Humidity Fluctuations over a Vegetated Surface Measured with a Lyman-Alpha Hygrometer and a Fine-Wire Thermocouple Psychrometer[1]

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ABSTRACT

Simultaneous measurements of humidity fluctuations over a crop made with a specially modified Lyman-alpha hygrometer and a fine-wire thermocouple psychrometer are compared. Standard deviations of the two sets of data are comparable except occasionally when wind speeds were low. The psychrometer appears to underestimate the vertical flux of water vapor due to its slow response. Analysis of humidity spectra and moisture flux cospectra shows that the Lyman-alpha hygrometer is superior to the psychrometer in response at high frequencies and low wind speeds.

1. Introduction

Humidity is one of the more difficult meteorological parameters to measure with accuracy and rapidity. Most of the commonly used instruments depend, in some way, on adjustment of the sensor to evaporation or condensation of water, a relatively slow process. Recent innovations in electronics technology, however, now permit the development of instruments capable of rapid response to fluctuations in the atmospheric content of water vapor. The Lyman-alpha hygrometer used in this study is an adaptation of an instrument developed for use on aircraft for turbulence measurements. This instrument was tested during the summer of 1978 at the University of Nebraska Agricultural Meteorology Laboratory near Mead. It was used to measure humidity fluctuations over crops during a variety of meteorological conditions, including conditions of regional sensible heat advection.[3] Few data of this type are presently available in the literature. The Lyman-alpha hygrometer and a fine wire wet- and dry-bulb thermocouple psychrometer (Fig. 1) were used to make simultaneous measurements of atmospheric humidity over an alfalfa field during July and August. At the same time fluctuations of vertical and horizontal wind speed were measured with a drag anemometer (Norman *et al.*, 1976). All sensors were located near the center of the north end of a field 400 m (N-S) by 110 m (E-W) in dimension. Predominant winds in the region are from southeast-southwest. The field was surrounded, except on the north, by alfalfa of the same age and cultivar. Both humidity sensors were mounted ~17 cm apart on masts at 4.5 m above ground. The drag anemometer sensor was placed between the Lyman-alpha hygrometer and thermocouple psychrometer, the two instruments being compared.

The alfalfa crop ranged in height from 58 to 68 cm during periods of observation, except for 3 h of data obtained over a newly clipped crop (~18 cm). In order to provide the necessary fetch, measurements were made only when the wind blew from between 135 and 225°. Data used in analysis were collected during daylight under minimal cloudiness and no precipitation. These measurements include lapse as well as daytime inversion (advection) conditions.[3]

2. Instrumentation

a. Lyman-alpha hygrometer

The Lyman-alpha hygrometer was originally designed by Buck (1976) at the National Center for Atmospheric Research. The instrument was designed for aircraft mounting to measure atmospheric humidity with forced ventilation. In our application the hygrometer required static mounting above a crop with natural ventilation. Additionally, it was necessary to position the sensors fairly close (≤ 10 cm) to the wind sensors for proper spectral analysis (Kaimal, 1975). Supporting hardware and electronics of the hygrometer were redesigned by staff

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[3] For a detailed discussion of sensible heat advection conditions see Brakke *et al.* (1978) and Rosenberg and Verma (1978).

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of the Center for Agricultural Meteorology and Climatology to accommodate these needs.

1) PRINCIPLE OF OPERATION

The main parts of the Lyman-alpha hygrometer are a hydrogen filled glow discharge tube, a nitric oxide-filled ion chamber and an electrometer. The hydrogen is electrically ionized in the discharge tube and the resulting atomic hydrogen emits Lyman-alpha radiation of wavelength 1.216×10^{-7} m. This radiation passes through magnesium fluoride windows in each of the chambers. In the ion chamber the nitric oxide is ionized in proportion to the amount of radiation entering. That radiant flux density is a function of the concentration of water vapor in the path between the chambers. The ionization gives rise to small current between the chamber's electrodes which is amplified by the electrometer.

