series, Nebraska Agricultural Experiment Station. The work reported was conducted under Regional Research Project 11-33 and Nebraska Agricultural Experiment Station Project 11-49.

[2] Former Research Associate, Associate Professor and Professor, Center for Agricultural Meteorology and Climatology, Institute of Agriculture and Natural Resources, University of Nebraska, Lincoln 68583.

0021-8952/81/101222-09$06.25

instrument we tested (Fig. 1) was designed by Norman and built at the Pennsylvania State University. The drag force of the wind on an aerodynamic shape is proportional to the square of the wind speed. This force can be measured by the deflection of a strain gage attached to an object held perpendicular to the wind. Since the wind is not constant in direction, three mutually perpendicular wind sensing elements (1.5 cm in diameter and 4.5 cm in length) with strain gages attached can be used to resolve the instantaneous wind speed and direction. The basic equation used to compute the wind components from the strain gage output voltage V is

$$U = C_1 + C_2V^{1/2}, \qquad (1)$$

where the intercept C_1, which is very small, is a function of Reynolds number and the shape of the sensing element (Perry, 1977). Adjustments to the basic equation are required to account for interaction between the components and misalignment of the drag anemometer with respect to true vertical. This misalignment is accounted for by means of a coordinate transformation procedure following Tanner and Thurtell (1969). The internal alignment between the "mutually perpendicular" strain gages may be more critical than the "external" alignment discussed above. With care, the strain gages can be aligned to within about ¼ degree (of perpendicular) thereby minimizing the effect of misalignment on flux measurements (Dyer and Hicks, 1972).

Calibration was accomplished in a wind tunnel at the University of Nebraska Engineering Research Center. Each wind speed component was compared with the wind speed measured with a pitot tube mounted in the tunnel. The voltage output of the drag anemometer under no wind (V_0) was recorded before and after each calibration and its value was subtracted from the voltage measured in wind movement.

In operation the drag anemometer strain gage voltages were amplified in the field. Amplification for the horizontal components is selectable in order to retain maximum sensitivity over a wide range of wind speed. Strong winds pose no problem for the vertical component. Vibrations are viscously damped. Norman *et al.* (1976) and Perry (1977) give considerable detail on the operation and response characteristics of the anemometer.

b. Ancillary instrumentation

Drag anemometer performance was compared in the field with a Gill UVW propeller anemometer. The propeller consists of four helicoid polystyrene blades with a diameter of 23 cm. This instrument was also calibrated in the wind tunnel. The calibrations were used to correct the propeller anemometer data for its deviation from perfect cosine response. An iteration procedure similar to that of Horst (1972, 1973) was used for this purpose.

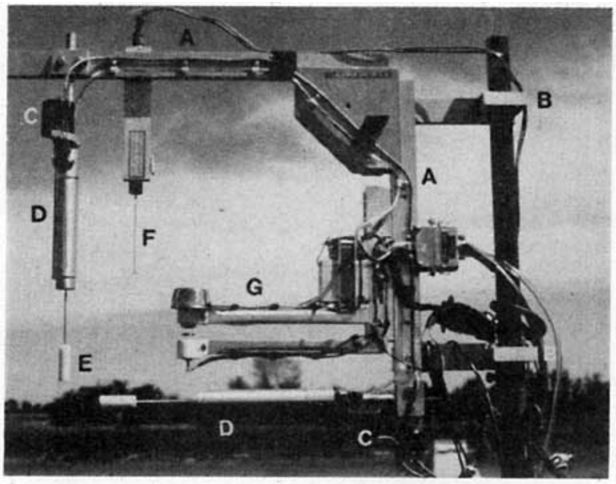

FIG. 1. Drag anemometer. (A) frame, (B) mounting brackets, (C) shroud motors, (D) strain gage assembly housing and shrouds, (E) wind sensing elements with a fine wire thermocouple (F) and a Lyman-alpha hygrometer (G).

A fine wire thermocouple psychrometer (dry and wet bulb thermocouples) (Tillman, 1973) was mounted at 4.5 m between the two vertical wind sensors to measure fluctuations in temperature and moisture content of the air and to allow calculation of vertical fluxes of water vapor and sensible heat. At the lower level (2.4 m) a Lyman-alpha hygrometer and a fine wire (dry-bulb) thermocouple were used to measure humidity and temperature fluctuations. The Lyman-alpha hygrometer and fine wire thermocouples are described in detail by Buck (1976), Redford *et al.* (1980), and Verma *et al.* (1979).

A computer-controlled data acquisition system, consisting of a minicomputer, analog-to-digital converters and a magnetic tape drive, was used to record all data. The turbulence signals were electrically filtered by a 5.2 Hz low-pass filter and sampled at 12.8 Hz. The slow response signals were sampled three times per minute.

The spectra were computed using fast Fourier transform. The spectra were run on series of 4096 data points. Eight such series were measured during the first 42 min, 40 s of each hour. Each series was tapered at the ends and linear trends were removed. The raw spectral estimates were logarithmically blocked to provide 25 smooth estimates over the range of frequencies. The eight spectra resulting were ensemble averaged by frequency for each hour of data. Cospectra were computed at the same time to allow analysis of the fluxes of momentum, sensible heat and moisture.

