Three-Dimensional Pressure-Sphere Anemometer System

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(Manuscript received 23 May 1969, in revised form 26 January 1970)

ABSTRACT

A rugged and stable pressure-sphere anemometer system is described which provides an accurate measurement of wind velocity and direction within a meter of the ground. The horizontal wind velocity, $(u^2+v^2)^{\frac{1}{2}}$, agreed very closely with cup anemometer measurements, indicating good accuracy in the measurement of the dominant term u. Eddy correlation measurements of shear stress with the pressure sphere agreed very well with Davis shear-stress meter measurements and satisfactory agreement was found with data obtained from wind velocity profiles and from wind measurements using a drag coefficient. Ratios of σ_w/u_* during neutral periods were found to be in excellent agreement with values derived by Panofsky and Lettau, providing further indication of the accuracy obtainable with the pressure-sphere system.

1. Introduction

The basic mechanisms of turbulent transport in the layers of air within a few meters of the earth's surface are receiving increasing attention from researchers from many disciplines. Inadequate diffusion models are limiting research progress in meteorology, ecology, agriculture, water resources and air pollution, since many of the critical problems in these fields are associated with the exchange of energy, gases and aerosols between the earth and its atmosphere. The testing and development of improved transport models requires accurate experimental data which is at present insufficient.

Field measurements of turbulent mixing processes have been few and generally inadequate because of the stringent requirements for the instrumentation. The wind velocity sensors must be accurate, stable under field conditions, fast responding, small for measurements near the ground, rugged, and must measure both the flow direction and velocity without seriously disturbing the flow. Sonic anemometers (Kaimal *et al.*, 1964, 1968), bivanes (Gill, 1963; MacCready and Jex, 1964; Cramer *et al.*, 1961), two types of heat-transfer anemometers (Miyake and Badgley, 1967; Dyer, 1960), fast-response cup anemometers (Frenzen, 1965) and vertical, propeller-type anemometers (Thornthwaite *et al.*, 1961; Holmes *et al.*, 1964) have all been used in the atmospheric surface layer but each fails to meet one or more of the essential criteria mentioned above for measurements near the ground. The pressure sphere is well-suited to measuring the lateral and vertical wind components because they appear as products with the large longitudinal velocity in the basic pressure measurement. It is felt that the anemometer system to be described does meet these requirements to a greater degree than do other available instruments and will thus aid research on turbulent diffusion processes.

The basic sensor of our system is the anemoclinometer described by Martinot-Lagarde *et al.* (1952) and made by the Institut de Mecanique des Fluides.[2] The tests to be described were conducted at the University of California at Davis as part of the 1967 Cooperative Field Experiment sponsored by the Atmospheric Sciences Laboratory, U. S. Army Electronics Command, Ft. Huachuca, Ariz. Wind velocity measurements made with our anemometer system were compared with cup anemometers. Eddy correlation shear-stress measurements were compared both with wind profile data and with data from the large Davis shear-stress meter (Brooks and Pruitt, 1966). In addition, measurements of the standard deviation of the vertical component of wind velocity are presented for Davis and also some from Hancock, Wis.

2. Anemometer system

The anemometer system consists of a spherical probe with pressure ports drilled into its surface. This particular design of sphere, called Philip I, can be replaced satisfactorily by other styles. The pressures developed at these ports are transmitted through small tubes and measured by pressure transducers. The electrical outputs of the pressure transducers can be analyzed to give the orthogonal components of the wind vector.

a. Spherical pressure probe

We used both 3- and 8-cm pressure probes as described by Martinot-Lagarde *et al.* The 3-cm probe,

