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KOLMOGOROV CONSTANTS FOR CO_2, WIND VELOCITY, AIR TEMPERATURE, AND HUMIDITY FLUCTUATIONS OVER A CROP SURFACE*

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Abstract. The Kolmogorov constants for CO_2, wind velocity, air temperature, and humidity fluctuations were evaluated from measurements made over soybean and grain sorghum fields and found to be 0.78 ± 0.11, 0.49 ± 0.08, 0.70 ± 0.15, and 0.99 ± 0.16, respectively. These results are consistent with recent observations reported in the literature.

1. Introduction

Hicks and Dyer (1972) described a spectral density technique for determining turbulent fluxes. This technique utilizes known characteristics of the inertial subrange (see, e.g., Kaimal *et al.*, 1972) and is particularly useful for measurements over the open ocean since it does not require explicit measurements of vertical velocity. Recently Large and Pond (1982) demonstrated the applicability of this approach in determining fluxes of sensible and latent heat from ships on the deep sea.

The flux computation technique mentioned above requires knowledge of the Kolmogorov constant for the fluctuating parameter with the appropriate spectral density value. The Kolmogorov constants for velocity and temperature fluctuations have been studied extensively. However, only a few studies have been reported on the Kolmogorov constant for humidity fluctuations. Except for one recent report (Ohtaki, 1982), the Kolmogorov constant for CO_2 fluctuations has not been evaluated.

There is considerable interest in determining CO_2 fluxes over the open ocean where the spectral density technique, using an appropriate value of the Kolmogorov constant, may be applied. In this paper, we present results of measurements of the Kolmogorov constants for CO_2, wind velocity, air temperature, and humidity made over soybean and grain sorghum fields.

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2. Procedure

2.1. MEASUREMENTS

Studies reported here were conducted at the University of Nebraska Agricultural Meteorology Laboratory near Mead, Nebraska (41°09′ N, 96°30′ W, altitude of 354 m above mean sea level). The Kolmogorov constants for velocity, humidity, and CO_2 fluctuations are computed from measurements made at 2.25 m during August 20–September 2, 1981 over a soybean crop (zero plane displacement, $d \approx 0.45$–0.50 m) with an upwind fetch of at least 210 m. The Kolmogorov constant for air temperature fluctuations was computed from measurements made during August 25–September 10, 1982 over a grain sorghum crop (zero plane displacement, $d \approx 0.75$ m) with an upwind fetch of 210 m.

A drag anemometer was used to measure velocity fluctuations. This anemometer is described in Norman *et al.* (1976) and Redford *et al.* (1981). Air temperature fluctuations were measured with a fine-wire thermocouple described in Verma *et al.* (1979). A Lyman-alpha hygrometer (Buck, 1975, 1976; Redford *et al.*, 1980) was used to measure humidity fluctuations. CO_2 fluctuations were measured with a rapid response sensor designed and built at the Lawrence Livermore National Laboratory, California, under the direction of Dr Gail Bingham. This sensor is a dual wavelength differential infrared absorption spectrometer. It makes use of a strong CO_2 absorption band centered at 4.27 μm and a 'reference' band centered at 3.85 μm in which absorption is minimal. The reference band is used to adjust for system instabilities arising from electronic drift, optical system degradation resulting from mirror contamination or variations in source emission. The difference in the sensor's output in the absorbed band and that in the reference band is directly proportional to the CO_2 concentration. Further details on the mechanical and electronic features of this sensor are given in Bingham *et al.* (1978) and Bingham (1980).

A computer-controlled data acquisition system, consisting of a minicomputer, analog-to-digital convertors and a magnetic tape drive, was used to record all data. In 1981 the signals were electrically filtered by 8-pole Butterworth filters with a 6.25 Hz cutoff and sampled at 12.8 Hz. In 1982 8-pole Butterworth filters with a 12.5 Hz cutoff were used and the sampling frequency was increased to 25 Hz.