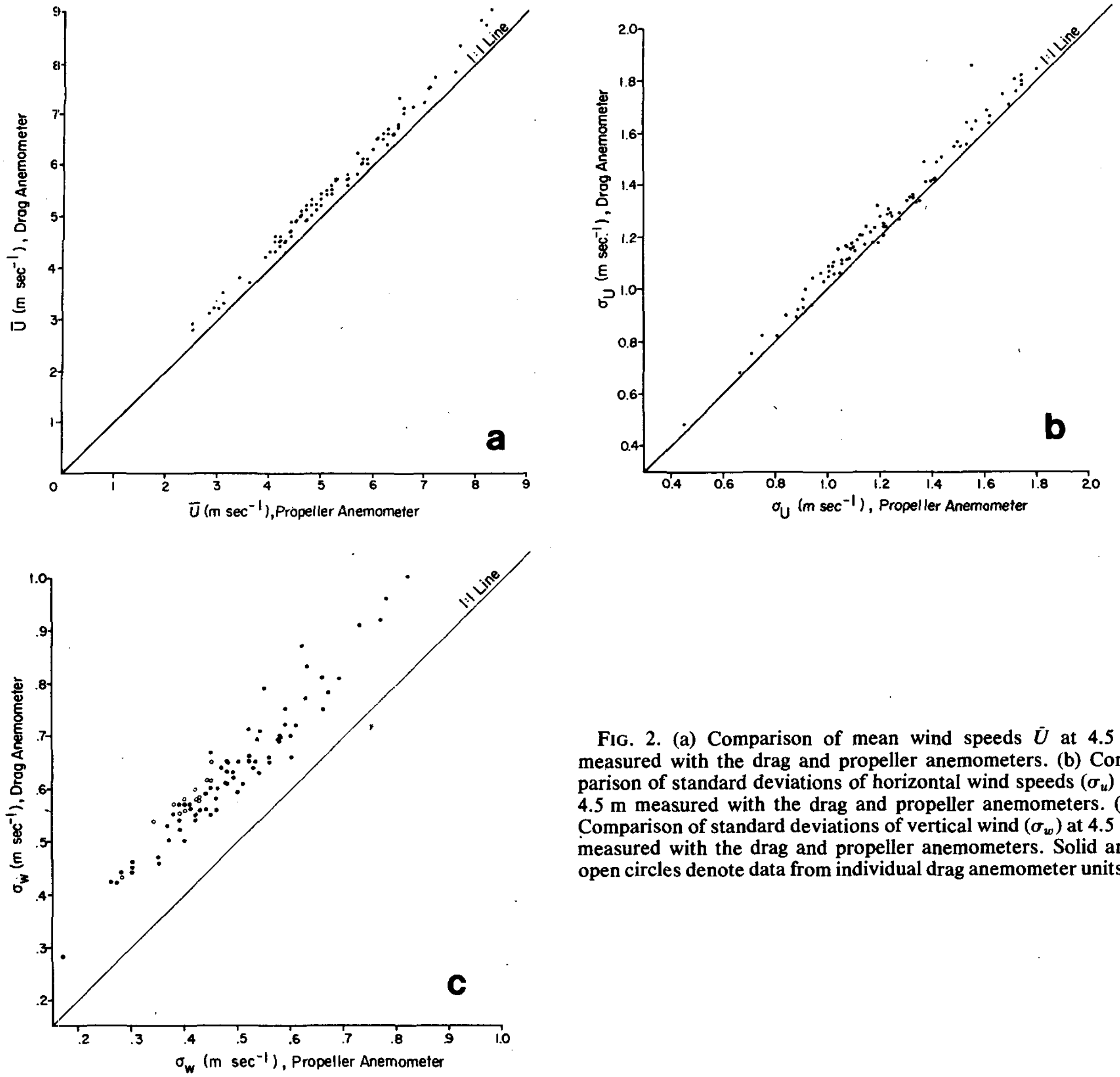

FIG. 2. (a) Comparison of mean wind speeds $\bar{U}$ at 4.5 m measured with the drag and propeller anemometers. (b) Comparison of standard deviations of horizontal wind speeds (σ_u) at 4.5 m measured with the drag and propeller anemometers. (c) Comparison of standard deviations of vertical wind (σ_w) at 4.5 m measured with the drag and propeller anemometers. Solid and open circles denote data from individual drag anemometer units.

3. Results

a. Mean wind speed and standard deviations

Standard deviations of vertical and horizontal wind speeds measured with the drag and propeller anemometers were computed as follows:

$$\sigma_x = (x^2 - \bar{x}^2)^{1/2}, \tag{2}$$

where the bar indicates a time average of the variable x measured during 43 min recording periods.