Lyman-alpha radiation is readily absorbed by water molecules. According to Beer's law, for the ideal case of a single wavelength and single absorbing gas, the decrease in flux density of radiation between the windows of the chambers will depend, in part, on the water vapor density there so that

$$I = I_0 \exp(-kqx/q_0), \qquad (1)$$

where I is the received flux density, I_0 the emitted flux density, k the absorption coefficient of water vapor, q the concentration of water vapor, q_0 the concentration of water vapor at standard temperature and pressure and x the path length (the distance between the MgF windows). The terms I and I_0 may be replaced by their sensed voltage equivalents (V and V_0) and Eq. (1) rearranged to obtain

$$qx = -(q_0/k) \ln(V/V_0). \qquad (2)$$

Buck (1975) assumed a polynomial solution for this equation which accounts for multiple radiation wavelengths and absorbing gases

$$qx = f_v(V'') = a_1 + a_2(V'') + a_3(V'')^2 + a_4(V'')^3 + \cdots, \qquad (3)$$

where

$$V'' = \ln V - \ln V_0 - f_{\mathrm{ox}} - f_{\mathrm{coll}}. \qquad (4)$$

f_{ox} is a correction for oxygen absorption of Lyman-alpha radiation and f_{coll} accounts for the fact that the radiation is not completely collimated; f_v is the function described by Eq. (3); and V_0 is system gain, calculated by comparison of the hygrometer with a reference psychrometer as described below. f_v, f_{ox} and f_{coll} are determined experimentally in a calibration procedure described by Buck (1974). Response time of the Lyman-alpha hygrometer is on the order of several milliseconds. The instrument is described in considerably greater detail by Buck (1973, 1974, 1975, 1976).

2) CALIBRATION

Calibration of the Lyman-alpha hygrometer involves two steps: 1) collimation correction and 2) moisture calibration. The collimation correction factor (f_{coll}) is determined by measurement of the sensor output at varying path lengths in an environment free of water and oxygen. A chamber filled with dry nitrogen is used for this purpose. The moisture calibration factor (f_v) is determined by measuring sensor output under a range of known humidity and path length conditions. Two to three values of humidity at three to five path lengths are sufficient for this purpose. f_{ox}, the oxygen absorption correction factor, is a function of temperature and pressure assuming that the percentage of oxygen in the environment is stable. Buck (1974) provides the necessary coefficients for use of the Lyman-alpha in the open atmosphere. V_0 is determined periodically during periods of operation by comparing averaged output of the Lyman-alpha hygrometer at known humidities. Maintenance involves cleaning the windows after every 100–200 h of operation.

In operation at the Agricultural Meteorology Laboratory, output of the hygrometer's electrometer was amplified in the field, electronically filtered by a 5.2 Hz cutoff low-pass RC filter, scanned at 12.8 Hz and recorded in digitized form on magnetic tape. Measurements were made for 43 minutes of each hour. The instrument was calibrated during the remaining 17 min of the hour. The output voltage of the hygrometer was averaged for 5 min each hour and absolute values of humidity compared to those registered by a "self-checking" psychrometer (Rosenberg and Brown, 1974) at the same elevation. The value of V_0 was adjusted by computer to correct for drift in the Lyman-alpha hygrometer.

b. Other sensors

The Lyman-alpha hygrometer was compared with a finewire wet- and dry-bulb thermocouple-psychrometer described by Tillman (1973). The thermocouple sensors consist of welded junctions of chromel-constantan wires (type E, 1 mil diameter) mounted on interchangeable probes. The probes connect directly into self-contained units that use low-drift integrated circuit operational amplifiers. Reference thermocouples are also included in the