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shown in Fig. 1, consists of a spherical head mounted on a supporting shaft. A drawing of the head, showing some of the ports, is given in Fig. 2. When in use, the probe is fixed with the sphere on the upstream end of the shaft. Twelve small ports are drilled into the spherical surface and a pitot tube is centered in a Venturi which is bored in the sphere on the axis of the shaft. Eight of the twelve ports on the surface of the sphere are located on a circle at an angle of 47.5° to the shaft axis and serve as reference ports for the pitot tube in the Venturi; these eight holes are connected to a common pressure-averaging cavity in the shaft. The other four holes lie at right angles in the x,z and x,y planes, and each hole is at 45° from the shaft axis. The x coordinate is taken parallel and the y and z coordinates perpendicular to the probe shaft, with z in the vertical plane. The open end of the pitot tube in the Venturi is in the upstream direction. The pressure difference

$$P_1 = P_t - P_m, \tag{1}$$

between the pitot tube and the cavity common to the eight reference ports, is proportional to the dynamic pressure

$$P_1 = \tfrac{1}{2} a \rho V^2, \tag{2}$$

where

$$V^2 = (u^2 + v^2 + w^2), \tag{3}$$

u, v, and w are the axial, cross-horizontal, and vertical wind components, ρ is the fluid density, and a is a constant of the probe equal to 1.015 according to data supplied by the manufacturer. The pressure difference between the two vertical ports (x,z plane) and that between the horizontal ports (x,y plane) are predicted reasonably well by

$$P_2 = b \rho u w, \tag{4}$$

$$P_3 = b \rho u v. \tag{5}$$

The factor b is a function of the Reynold's number but is relatively constant in the Reynold number range of 2000 to 200,000.

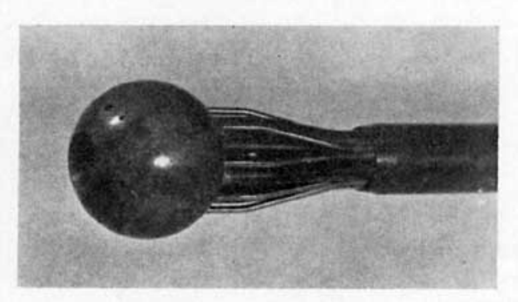

FIG. 1. Spherical sensing head of anemoclinometer showing pressure ports.

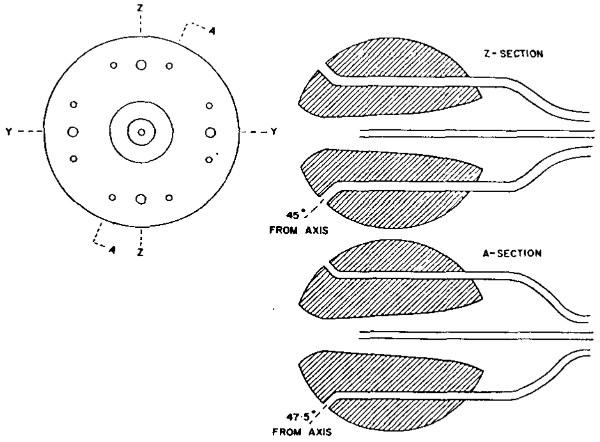

FIG. 2. Front and cross-section views of anemoclinometer head, with y and z coordinates shown in front view.

Calibration data supplied by the manufacturer indicated that for the 3-cm spheres, the pressure ratios P_2/P_1 and P_3/P_1 were linearly related to the angles F and G, respectively, by

$$F = cP_2/(P_1 \cos G), \tag{6a}$$

$$G = cP_3/(P_1 \cos F), \tag{6b}$$

where c is a constant and F and G are the complements of the directional angles. In the analysis a slightly different slope was used when F or $G > 20°$, allowing the measurement to be made with good accuracy for angles up to ±30.0. Accordingly,

$$\left.\begin{aligned} w &= V \sin F \\ v &= V \sin G \\ u &\approx V (\cos F)(\cos G) \end{aligned}\right\}. \tag{7}$$

The components of the wind vector are described more closely by Eqs. (3), (6) and (7) than by Eqs. (3), (4) and (5). When using (6), an iterative procedure is used to solve for F and G which are then used in (7).