Results are shown in Figs. 2a, 2b and 2c. The means and standard deviations in horizontal winds (Figs. 2a and 2b) measured by the drag anemometer are somewhat larger than those measured by the propellers. The agreement between the drag anemometer and propellers is within ~5%. The high threshold response of the propellers probably accounts for much of the remaining difference. The horizontal component propellers had not been oriented with the mean wind direction bisecting them, as Horst (1973) has recommended they should be. The ratios of horizontal standard deviation to mean windspeed obtained with both instruments are similar to those reported by SethuRaman and Brown (1975) for an Aerovane. High threshold response causes more severe problems for the vertical component propeller (Fig. 2c) and additional inaccuracies are introduced due to the deviations from perfect cosine response above 0.3 Hz (Horst, 1973). With increasing wind speed the propeller time constant decreases and agreement with the drag anemometer is, thereby, improved. A comparison of vertical velocity spectra (discussed in detail below) suggest that the propeller agrees with the drag anemometer at low frequencies, but begins to underestimate severely at frequencies >0.3 Hz.

b. *Fluxes of sensible heat, latent heat and momentum*

Covariances of sensible heat, latent heat and momentum were computed using propeller and drag anemometer data in conjunction with data from fine wire thermocouples and the Lyman-alpha hygrometer. The fluxes were derived as follows:[3]

$$\text{Sensible heat flux}, A = -\rho_a C_p \overline{W'T'}, \tag{3}$$

$$\text{Latent heat flux}, LE = -L\overline{W'\rho_w'}, \tag{4}$$

$$\text{Momentum flux}, \tau = -\rho_a \overline{W'u'} = \rho u_*^2, \tag{5}$$

where ρ_a is the air density, C_p the specific heat at constant pressure, L the latent heat of vaporization corrected for temperature, W the vertical velocity, T the temperature, ρ_w the moisture density and u_* the friction velocity. The overbar indicates a time average (over 43 min recording periods) and the prime denotes deviations from the averaged quantity.

Additionally, the friction velocities were computed from the mean wind speed and air temperature profile data [measured by cup anemometers and self-checking thermocouple psychrometers—for details see Rosenberg and Brown, (1974)]. The flux-gradient relationships of Dyer and Hicks (1970) were employed for this purpose.

1) FLUXES AT 4.5 M

Fig. 3 shows fluxes computed by eddy correlation methods with data measured at 4.5 m. Sensible heat flux measured with the propeller anemometer was ~35% less than that measured with the drag anemometer (Fig. 3a). This is true for both negative and positive (upward and downward)[4] fluxes. The drag anemometer measurements are in general agreement with reports of heat fluxes over crops by Wesely *et al.* (1970), Desjardins (1972) and Hogstrom (1974). Latent heat fluxes (Fig. 3b) measured with the propeller anemometer are smaller by ~25% than those measured with the drag anemometer. Both sensible and latent heat fluxes based on drag anemometer measurements agree well with energy balance computations (see below).

Friction velocities determined with the propeller anemometer appear to be ~25% smaller than those measured with the drag anemometer (Fig. 3c). Friction velocity at 4.5 m measured with the drag anemometer is also compared to values computed by the profile method (Fig. 3d). Scatter is greater in the latter comparison, but agreement is good up to ~0.5 m s^{-1}. Above that value drag anemometer friction velocities are less than those derived from the wind profile. Note that a few of the points are labeled in Figs. 3c and 3d. The two outlying points, 1B and 1C, in Fig. 3c lie well within the envelope of points in Fig. 3d. Points 4A and 39C, which are in disagreement in Fig. 3d lie in the main body of points in Fig. 3c. For contrast, points 17A, 19A, 39B, 5B and 7C lie in approximately the same positions relative to the main body of points in both figures. There are no points for which the drag anemometer data disagree with both the propeller and profile data.

2) FLUXES AT 2.4 M

Employing the Bowen ratio-energy balance method (see, e.g., Rosenberg, 1974) sensible and latent heat fluxes at 2.4 m were computed from concurrent measurements of temperature, vapor pressure, net radiation and soil heat flux. Gradients of mean air temperature and vapor pressure were obtained by differentiation of second-order polynomials in lnz fitted to air temperature and vapor pressure data near the level in question. Five data points were used, the level in question, two above and two below. Friction velocity was also computed, as described earlier.

We recognize the limitations of the Bowen ratio-energy balance methods (e.g., Blad and Rosenberg, 1974; Hicks, 1977). Our purpose here, however, is to provide comparative data against which turbulent fluxes measured with drag anemometer may be examined. Despite considerable scatter in Figs. 4a and 4b the sensible and latent heat fluxes measured by the two methods agree in general. During a few runs the net radiation values may be aberrant because of intermittent cloudiness.

Fig. 5 shows a comparison of friction velocities measured at 2.4 and 4.5 m. Agreement is good. Comparisons of fluxes at 2.4 and 4.5 m demonstrate, as expected, the existence of a constant flux layer.

c. *Energy balance considerations*

All but a small portion of the radiant energy absorbed by the surface (Rn) is dissipated by transfer into the soil (S), transfer to the air as sensible heat (A) or used to evaporate moisture from the surface (LE). This may be represented as

$$Rn + S + A + LE = 0. \tag{6}$$

It should be worthwhile to compare the sum ($A + LE$), measured with the turbulence sensors,

---

[3] The sign convention employed here is such that the fluxes toward the crop or ground surface are positive.