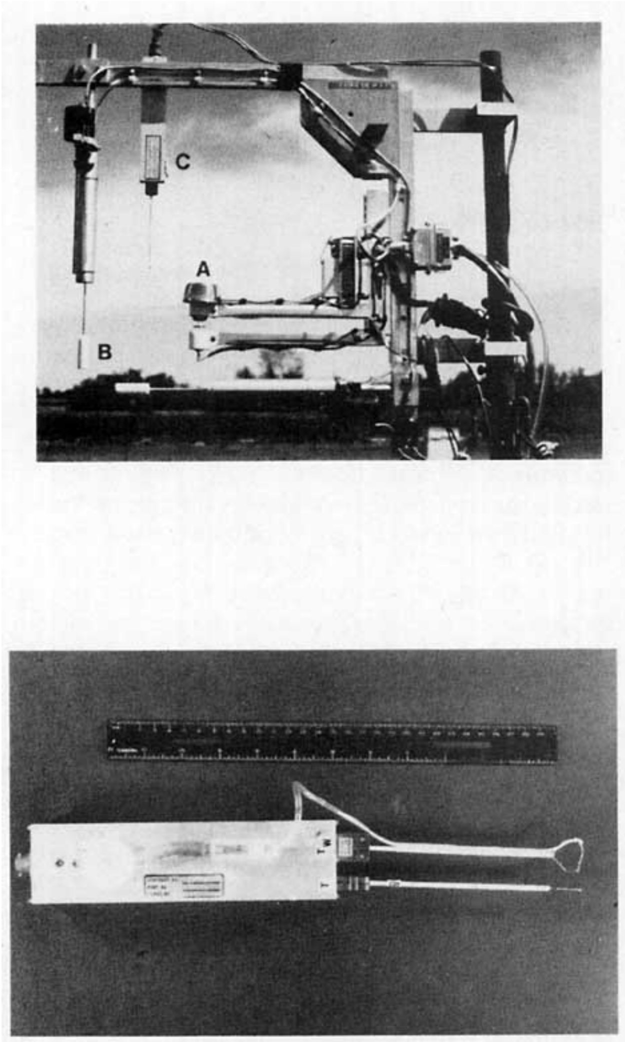

FIG. 1. Top: Lyman-alpha hygrometer (A) shown with a drag anemometer (B) and fine-wire dry-bulb thermocouple (C). Bottom: fine-wire dry- and wet-bulb thermocouple psychrometer.

electronics. Response characteristics and calibration procedures for these sensors are described in Tillman (1973) and Verma *et al.* (1979). Instrument output signals were filtered, scanned and recorded in a manner identical to that used for the Lyman-alpha hygrometer. From the recorded data, wet and dry bulb temperatures were computed[4] from which absolute humidity was derived since atmospheric pressure was also measured.

A three-dimensional drag anemometer (shown in Fig. 1) was used in conjunction with the humidity measuring instruments to determine the vertical flux of latent heat. The anemometer signals were recorded in the same way as were the humidity sensors. From the recorded data air motion in three dimensions were calculated. The anemometer system responds to wind fluctuations up to 5 Hz. Calibration, operation and detailed response characteristics of this instrument are fully described by Norman *et al.* (1976) and Redford *et al.* (1980).[5]

Pressure was measured three times per minute with a barometer located in the laboratory building. An average pressure value for 15 min was used in the computations. All instrument signals were monitored on an oscilloscope and computer analyses were carefully checked for instrument errors. All data runs used were free of such errors.

3. Results

a. Standard deviation

Standard deviations of humidity fluctuations (σ_q) were computed by:

$$\sigma_q = (\overline{q^2} - \bar{q}^2)^{1/2}, \qquad (5)$$

where the bar indicates a time average of data collected during the 43 min recording periods.

Fig. 2 is a comparison of the standard deviations (σ_q) of the data from the Lyman-alpha and the thermocouple-psychrometer for 22 runs when both instruments were maintained at 4.5 m above the ground. There is a considerable scatter (~20%) in the data.[6] Standard deviations are, on the average, 4% larger for the psychrometer than for the Lyman-alpha. The points showing the psychrometric standard deviations greater than the hygrometric standard deviations (indicated by circles), all occurred under conditions of low wind speed (~1 m s^{-1}). The remaining points represent standard deviations with average windspeeds of 4 m s^{-1} or more. The low wind occurred in periods of near calm interrupted by occasional breezes of a few meters per second. The wet-bulb temperature of the psychrometer depends on ventilation for evaporative cooling. Thus, in low wind, the psychrometer may have produced erroneously large standard deviations. Sample comparisons between time series of dry-bulb temperature and wet-bulb temperature during one period of low wind speed runs support this interpretation. Omission of the data from low wind speed runs reduces the scatter to ~16%, and remaining standard deviations of the psychrometer data are ~2% smaller than for the Lyman-alpha.

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[4] A recent manuscript by Shaw and Tillman (1979: The effect of and correction for different wet- and dry-bulb response thermocouple psychrometers. Submitted to *J. Appl. Meteor.* in which corrections are attempted to account for the difference in response time of the wet- and dry-bulb sensors has come to our attention. No such corrections were made in the data we present here.