b. Pressure transducers

Capacitive pressure transducers manufactured by Datametrics, Inc.[3] were chosen for the pressure measurement. The gains of the signal conditioners can be selected to provide full-scale outputs (±5.0V) for differential pressures of 10, 20, 30, 60, 100, 200, 300, 600, 1000, 2000, 3000, 6000, 10,000 dyn cm^{-2}. The transducer has a maximum nonlinearity of about ±0.1%, zero drift of 10^{-5} of maximum range (°C)$^{-1}$, and sensitivity change of 2×10^{-2}% (°C)$^{-1}$.

c. Frequency response

The frequency response and phase shift of a pressure transducer connected by tubing to a fluctuating pressure has been described by Iberall (1950), whose analysis was basic to our system design. The response of the transducer is controlled by the size and length of the tubing and the effective internal volume of the trans-

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[3] Datametrics Inc., Waltham, Mass. (Model 511-8 Barocel).

ducers. The transducers used in our system were a special design which used a stiffer than normal diaphragm and a reduced internal volume of 1.6 cm^3 to improve the frequency response of the system. The spherical probe was connected by approximately 43 cm of ~ 1.5 mm i.d. tubing to the pressure transducer; tests showed this tubulation optimized the system performance.

The frequency response and phase shift of the system were checked by producing known sinusoidal pressure differences at various frequencies between appropriate ports on the surface of the pressure spheres and monitoring the amplitude and phase of the transducer output. Instead of attempting to produce the pressure differences between ports on a single sphere, two identical spheres were placed in separate pressure chambers with tubing connecting appropriate ports to the pressure transducers. Equal pressure fluctuations, 180° out of phase with each other, were produced in the two chambers by pistons which were closely coupled to the chambers. The pistons were driven by a variable speed motor and the phase of the pressure fluctuation was determined by optically sensing the position of the Scotch yoke piston drive. Typical amplitude and phase shift characteristics of the 3-cm anemoclinometer and pressure transducer are shown in Table 1. The response was limited by the tubing supplied by the manufacturer as an integral part of the anemoclinometers and could be improved by redesigning the pressure sphere, tubulation and transducer system for optimum performance.

d. Field installation

For field measurements, the pressure-sphere anemometer is mounted on a 2.5-cm diameter mast (Fig. 3) at the desired height. The anemometer is oriented with the shaft axis parallel to the anticipated direction of mean flow. The three pressure transducers are housed in a temperature-controlled (±0.2C) box which is an integral part of the mounting assembly located at the opposite side of mast to the pressure sphere. The temperature control provides the required zero stability. The whole assembly can be moved to different levels on the mast or completely removed as one unit without disconnecting the pressure transducers from the pressure sphere. The pressure transducers are connected by 150 m of cable to their power supply and signal conditioners which are housed in a 2.5×6 m air-conditioned instrument trailer.

Table 1. Anemometer system frequency response and phase shift.

Frequency (Hz)	Relative amplitude	Phase shift (deg)
1	1.00	0
5	1.02	18
10	1.05	48
15	1.00	76
20	0.84	100
25	0.63	126
30	0.47	145

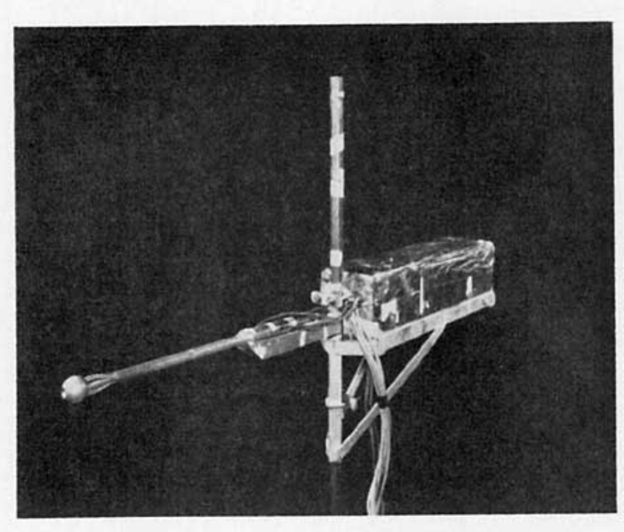

Fig. 3. View of the anemometer assembly on its mast.