[4] Under conditions of regional sensible heat advection the sensible heat flux was directed toward the crop and daytime temperature inversions prevailed. For a detailed discussion of sensible heat advection conditions, see Brakke *et al.* (1978) and Rosenberg and Verma (1978).

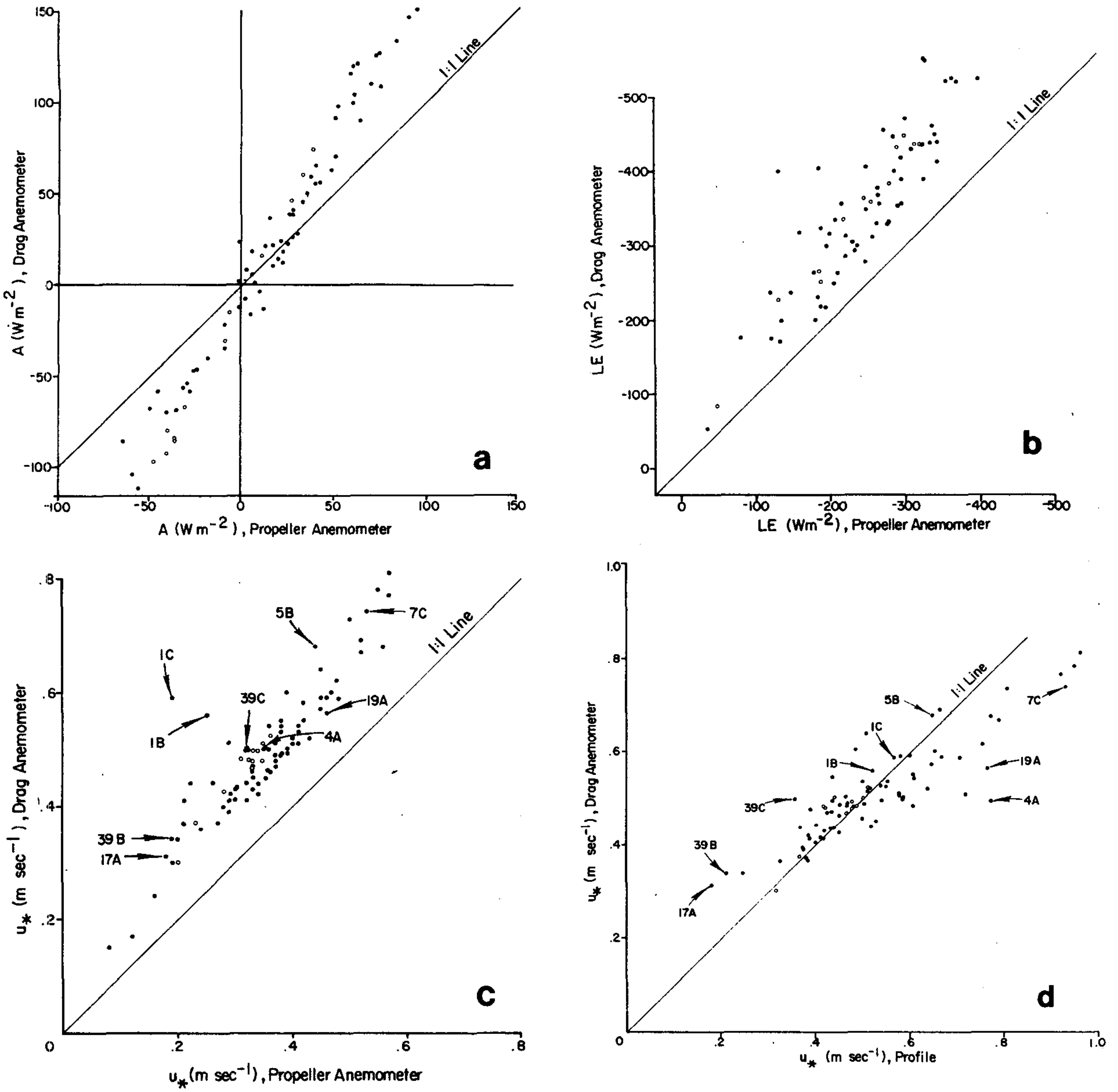

FIG. 3. (a) Comparison of eddy correlation values of sensible heat fluxes (A) at 4.5 m based on drag and propeller anemometer data. Fine wire thermocouples were used to measure temperature fluctuations. (b) Comparison of eddy correlation values of latent heat fluxes (LE) at 4.5 m based on drag and propeller anemometer data. Fine wire thermocouple psychrometers were used to measure humidity fluctuations. (c) Comparison of friction velocities (u_*) derived from drag and propeller anemometer measurements at 4.5 m. (d) Friction velocities (u_*) measured at 4.5 m with a drag anemometer and computed from mean wind speed profile data (see text for details). Solid and open circles denote data from individual drag anemometers.