[5] Redford, T. G., S. B. Verma and N. J. Rosenberg, 1980: Drag anemometer measurements of turbulence over a vegetated surface. Submitted to *J. Appl. Meteor.*

[6] (Range/maximum) is used as a description of scatter in the data.

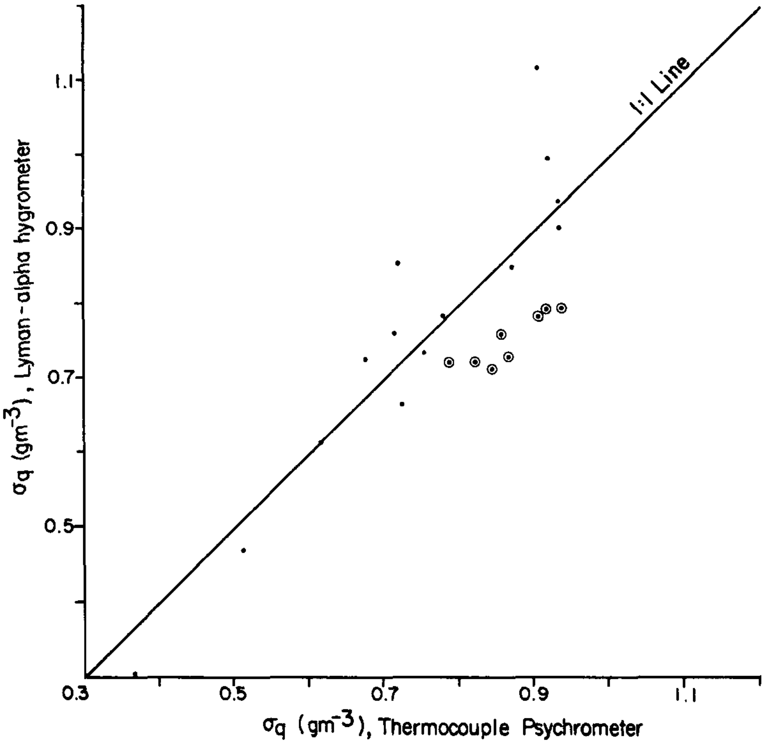

FIG. 2. Comparison of σ_q measured over alfalfa with a Lyman-alpha hydrometer and a fine wire thermocouple psychrometer (July–August 1978). Data for periods of low wind speed are denoted by circles.

The values of σ_q shown in Fig. 2 agree as to order of magnitude with measurements made over water by Phelps and Pond (1971) and over grass by Miyake and McBean (1970).

b. Latent heat flux

Covariances between the vertical velocity and humidity fluctuations were obtained in order to compute latent heat fluxes (*LE*). For this purpose each of the humidity sensors was used in conjunction with the same drag anemometer. Comparison of the flux derived from each of the two humidity sensors is shown in Fig. 3. The circled points represent, as in Fig. 2, data measured during periods of very low average windspeed. Considering all data, the Lyman-alpha measurements of flux are 10–15% greater than those made with the psychrometer. The same argument may apply during periods of low wind speed to the vertical moisture flux as to the standard deviation of humidity fluctuations. The psychrometer may have overestimated the flux. In this case the overestimation may have been partially offset by an underestimation due to incompatible response times of the drag anemometer and psychrometer. This matter is discussed below.

The fluxes reported above agree well with energy balance data measured simultaneously at Mead (details are given in Redford *et al.*, 1980).[5]

c. Spectral analysis

Spectra were computed for several of the periods of measurement represented in Figs. 2 and 3. Some representative results are presented in Figs. 4, 5 and 6. The spectra were computed by fast Fourier transform using a program from The Pennsylvania State University tape library called SAFFT (Parhami, 1971). The spectra were calculated from data series of 4096 points each collected during 5 min, 20 s periods. Eight such series were collected in each hour of operation (42 min, 40 s plus calibration time). Each series was tapered at the ends and linear trends were removed. The raw spectral estimates were logarithmically blocked to provide 25 smoothed estimates over the range of frequencies. The eight spectra resulting were ensemble averaged by frequency to provide one high-frequency spectrum ($n = 10^{-2}$ to 10 Hz) for each hour of data. To obtain low frequency spectra ($n = 10^{-4}$ to 1 Hz) the time series for the whole hour was averaged, eight points at a time, to produce one set of 4096 data points covering the whole time span. Where the