2.2. MATHEMATICAL BACKGROUND AND COMPUTATION

Following the formulations outlined in Hicks and Dyer (1972) and Dyer and Hicks (1982), the spectral densities S_u, S_T, S_q, and S_c for velocity, temperature, humidity, and CO_2 fluctuations can be expressed as:

$$\frac{nS_u(n)}{u_*^2} = \alpha_u(2\pi kf)^{-2/3}\,(\phi_m - z/L)^{2/3} \tag{1}$$

$$\frac{nS_T(n)}{T_*^2} = \alpha_T(2\pi kf)^{-2/3}\,\phi_H(\phi_m - z/L)^{-1/3} \tag{2}$$

$$\frac{nS_q(n)}{q_*^2} = \alpha_q(2\pi kf)^{-2/3}\,\phi_w(\phi_m - z/L)^{-1/3} \tag{3}$$

$$\frac{nS_c(n)}{C_*^2} = \alpha_c(2\pi kf)^{-2/3}\,\phi_c(\phi_m - z/L)^{-1/3} \tag{4}$$

where ϕ_m, ϕ_H, ϕ_w, and ϕ_c are the respective non-dimensional gradients; f is normalized frequency = $[n(z - d)]/U$, n is the natural frequency, z is the elevation above ground, U is the mean horizontal wind speed; $T_* = H/(\rho c_p u_*)$; $q_* = E/(\rho u_*)$; $C_* = F_c/u_*$; ρ is the air density; c_p is the specific heat at constant pressure; L is the moisture-corrected Monin–Obukhov length; H, E, and F_c are fluxes of sensible heat, water vapor and CO$_2$, respectively; u_* is the friction velocity and k is the von Karman constant (taken here to be 0.4). In deriving the above equations, the Kolmogorov hypothesis is followed. Incompressibility, stationarity, and horizontal homogeneity are assumed. Production and dissipation rates are assumed to be equal.

Dyer and Hicks (1970) have determined the following empirical relationships for ϕ_m, ϕ_H, and ϕ_w in unstable thermal stability:

$$\phi_m = (1 - 16z/L)^{-0.25} \tag{5}$$

and

$$\phi_H = \phi_w = (1 - 16z/L)^{-0.50}\,. \tag{6}$$

Similarity of turbulence mechanisms of CO$_2$, temperature and humidity was assumed, leading to:

$$\phi_c = \phi_H = \phi_w\,. \tag{7}$$

It is now possible to solve for the Kolmogorov constants using the relationships presented above. For a given z/L, corresponding values of ϕ_m, ϕ_H, ϕ_w, and ϕ_c can be computed from Equations (5)–(7). Using these values in conjunction with the spectral density values (S_u, S_T, S_q, and S_c), turbulent fluxes (H, E, F_c), friction velocity (u_*), natural frequency (n), mean winds peed (U), height of measurement (z), and zero plane displacement (d) in Equations (1)–(4), the Kolmogorov constants (α_u, α_T, α_q, and α_c) can be calculated.

Spectral densities were computed by fast Fourier transform using a program from the Pennsylvania State University tape library called SAFFT (Parhami, 1971). Ten sets of spectra were analyzed using data recorded during thermally unstable conditions ($-0.1 < z/L < -0.01$). From individual spectra (at a given z/L), three values of $nS(n)$ in the inertial subrange around $f = 0.8$–1.2 were used to compute the Kolmogorov constants (α). Mean α values for a given z/L are reported below. Fluxes of momentum, sensible heat, water vapor and CO$_2$ were obtained from appropriate covariances. CO$_2$ fluxes were corrected for the effects of water vapor exchange on the density of air (Webb *et al.*, 1980).