against the remainder of the equation ($Rn + S$), measured independently. In Fig. 6 the turbulent fluxes of LE and A measured at 2.4 m with the drag anemometer, fine wire dry-bulb thermocouple and Lyman-alpha hygrometer are compared with the concurrent measurements of net radiation and soil heat flux. We assume that the fluxes (A and LE) are constant between the surface and 2.4 m above ground. We further assume that soil heat flux measured at 4 cm depth represents the surface heat flux. Net radiation and soil heat flux measured in the center of the field are assumed representative of the area beneath the turbulence instrumentation. Agreement shown in Fig. 6 is reasonable.

d. Spectral analysis

A total of nine hourly runs were fully analyzed representing a variety of meteorological conditions. The sample shown in Figs. 7a and 7b was run on observations made at 4.5 m above ground between 1300 and 1343 solar time 17 July. The mean wind speed was 7.1 m s^{-1} from the south (181° ± 5°) and the mean air temperature was 33.9°C.

Fig. 7a shows the power spectrum (S_w) of vertical velocity as measured by the drag and propeller anemometers. The solid line is taken from Kaimal *et al.* (1972) for comparative purposes. The propeller data above 0.2 Hz have been corrected for inadequate response (Horst, 1972). There appears to be some aliasing above 2.0 Hz. Above 1.5 Hz the drag anemometer data have been corrected to account for the effect of the low-pass filter (the propeller estimates dropped off too rapidly to have been affected by the filter). Both the original and the reconstructed estimates are shown. There is excellent agreement between the propeller (corrected for inadequate response) and drag anemometers from 0.02 to 2.0 Hz. Below 0.4 Hz both instruments produce estimates greater than predicted by Kaimal's curve. From 0.4 to 5.0 Hz the drag anemometer estimates fit the curve very well. While the horizontal axis has been labelled in both n(Hz) and nondimensional frequency ($f = nz/u$), the vertical axis has not been normalized (z = elevation above ground). This allows a truer comparison to be made between the two sets of estimates. In order to position Kaimal's curve, it was multiplied by the value of u_*^2 obtained from the drag anemometer.[5] It may be worthwhile to note that the energy difference between the uncorrected propeller and drag anemometer estimates from 0.5 to 6.0 Hz accounts for ~80% of the difference between their respective variances (as discussed above).

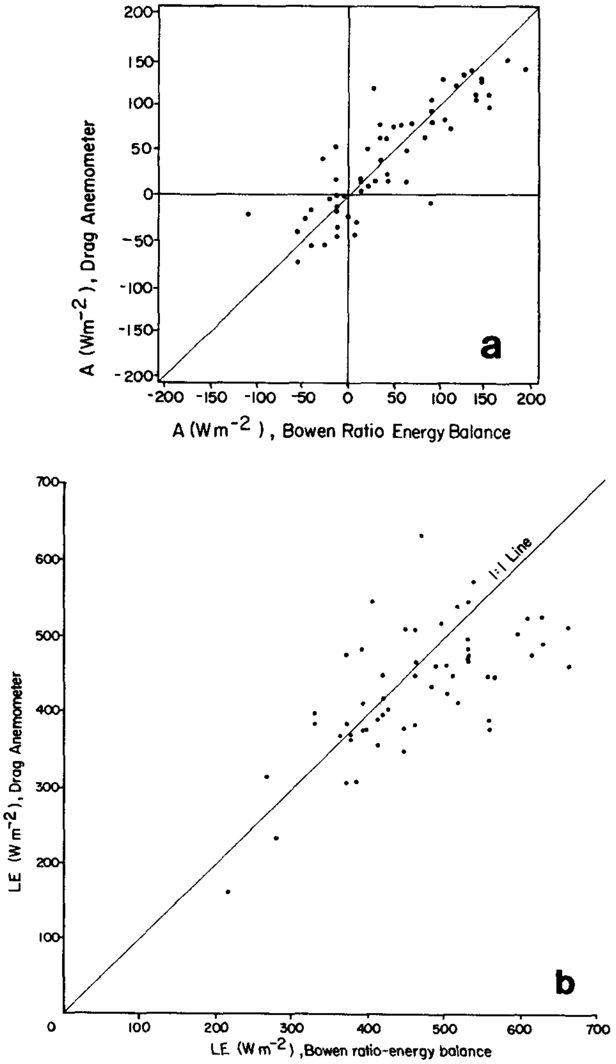

FIG. 4. (a) Sensible heat flux (A) by eddy correlation with a drag anemometer and fine wire thermocouple and by the Bowen ratio-energy balance method. (b) Latent heat flux (LE) at 2.4 m by eddy correlation with a drag anemometer and Lyman-alpha hygrometer and by the Bowen ratio-energy balance method. Solid and open circles denote data from individual drag anemometers.