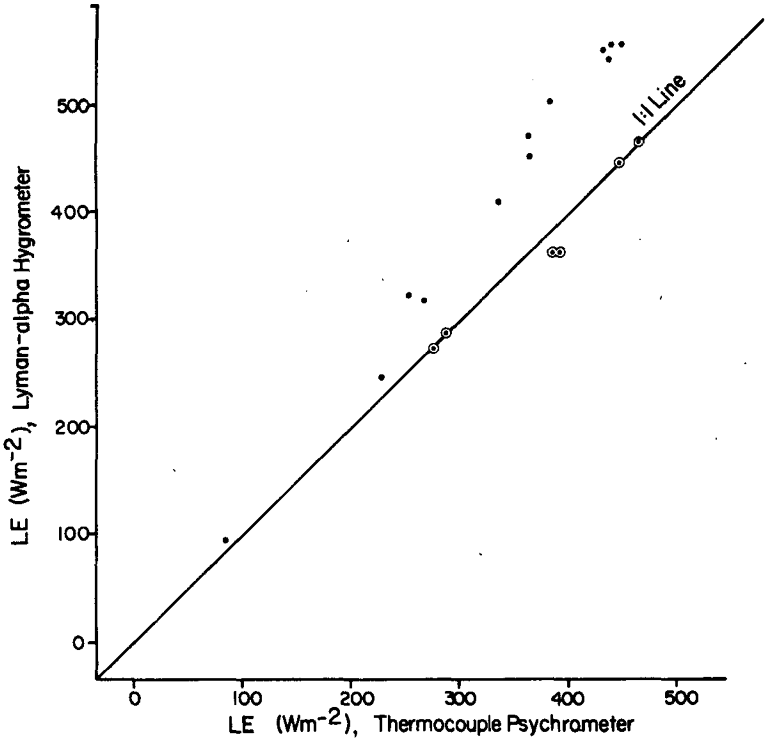

FIG. 3. Comparison of latent heat flux densities measured over alfalfa with a Lyman-alpha hygrometer and a fine wire thermocouple psychrometer (July–August 1978). Vertical wind velocities were measured with a drag anemometer. Low wind speed runs are denoted by circles.