The masts are on pivot points and supported higher up by guy wires attached to bearings. This arrangement allows the mast to be rotated so that the probe can be easily oriented into the mean wind. When the data discussed below were obtained, the anemometer was rotated in azimuth manually into the mean wind; at the beginning of each half-hour run the orientation was adjusted to the position of the mean wind for the previous half hour. Since then, a motor assembly, controlled by the $P_3 = b\rho uv$ output of the wind probe, has been used to continuously but slowly adjust the position of the probe into the wind. The orientation of the mast is monitored through the output of a potentiometer attached to the base of the mast and is included in the calculation of the components of the wind vector.

3. Data handling

Since the sensors respond to frequencies as high as 30 Hz, a large amount of data must be analyzed if the system is operated over extended periods of time. Storing large quantities of data under field conditions is costly and often results in a serious reduction in data quality. In addition, it is highly desirable that some data analysis capability be available at the experimental site so that the experiment can be run efficiently and instrumentation faults detected as soon as possible. After a careful study of the available alternatives, we elected to drastically reduce, by digital on-line computation, the quantity of data to be stored to the point where it could be typed out in table form by a typewriter or stored on paper tape. In 1967, this amounted to a data reduction of approximately 18,000:1.

In 1967 the data analysis was performed on an EMR 6020 computer[4] and later on the faster and smaller

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[4] Electro-Mechanical Research, Inc., Minneapolis, Minn.

EMR 6130. The 1967 system included a Raytheon A-D converter, 6020 computer and model 33 teletype with paper tape reader with punch. The 6130 system includes an EMR 2701 converter, and a higher speed paper tape reader and punch in addition to the model 33 teletype.

Five channels of analogue data were obtained at each of three sites to give a total of 15 channels. At each site three channels represented the three pressure differences P_1, P_2, P_3, and the other two channels represented a fast-response resistance thermometer (Wesely *et al.*, 1969) and a fast-response barium fluoride relative humidity element (Jones, 1967). The velocity components of the wind vector were calculated using Eqs. (6) and (7), and means, squares, and cross-products of the five parameters (u, v, w, T, e) were calculated, where T and e were the temperature and vapor pressure, respectively.

The complete operation (i.e., 15 channels of analogue-to-digital conversion and the data analysis) was repeated 40 times sec^{-1}. At the end of each half-hour sampling period, the necessary scaling operations were performed and the outputs were teletyped. Approximately 2.5 min of each half-hour period were required for output and no data were collected during this time.

This data system has proven to be a very efficient and powerful research tool and it is felt that the success achieved with the anemometer system would not have been possible if, alternatively, data storage equipment had been selected.

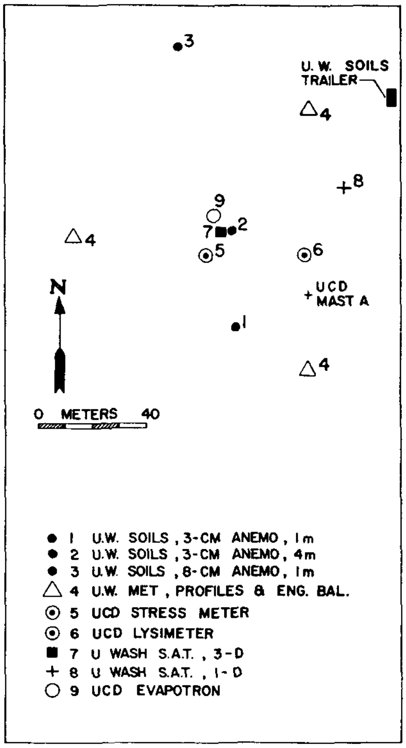

FIG. 4. Plan of the site of the 1967 cooperative field experiment.