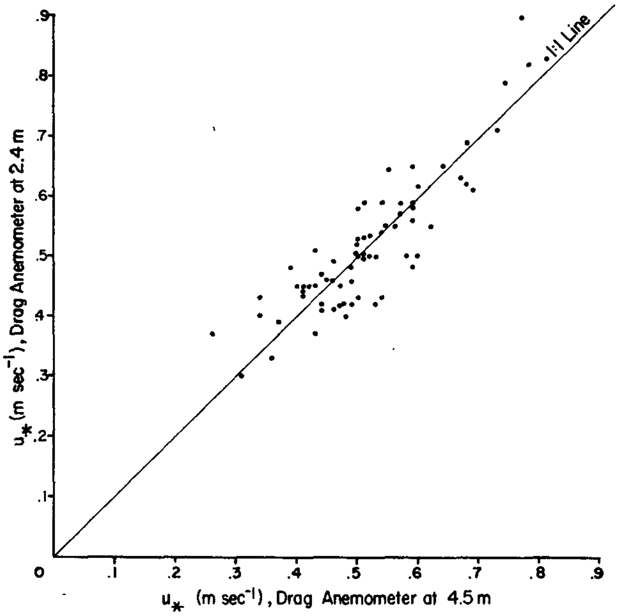

FIG. 5. Friction velocities (u_*) measured with drag anemometers at 2.4 and 4.5 m.

Cospectra of momentum flux (C_{uw}) measured by the propellers and by the drag anemometers are shown in Fig. 7b. Again, a curve from Kaimal *et al.* (1972) is superimposed. The same corrections have been applied to the sets of estimates as for the power spectra, except that the response length for the propellers was increased to account for increased loading (greater friction) due to extensive field use in a manner recommended by Hicks (1972). The cospectral estimates of the propeller system are

---

[5] In Kaimal *et al.* (1972) the curve had been normalized by u_*^2.

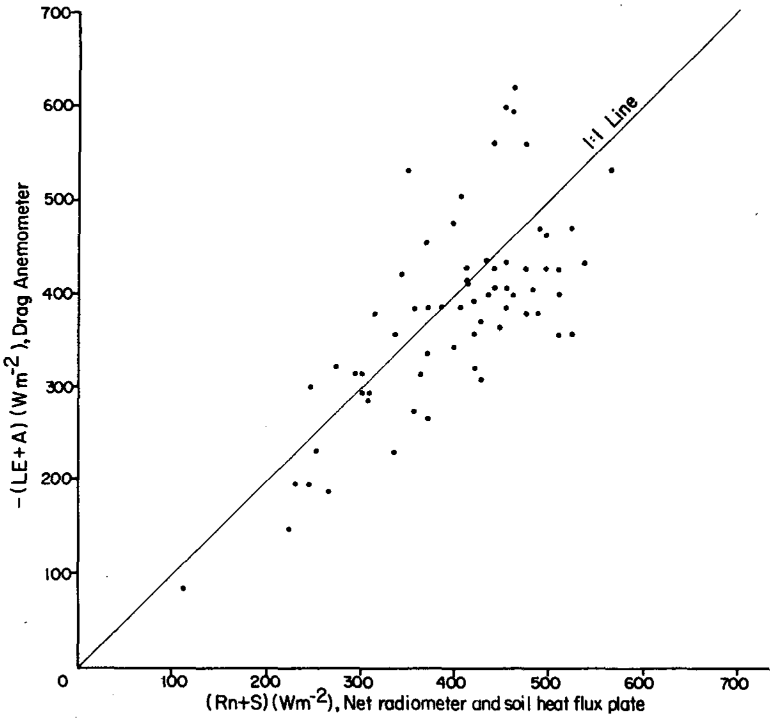

FIG. 6. Sum of the turbulent fluxes of latent (*LE*) and sensible (*A*) heat at 2.4 m by eddy correlation using a drag anemometer, Lyman-alpha hygrometer and fine wire thermocouple, compared with the sum of net radiation and soil heat flux, measured independently.

smaller than those of the drag system and begin to drop off more rapidly above 0.6 Hz. The drag anemometer estimates fit the curve well from 0.05 to 5.0 Hz, with a slight bulge between 0.5 and 2.0 Hz.

4. Discussion

The drag anemometer has few moving parts, and so is not nearly as susceptible to frictional and momentum errors as is the propeller anemometer. Hicks (1972) reports substantial changes (due to friction) in response length of propeller anemometers used at Tsimlyansk, U.S.S.R. While our propellers were not constantly exposed for six weeks as were those mentioned by Hicks (1972), the cumulative effects of repeated use probably increased internal friction giving rise to the lower mean wind speeds and standard deviations as shown in Figs. 1a–1c. The effects of inertia, i.e., resistance to change in speed, would be more apparent at low wind speeds and would be added to the friction effects. This combination may be responsible for the larger percentage differences in $\bar{U}$, σ_u and σ_w measured by the two anemometers at low than at high speeds.