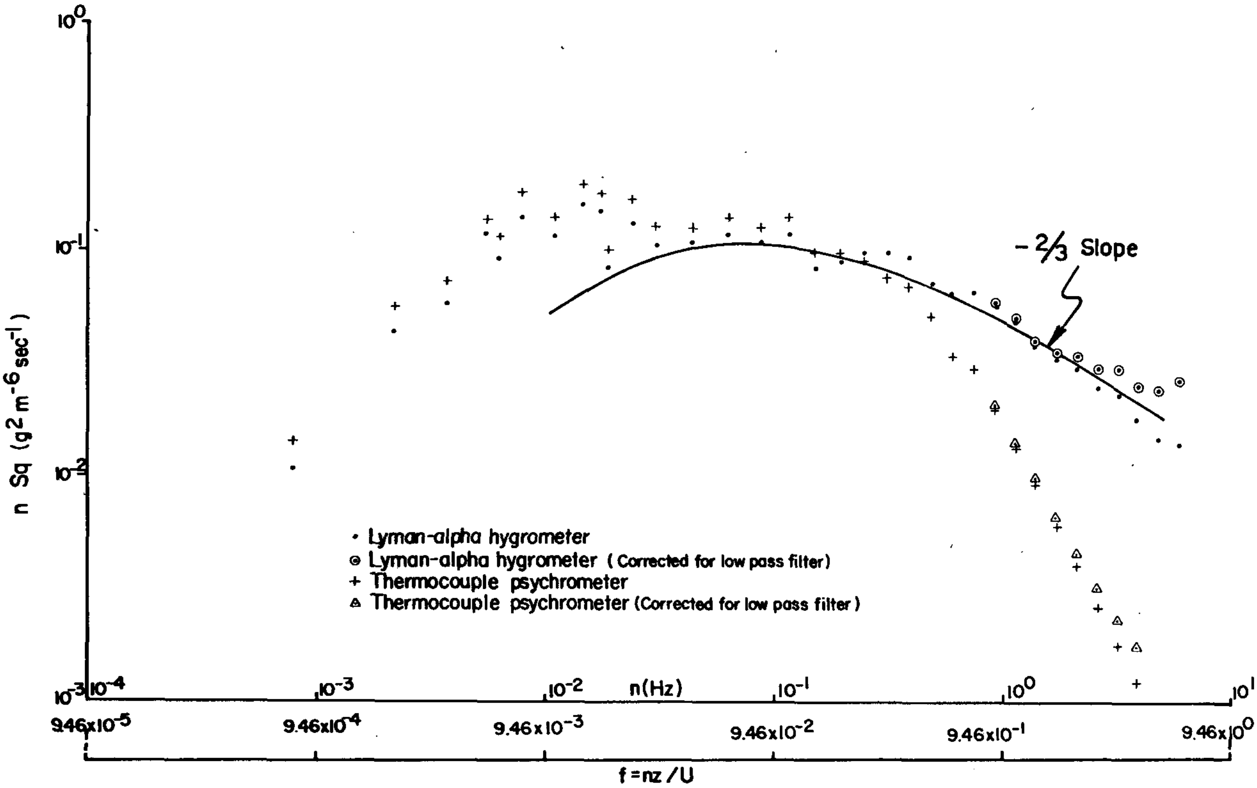

FIG. 4. Spectra of humidity fluctuations measured over alfalfa with a Lyman-alpha hygrometer and a fine wire thermocouple psychrometer (1200 Solar time, 24 July 1978).