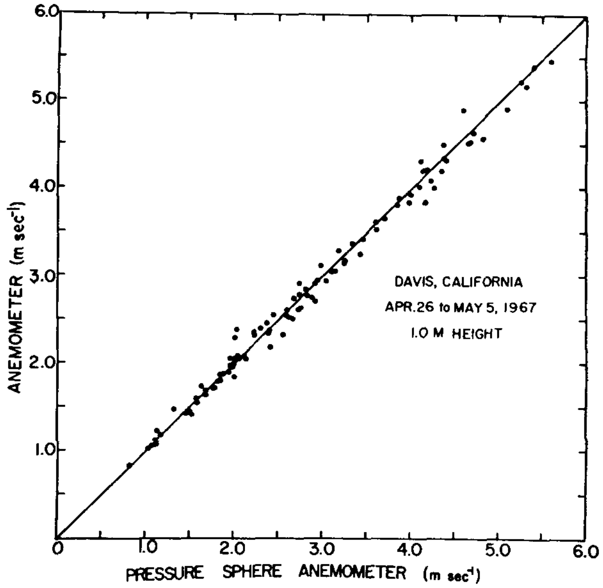

FIG. 5. Comparison of horizontal wind measured with the three-dimension anemometer and with cup anemometers.

4. Tests of anemometer system

A complete description of the experimental area may be found in Brooks and Pruitt (1966). A plan of the field site is given in Fig. 4, showing the heights and spatial arrangement of our three anemometers with respect to the 6 m Davis shear-stress lysimeter and the triangular array of masts installed by Dr. C. R. Stearns of the University of Wisconsin Department of Meteorology. These masts carried cup anemometer and aspirated dry- and wet-bulb thermometers. The surface was uniform *alta fescue*, 5–10 cm high, which was peridodically mown.

Wind velocity measurements with our pressure probe are compared with cup anemometer data, and our eddy-correlation, shear-stress measurements with both shear-stress lysimeter data and the shear stresses obtained by Dr. Stearns' preliminary analysis of his vertical profiles of wind velocity and of temperature (KEYPS-type, diabatic profile analysis). In addition, a graphical description of the vertical fluctuations of wind velocity as a function of the stability parameter z/L is presented.

a. Comparison of wind velocity measurements

The on-line computer program which was used to analyze our anemometer data included the calculation of the horizontal wind

$$\overline{V_H}=\overline{(u^2+v^2)^{\frac{1}{2}}},$$

where u and v are the instantaneous values of the horizontal components of the wind vector. The value of $\overline{V_H}$ is primarily dependent upon P_1, as given in (2), and since u generally is much larger than either v or w, errors associated with the measurement of wind angles calculated from (6) do not seriously degrade the estimate of $\overline{V_H}$. The good agreement between $\overline{V_H}$ and cup anemometer (C. W. Thornthwaite Associates) measurements presented in Fig. 5 demonstrates the accuracy of pressure-sphere measurements of u.

b. Comparison of shear-stress measurements

Shear-stress measurements obtained with the pressure-sphere anemometer are compared with data from the shear-stress lysimeter and from analysis of the wind profiles. The data obtained on 2–5 May are presented in Figs. 6 and 7. The pressure-sphere anemometer data represent the average of measurements available at the three sites. The shear stress data from the three wind profile sites also were averaged. The Davis shear-stress lysimeter independently measures the north-south and east-west components of the surface shear stress and data used were computed by W. O. Pruitt as the vector sum of the half-hour means of these components.