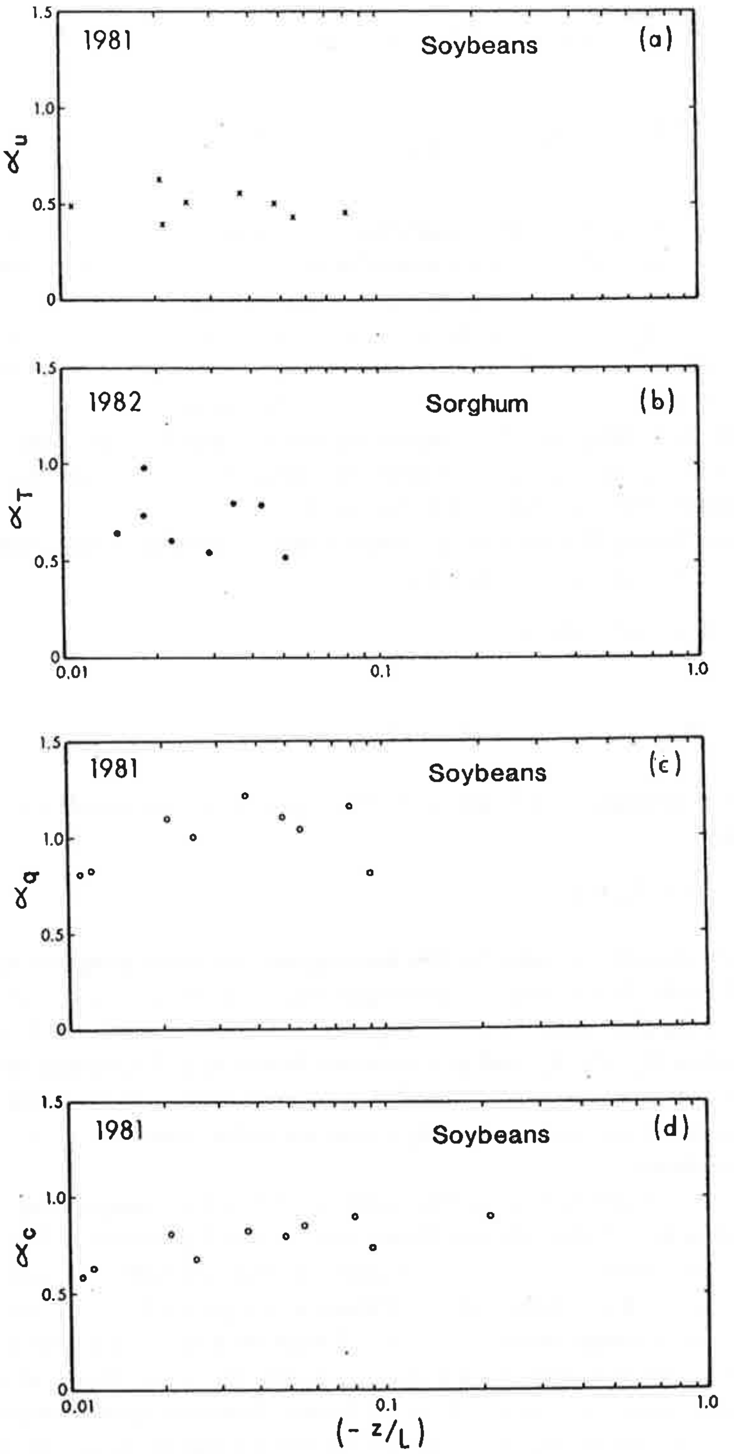

Fig. 1. Kolmogorov constants α_u, α_T, α_q, and α_c plotted against thermal stability (z/L).

3. Results and Conclusions

The values of the Kolmogorov constants obtained by using the procedure described above are presented in Figure 1 and Table I. In Figure 1, α_u, α_T, α_q, and α_c are plotted as functions of stability (z/L). The values of α appear to be independent of z/L in the range of stability considered here.

The values of the Kolmogorov constant for velocity (α_u) and temperature (α_T) fluctuations were found to be 0.49 ± 0.08 and 0.70 ± 0.15 (Table I). These compare closely with the values obtained by Wyngaard and Coté (1971), Kaimal *et al.* (1972), Hicks and Dyer (1972), and Dyer and Hicks (1982).

TABLE I

Values of Kolmogorov constants*

Fluctuation	Kolmogorov constant	Value	Source
Velocity	α_u	0.49 ± 0.08	Present study
		0.52 ± 0.05	Wyngaard and Coté (1971)
		0.50 ± 0.05	Kaimal *et al.* (1972)
		0.54 ± 0.03	Hicks and Dyer (1972)
		0.59 ± 0.01	Dyer and Hicks (1982)
Temperature	α_T	0.70 ± 0.15	Present study
		0.79 ± 0.10	Wyngaard and Coté (1971)
		0.82 ± 0.08	Kaimal *et al.* (1972)
		0.68 ± 0.02	Dyer and Hicks (1982)
Humidity	α_q	0.99 ± 0.16	Present study
		0.80 ± 0.20	Paquin and Pond (1971)
		0.88 ± 0.26	Raupach (1978)
		0.76 ± 0.03	Dyer and Hicks (1982)
CO_2	α_c	0.78 ± 0.11	Present study
		0.89 ± 0.13	Ohtaki (1982)

* Note that α values vary as $k^{2/3}$. We chose $k = 0.4$. If $k = 0.37$, α values would be reduced by 5.1%. If $k = 0.41$, α values would be increased by 1.7%.

The Kolmogorov constant for humidity fluctuations (α_q) was found to be 0.99 ± 0.16 (Table I), a little larger than those generally found in the literature (e.g., Paquin and Pond, 1971; Raupach, 1978; and Dyer and Hicks, 1982). Smedman-Högström (1973), on the other hand, reported a value (0.58 ± 0.2), considerably lower than that found in this study and those in the literature mentioned above.

The Kolmogorov constant for CO_2 fluctuations (α_c) was found to be 0.78 ± 0.11. This is in reasonable agreement with a value of 0.89 ± 0.13 reported by Ohtaki (1982), the only study known to us in which the Kolmogorov constant for CO_2 has been evaluated.