The flux comparisons present a knottier problem. If we assume the drag anemometer fluxes to be correct, then the propeller has underestimated the friction velocities and fluxes of sensible and latent heat. The underestimates were greater than those cited by Garratt (1975). The agreement of the drag anemometer friction velocity with profile data at 4.5 m lends some credence to the drag anemometer data. Comparison of cospectra shows that the propeller (before correction for inadequate response) underestimated the momentum flux measured by the drag anemometer.

It is unfortunate that the psychrometers used for measuring the heat fluxes by the Bowen ratio method were not properly calibrated at the upper level. At the lower level there was good agreement—a further indication of the ability of the drag anemometer to measure fluxes. Friction velocities at 2.4 and 4.5 m determined by the drag anemometer agreed well, which should be the case in a constant flux layer.

The equivalence of (*Rn* + *S*) with the turbulent heat fluxes (*A* + *LE*) (Fig. 6) provides additional evidence that the drag anemometer, in conjunction with temperature and moisture sensors, correctly measured the vertical sensible and latent heat fluxes.

Spectral analyses of drag anemometer and propeller data show, beyond doubt, the superiority of the former at frequencies above 1.0 Hz.

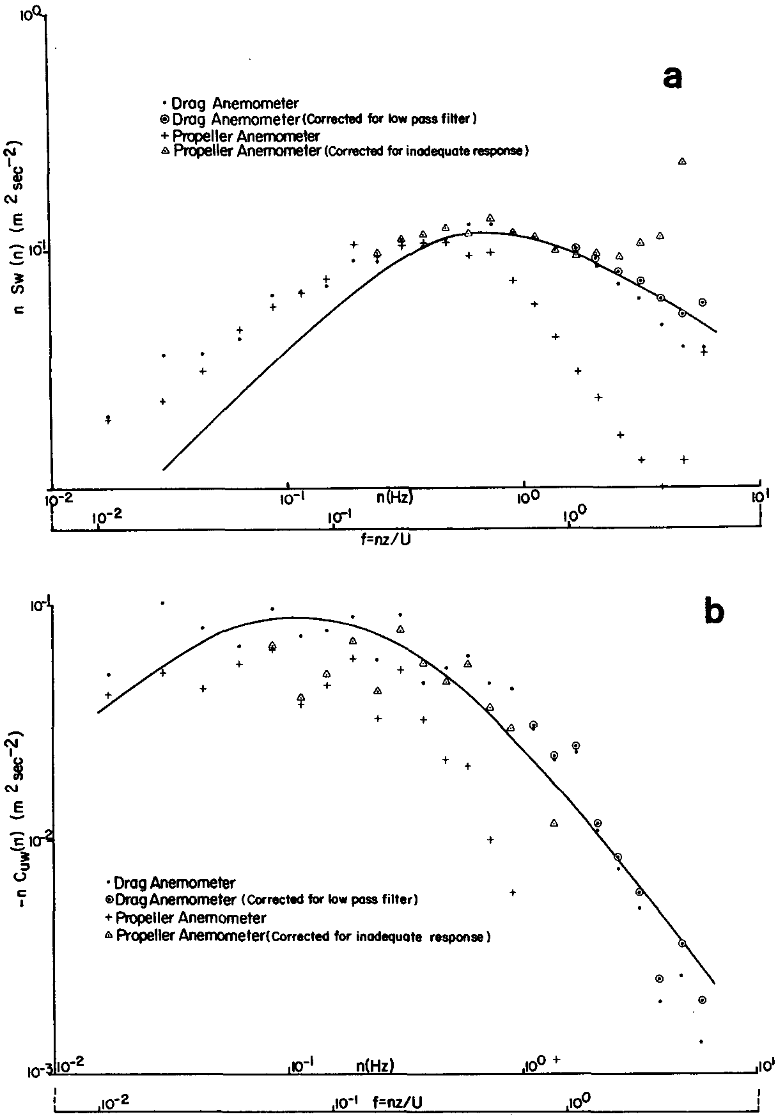

FIG. 7. (a) Spectra of vertical velocity fluctuations measured with the drag and propeller anemometers (1300 solar time 17 July 1978). (b) Cospectra of momentum flux measured with the drag and propeller anemometers (1300 solar time 17 July 1978).

5. Concluding remarks

The drag anemometer performed better than did the Gill propeller anemometer at all wind speeds and all frequencies. Mean fluxes computed from drag anemometer measurements agreed with fluxes computed from mean profiles and from an energy balance equation. Between the frequencies of 0.4 and 5.0 Hz the drag anemometer spectra compare well with the curve of Kaimal *et al.* (1972) which was based on sonic anemometer data.

Acknowledgments. This study was conducted with support of the Atmospheric Research Section, National Science Foundation, under Grant ATM 75-10000 A01. Our special thanks to Dr. John M. Norman for his advice and assistance on operation, calibration and maintenance of the drag anemometers and for his suggestions concerning analysis of the data. Our thanks to Messrs. Dale E. Sandin, Thomas Keber, Dean Anderson and James Hines who assisted in the field observation, calibration and data computations; to Mrs. Roberta Sandhorst and Mrs. Nancy Brown for stenographic work, to Miss Sheila Smith and Mr. Bruce Sandhorst for drafting the figures and to Mr. Bruce B. Hicks of Argonne National Laboratory for his review of this paper.