Agreement among the three methods is satisfactory, even though the values obtained from aerodynamic analysis averaged 40% greater than the pressure-sphere anemometer data and 34% greater than the shear-stress lysimeter data. A correlation of pressure-sphere anemometer data against shear-stress lysimeter and aerodynamic analysis data provided correlation coefficients of 0.970 and 0.957, respectively. The discrepancy between the aerodynamic and the other two methods appears unduly large on 4 and 5 May. The average z_0 value computed from the wind profiles is 0.95 cm

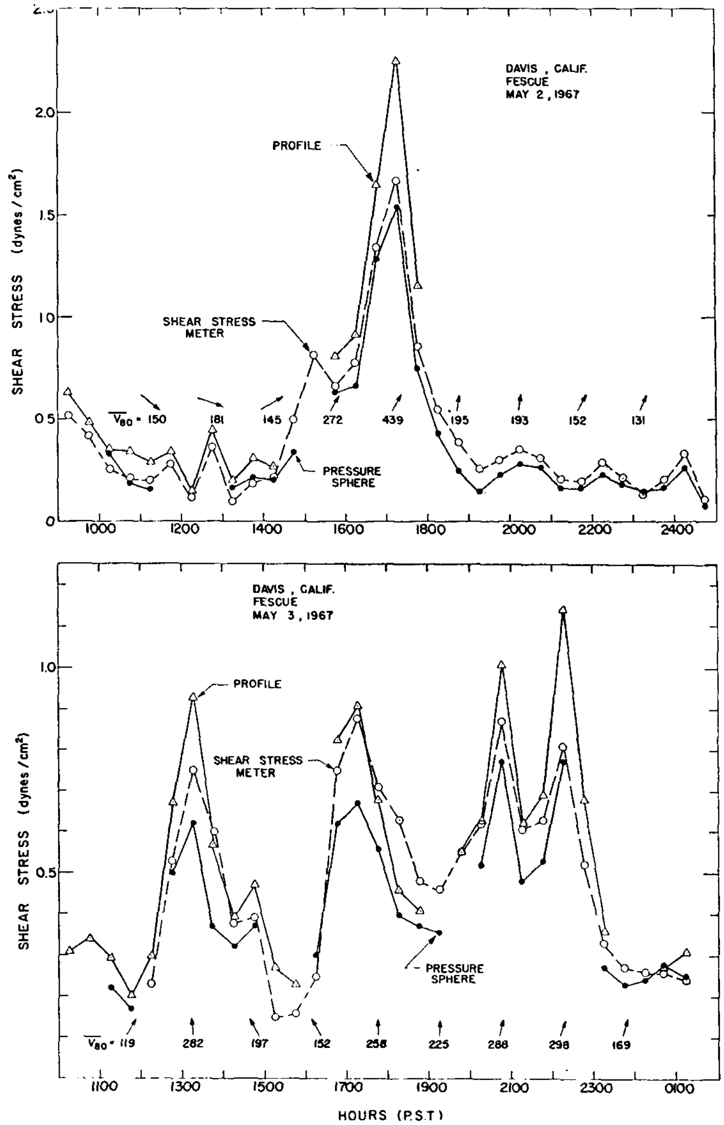

Fig. 6. Comparison of shear stress measurements on 2 and 3 May 1967.

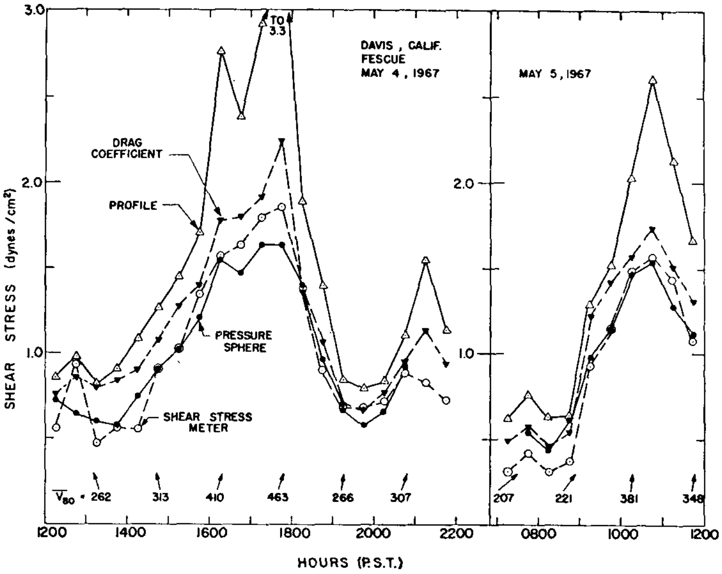

FIG. 7. Comparison of shear stress measurements on 4 and 5 May 1967.