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References

Bingham, G. E.: 1980, 'A Miniature Rapid Response Sensor for Atmospheric Concentrations of Carbon Dioxide', Annual Report to DOE, Contract #LLL/EV–81–65.

Bingham, G. E., Gillespie, C. H., and McQuaid, J. H.: 1978, 'Development of a Miniature, Rapid Response CO_2 Sensor', Lawrence Livermore National Laboratory, Rept. UCRL–52440.

Buck, A.: 1975, 'Variable-Path Lyman-alpha Hygrometer Operating and Maintenance Manual 023032002, NCAR', Boulder, CO, 116 pp.

Buck, A.: 1976, 'The Variable Path Lyman-alpha Hygrometer and its Operating Characteristics', *Bull. Amer. Meteorol. Soc.* **57**, 1113–1118.

Dyer, A. J. and Hicks, B. B.: 1970, 'Flux-Gradient Relationships in the Constant Flux Layer', *Quart. J. Roy. Meteorol. Soc.* **96**, 715–721.

Dyer, A. J. and Hicks, B. B.: 1982, 'Kolmogoroff Constants at the 1976 ITCE', *Boundary-Layer Meteorol.* **22**, 137–150.

Hicks, B. B. and Dyer, A. J.: 1972, 'The Spectral Density Technique for the Determination of Eddy Fluxes', *Quart. J. Roy. Meteorol. Soc.* **98**, 838–844.

Kaimal, J. C., Wyngaard, J. C., Izumi, Y., and Coté, O. R.: 1972, 'Spectral Characteristics of Surface-Layer Turbulence', *Quart. J. Roy. Meteorol. Soc.* **98**, 563–589.

Large, W. G. and Pond, S.: 1982, 'Sensible and Latent Heat Flux Measurements over the Ocean', *J. Phys. Oceanog.* **12**, 464–482.

Norman, J. M., Perry, S. G., and Panofsky, H. A.: 1976, *Measurement and Theory of Horizontal Coherence at a Two Meter Height*, 3rd Symposium on Atmospheric Turbulence, Diffusion, and Air Quality, Raleigh, NC, AMS preprint, pp. 19–22.

Ohtaki, E.: 1982, 'The Kolmogorov Constant for Carbon Dioxide in the Atmospheric Surface Layer over a Paddy Field', *Boundary-Layer Meteorol.* **23**, 153–159.

Paquin, J. E. and Pond, S.: 1971, 'The Determination of the Kolmogoroff Constants for Velocity, Temperature, and Humidity Fluctuations from Second- and Third-Order Structure Functions', *J. Fluid Mech.* **50**, 257–269.

Parhami, B.: 1971, 'Spectral Analysis by Fast Fourier Transform', Contributed computer program and write-up to the Computation Center, Dept. of Meteorology, The Pennsylvania State University, 24 pp.

Raupach, M. R.: 1978, 'Infrared Fluctuation Hygrometry in the Atmospheric Surface Layer', *Quart. J. Roy. Meteorol. Soc.* **104**, 309–322.

Redford, T. G., Jr., Verma, S. B., and Rosenberg, N. J.: 1980, 'Humidity Fluctuations over a Vegetated Surface Measured with a Lyman-alpha Hygrometer and a Fine-Wire Thermocouple Psychrometer', *J. Amer. Meteorol.* **19**, 860–867.

Redford, T. G., Jr., Verma, S. B., and Rosenberg, N. J.: 1981, 'Drag Anemometer Measurements of Turbulence over a Vegetated Surface', *J. Appl. Meteorol.* **20**, 1222–1230.

Smedman-Högström, A.: 1973, 'Temperature and Humidity Spectra in the Atmospheric Surface Layer', *Boundary-Layer Meteorol.* **3**, 329–347.

Verma, S. B., Motha, R. P., and Rosenberg, N. J.: 1979, 'A Comparison of Temperature Fluctuations Measured by a Microbead Thermistor and a Fine Wire Thermocouple over a Crop Surface', *Agr. Meteorol.* **20**, 281–289.

Webb, E. K., Pearman, G. I., and Leuning, R.: 1980, 'Correction of Flux Measurements for Density Effects Due to Heat and Water Vapour Transfer', *Quart. J. Roy. Meteorol. Soc.* **106**, 85–100.

Wyngaard, J. C. and Coté, O. R.: 1971, 'The Budgets of Turbulent Kinetic Energy and Temperature Variance in the Atmospheric Surface Layer', *J. Atmos. Sci.* **28**, 190–201.