REFERENCES

Blad, B. L., and N. J. Rosenberg, 1974: Lysimetric calibration of the Bowen ratio-energy balance method for evapotranspiration estimation in the central Great Plains. *J. Appl. Meteor.*, **13**, 227–236.

Brakke, T. W., S. B. Verma and N. J. Rosenberg, 1978: Local and regional components of sensible heat advection. *J. Appl. Meteor.*, **17**, 955–963.

Buck, A., 1976: Notes on the fabrication of a fixed path Lyman-alpha hygrometer. National Center for Atmospheric Research, Boulder, Colorado, Research Systems Facility, No. 040-032-004, 23 pp.

Desjardins, R. L., 1972: A study of CO_2 and sensible heat fluxes using the eddy correlation technique. Ph.D. thesis, Cornell University, 174 pp.

Dyer, A. J., and B. B. Hicks, 1970: Flux gradient relationships in the constant flux layer. *Quart. J. Roy. Meteor. Soc.*, **96**, 715–721.

——, and ——, 1972: The spatial variability of eddy fluxes in the constant flux layer. *Quart. J. Roy. Meteor. Soc.*, **98**, 206–212.

Garratt, J. R., 1975: Limitations of the eddy correlation technique for the determination of turbulent fluxes near the surface. *Bound.-Layer Meteor.*, **8**, 255–259.

Hicks, B. B., 1972: Propeller anemometers as sensors of atmospheric turbulence. *Bound.-Layer Meteor.*, **3**, 214–228.

——, 1977: Some effects of displacement height variability in tall vegetation. Radiological and Environment Research Div. Ann. Rep. ANL-77-65, Part IV, Argonne National Lab., Argonne, IL, 178 pp.

Hogström, U., 1974: A field study of the turbulent fluxes of heat, water vapor and momentum at a 'typical' agricultural site. *Quart. J. Roy. Meteor. Soc.*, **100**, 624–639.

Horst, T. W., 1972: A computer algorithm for correcting noncosine response of the Gill anemometer. Annual Report for 1971 to the USAEC Biology and Medicine, Vol. II: *Physical Sciences*, Part I: *Atmospheric Sciences*, BNWL-1651-1, Battelle Pacific Northwest Laboratories, Richland, WA.

——, 1973: Corrections for response errors in a three-component propeller anemometer. *J. Appl. Meteor.*, **12**, 716–725.

Kaimal, J. C., J. C. Wyngaard, Y. Izumi and O. R. Coté, 1972: Spectral characteristics of surface-layer turbulence. *Quart. J. Roy. Meteor. Soc.*, **98**, 563–589.

Norman, J. M., S. G. Perry and H. A. Panofsky, 1976: Measurements and theory of horizontal coherence at a two meter height. *Preprints Third Symp. Atmospheric Turbulence, Diffusion and Air Quality,* Raleigh, Amer. Meteor. Soc. 19–22.

Perry, S. B., 1977: Measurement and theory of horizontal coherence at a two meter height. Master's thesis, The Pennsylvania State University, 83 pp.

Redford, T. G., Jr., S. B. Verma and N. J. Rosenberg, 1980: Humidity fluctuations over a vegetated surface measured with a Lyman-alpha hygrometer and a fine-wire thermocouple psychrometer. *J. Appl. Meteor.*, **19**, 860–867.

Rosenberg, N. J., 1974: *Microclimate: The Biological Environment.* Wiley, 315 pp.

——, and K. W. Brown. 1974: 'Self-checking' psychrometer system for gradient and profile determinations near the ground. *Agric. Meteor.*, **13**, 215–226.

——, and S. B. Verma, 1978: Extreme evapotranspiration by irrigated alfalfa: A consequence of the 1976 midwestern drought. *J. Appl. Meteor.*, **17**, 934–941.

SethuRaman, S., and R. M. Brown. 1976: A comparison of turbulence measurements made by a hot-film probe, a bivane and a directional vane in the atmospheric surface layer. *J. Appl. Meteor.*, **15**, 138–144.

Tanner, C. B., and G. W. Thurtell, 1969: Anemoclinometer measurements of Reynolds stress and heat transport in the atmospheric surface layer. Rep. RI-R10, USAEC Army Electronics Command, Ft. Huachuca, Arizona.

Tillman, J., 1973: Wet- and dry-bulb thermocouple psychrometry. *Atmos. Tech.*, No. 2, NCAR, p. 77.

Wesely, M. L., G. W. Thurtell and C. B. Tanner, 1970: Eddy correlation measurements of sensible heat flux near the earth's surface. *J. Appl. Meteor.*, **9**, 45–50.

Verma, S. B., R. P. Motha and N. J. Rosenberg, 1979: A comparison of temperature fluctuations measured by a microbead thermistor and a fine wire thermocouple over a crop surface. *Agric. Meteor.*, **20**, 281–289.