for 2 and 3 May, and ~1.4 cm for 4 and 5 May. For the latter two days new estimates of the shear stress were calculated via a drag coefficient using $z_0=0.95$ cm, a KEYPS diabatic correction, and the cup anemometer wind velocity at 80 cm. The results of this calculation are more consistent with the comparisons on 2 and 3 May. Calculations indicate that best agreement between drag coefficient and eddy corrrelation determinations would have been obtained by using $z_0 \approx 0.7$ cm.

c. Standard deviation of the vertical wind

Ratios of the standard deviation of the vertical component w of wind velocity to the friction velocity u_*, as measured at the two 1 m sites and one 4 m site, are plotted in Fig. 8. The comparison of horizontal wind measured with our anemometer system and with cup anemometers indicates that our pressure-sphere anemometer measures the u component of wind velocity accurately. Accordingly, the ratio σ_w/u_* would vary as the square root of a constant percentage error in the measurement of w. This is not a very sensitive test of the measurement of the vertical component of velocity since the error in w would be twice that in σ_w/u_*, but our value of 1.25 for σ_w/u_* under neutral conditions is the same as that derived by Panofsky *et al.* (1967) and close to the value of 1.33 predicted by Lettau (1968). Over 100 additional data points were collected over

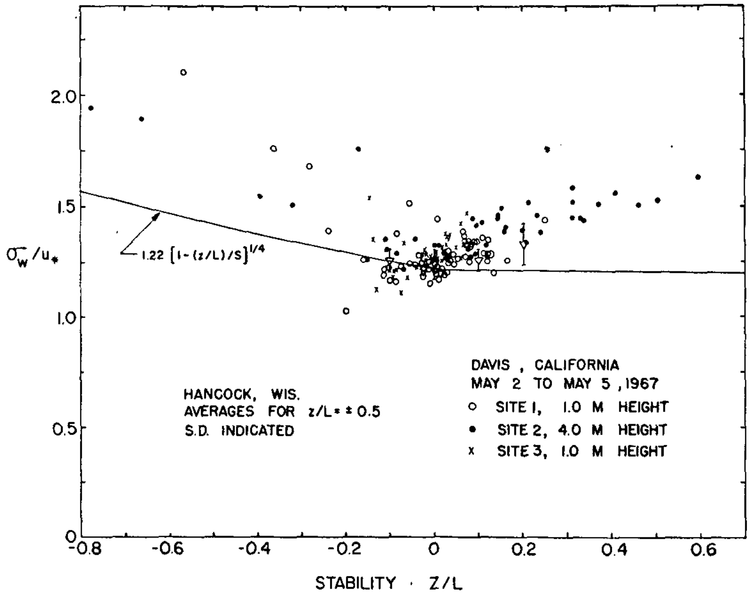

FIG. 8. Ratio of σ_w/u_* as a function of z/L.

snap beams ($z_0=4$ cm) in 1968 at Hancock, Wis. The data, averaged over stability ranges of $z/L=-0.15$ to 0.25, are also presented in Fig. 8 and are very similar to the Davis data. For ready comparison with Panofsky and Prasad (1965) and Panofsky *et al.* (1967), the curve they derived involving $[1-(z/L)/s]^{\frac{1}{4}}$ is plotted.

Acknowledgments. Published with the permission of the Director of the Wisconsin Agricultural Experiment Station. The research was supported in part by the Atmospheric Sciences Laboratory, U. S. Army Electronics Command, Fort Huachuca, Ariz., under Grant DA-AMC-28-043-66-G22, and in part by USDA Hatch Act Funds. We are grateful to Dr. C. R. Stearns, of the University of Wisconsin, for making available his wind profile results and to Dr. W. O. Pruitt, of the University of California-Davis, for his shear-stress meter data.

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