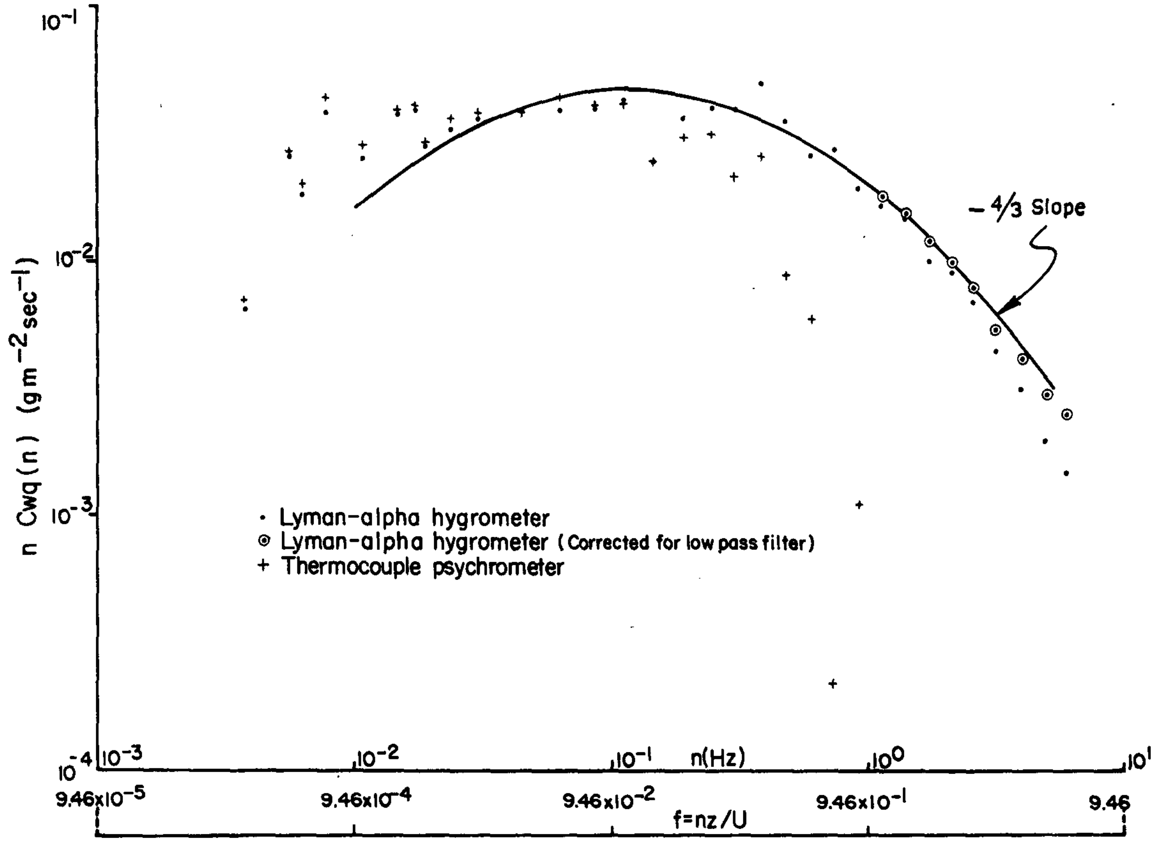

FIG. 5. Cospectra of vertical velocity and humidity fluctuations over alfalfa (1200 Solar time, 24 July 1978). Humidity fluctuations were measured with a Lyman-alpha hygrometer and a fine wire thermocouple psychrometer. Vertical wind velocity fluctuations were measured with a drag anemometer (mean horizontal wind speed 4.7 m s^{-1}).

low- and high-frequency spectra overlapped, agreement was excellent.

Fig. 4 shows the spectra (S_q) of humidity fluctuations measured with Lyman-alpha hygrometer and thermocouple psychrometer between 1200 and 1243 solar time on 24 July 1978. In Fig. 4 nine points from the low-frequency spectra have been added to the 25 from the high-frequency spectra to display one set of spectra from 8×10^{-4} Hz to 6 Hz. The mean wind for the period shown in Fig. 4 was 4.7 m s^{-1} from 183° (±5°), the mean temperature was 26.4°C and the mean absolute humidity was 14.73 g m^{-3}. The high frequency end of both spectra have been corrected for effects of the low-pass filter. Both the original and reconstructed estimates are shown. The solid line is the empirical curve taken from Kaimal *et al.* (1972) for temperature spectra.[7] The slope of the high-frequency end of this curve approaches $-2/3$ which corresponds to the $-5/3$ Kolmogoroff law. The $-2/3$ slope has been used by other investigators (Phelps and Pond, 1971; Pond *et al.*, 1971; Thorpe *et al.*, 1973) as a basis for comparison in the inertial subrange.

The horizontal axis of Fig. 4 has been labeled in both n (Hz) and nondimensional frequency ($f = nz/U$; z = elevation above ground and U = mean horizontal wind speed), but the vertical axis has not been normalized. This allows a truer comparison between the two sets of estimates. Kaimal's curve was multiplied by the value of q_*^2 obtained with the Lyman-alpha hygrometer.[8]

The humidity spectra derived from the Lyman-alpha hygrometer and thermocouple psychrometer agree in the frequency range 8×10^{-4} to 0.2 Hz, with the psychrometric estimates exceeding the hygrometric by ~20%. Above 0.2 Hz the psychrometric spectrum falls off rapidly. From 0.03 to 5 Hz our hygrometric spectral estimates fit Kaimal's curve. Our humidity spectra show more energy than Kaimal's empirical temperature spectra below a fre-

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[7] The report of Kaimal *et al.* (1972) on an experiment in Kansas did not include humidity spectra, and we know of no empirical curve for moisture corresponding to that for temperature used here. We include this curve since many workers have assumed that temperature and humidity spectra behave similarly in the inertial subrange.

[8] In the paper from which the formula was obtained, the curve had been normalized by T_*^2.

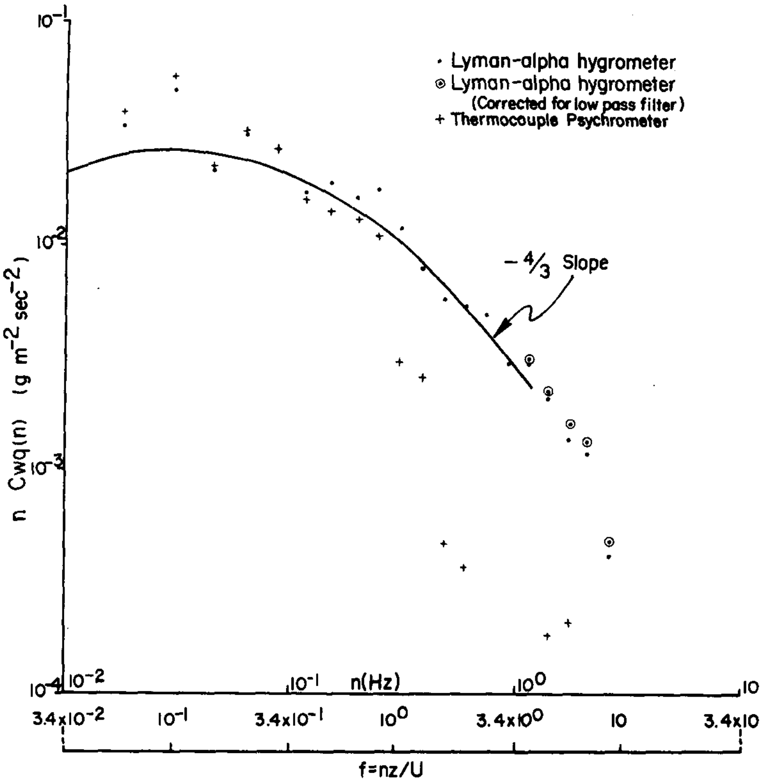

FIG. 6. Cospectra of vertical velocity and humidity fluctuations over alfalfa (mean horizontal wind speed 1.3 m s^{-1}) (1100 Solar time, 4 August 1978). Humidity fluctuations were measured with a Lyman-alpha hygrometer and a fine-wire thermocouple psychrometer. Vertical velocity fluctuations were measured with drag anemometer.

quency of 0.03 Hz which is in agreement with Miyake and McBean (1970).

Although the sum of the spectral estimates from all frequencies covered is a measure of the variance, one should not expect exact agreement between this sum and the independently computed variance. The spectral data have been treated somewhat differently, having been tapered and having had linear trends removed. It should be noted that, at low wind speeds, linear trends were greater in the psychrometric than in the hygrometric time series.

The cospectral estimates (C_{wq}) for vertical moisture flux are shown in Fig. 5. The Lyman-alpha estimates were corrected for filter effects, but the psychrometer estimates dropped off too rapidly to have been affected by the filter. Agreement between the two sets of estimates is excellent at low frequencies up to 0.15 Hz. At greater frequencies the thermocouple psychrometer data begin to fall. The radical dropoff is probably due to the slower response of the psychrometer which puts the humidity data out of phase with the vertical velocity measured by the drag anemometer at high frequencies. This effect is even more apparent at lower wind speeds when the psychrometer response is reduced. Fig. 6 shows data measured when wind speed was about one-fourth of that in Fig. 5. The psychrometric estimates begin rolling off above 0.1 Hz.

Our Lyman-alpha cospectral estimates are in general agreement with the empirical curve for sensible heat cospectra of Kaimal *et al.* (1972).

4. Summary and conclusions

Similar estimates of standard deviation in absolute humidity fluctuations were obtained with a Lyman-alpha hygrometer and a thermocouple psychrometer. An inspection of simultaneous spectra reveals that the psychrometer underestimates the importance of the high frequencies while the Lyman-alpha shows somewhat less energy at lower frequencies.

In agricultural situations it is not often easy to achieve sufficient fetch to allow placement of turbulence sensors 4 or 5 m above the surface. Thus one must work closer to the surface to avoid unwanted effects of upwind surface inhomogeneity. Since the spectra shift toward higher frequencies as the surface is approached, the psychrometer response will be inadequate to reveal the peak of the spectrum.

The psychrometer will begin to fall off at frequencies below the frequency of greatest interest. For this reason, the Lyman-alpha hygrometer is preferable for use at elevations below 4 m.

Vertical fluxes of moisture were underestimated by the psychrometer due, probably, to its increasing phase lag against the drag anemometer as frequency increases above 0.15 Hz. This problem is more critical at lower elevations, since the higher frequencies become relatively more important as the surface is approached. Lower windspeeds apparently reduce the response of the psychrometer, causing it to lag the anemometer.

The Lyman-alpha hygrometer performed well at all wind speeds and all frequencies. It performed better than did the thermocouple psychrometer at high frequencies and low wind speeds. Thus, the Lyman-alpha hygrometer appears to be particularly well-suited for the measurement of moisture flux and for detailed study of humidity spectra close to the ground.

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