1986

Aerodynamic Characteristics of Grain Sorghum

S. B. Verma
University of Nebraska - Lincoln

Agricultural and Forest Meteorology, 38 (1986) 193—204
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

AERODYNAMIC CHARACTERISTICS OF GRAIN SORGHUM*

PEDRO V. AZEVEDO and SHASHI B. VERMA

Center for Agricultural Meteorology and Climatology, Institute of Agriculture and Natural Resources, University of Nebraska, Lincoln, NE 68583-0728 (U.S.A.)

(Received November 26, 1985; revision accepted, April 22, 1986)

ABSTRACT

Azevedo, P.V. and Verma, S.B., 1986. Aerodynamic characteristics of grain sorghum, Agric. For. Meteorol., 38: 193—204.

Wind speeds were measured above grain sorghum (*Sorghum bicolor* L. Moench cv. DK-57) canopies at Mead, Nebraska, during the 1982 and 1983 growing seasons. The crop was planted in north—south-oriented rows 0.76 m apart. The plant population per ha was about 276 000 in 1982 and 118 500 in 1983.

The measured above-canopy wind speed profiles were employed to evaluate the aerodynamic characteristics of the crop throughout the growing season. The roughness parameter (z_0) and the zero-plane displacement (d) increased with increasing crop height (h). The rate of increase, however, appeared to be dependent on the stage of crop growth. The emergence of the heads played an important role in the seasonal variation of z_0 and d. z_0/h and d/h reached maximum values at the time of the emergence of the heads, asymptotically decreasing to constant values as the crop approached full development. Mean values of z_0/h and d/h for the fully developed sorghum crop at moderate windiness were 0.096 and 0.60, respectively, in 1982. Corresponding values in 1983 (sparser crop) were 0.076 and 0.54. In both years, z_0/h and d/h values at full crop development decreased with increasing wind speed.

Mean values of the crop drag coefficient (C_d) for the fully developed canopies at moderate windiness were 0.055 in 1982 and 0.035 in 1983. Values of C_d decreased with increasing wind speed according to the following relationships: $C_d = 0.037u_*^{-0.435}$ in 1982 and $C_d = 0.0177u_*^{-0.743}$ in 1983 (where u_* = friction velocity).

INTRODUCTION

An accurate description of the aerodynamic characteristics of the crop is needed for a thorough understanding of the turbulent exchanges of energy and mass between the vegetation and the atmosphere. The aerodynamic characteristics of a crop can be expressed in terms of: roughness parameter (z_0), zero-plane displacement (d) and crop drag coefficient (C_d). Functional dependence of these parameters on crop height (h) has been established for various crops, primarily for the fully developed stage of growth. Very little information is available about the behavior of these parameters during earlier stages of crop growth. Their dependence on flow regime is also not well

* Published as Paper No. 7921 Journal Series, Nebraska Agricultural Research Division. The work reported was conducted under Regional Research Project 11-33 and Nebraska Research Division Project 27-003.

0168-1923/86/$03.50

established. This lack of information certainly applies to grain sorghum, an important crop for semi-arid and arid regions of the world.

This paper reports the results of observations on air flow made above grain sorghum canopies. The data were used to develop information on roughness parameter, zero-plane displacement and crop drag coefficient at various stages of growth. The influence of wind speed on these parameters was investigated.

MATERIALS AND METHODS

Experimental site and instrumentation

Observations were made during the 1982 and 1983 growing seasons at Mead, Nebraska (41°09′ N; 96°30′ W; 354 m above mean sea level). The experimental field, 210 (N—S) by 110 m (E—W) was planted on 8 June, 1982 with grain sorghum (*Sorghum bicolor* L. Moench cv. DK-57) in 0.76-m wide, N—S-oriented rows. The plant population was about 276 000 ha^{-1}. Border fields were planted with grain sorghum to the southeast, south and west and with soybean to the north. Grain sorghum was planted again on 8 June 1983 in the same experimental field. However, the plant population was reduced to ~ 118 500 plants ha^{-1}.

Wind speeds were measured at 0.25-m intervals above the canopy with Cayuga three-cup anemometers (Cayuga Development, Ithaca, NY; Model WP-1). In the beginning of the measurement period, when plant height was < 0.25 m, wind speed was measured at 11 levels (from 0.25 to 2.75 m). As the crop grew, the lower anemometers were progressively removed. At the stage of full crop development, seven levels of anemometers remained. The cup anemometers were calibrated in a wind tunnel before and after each growing season. Dry and wet bulb air temperature were measured above each canopy with six level self-checking aspirated psychrometers (Rosenberg and Brown, 1974). All meteorological data were averaged over 15-min periods.

Data included in this paper are for periods when the wind direction ranged from southeast to southwest, which provided a fetch of approximately 200 m. The thermal stratification of the first 1.5-m air layer above the canopy during these time periods was nearly neutral ($|Ri| < 0.003$, where Ri = Richardson number corrected for the effects of water vapor; for details, see Webb, 1965). Measured dry and wet bulb air temperature profiles were used in the computation of Richardson number.

Computational procedures: zero-plane displacement (d) and roughness parameter (z_0)

Methods employed for estimating the roughness parameter (z_0) and zero-plane displacement (d) are described below.

Logarithmic profile analysis

In the constant flux layer above vegetated surfaces under nearly neutral conditions, the variation of the mean wind speed ($\bar{U}$) with height (z) can be expressed by:

$$\bar{U}(z) = \frac{u_*}{k} \ln\left(\frac{z-d}{z_0}\right), \qquad z > h \tag{1}$$

where u_* is friction velocity, k is von Karman's constant (assumed to be 0.4 here, z_0 is the roughness parameter, d is the zero-plane displacement and h is the crop height. The value of d was obtained subjectively by plotting mean wind speed ($\bar{U}$) against $\ln(z-d)$ in a trial and error procedure. Once d was found, values of z_0 and u_* were determined as the intercept and slope of the line, respectively.

Mass conservation approach

Recently, Molion and Moore (1983) and deBruin and Moore (1983) have applied a method for estimating d and z_0 based on mass conservation principles. This approach is expressed mathematically by:

$$\int_0^{z_f} \bar{U}(z)\mathrm{d}z = \int_{d+z_0}^{z_f} \frac{u_*}{k} \ln\left(\frac{z-d}{z_0}\right)\mathrm{d}z \tag{2}$$

where z_f is the height above the roughness sublayer (in this study z_f was taken as 2.75 m, the highest level of measurements). Equation 2 can be reduced to:

$$d = z_f - \frac{z_m}{\{1 - Y_d^{-1} + [Y_d \exp(Y_d)]^{-1}\}} \tag{3}$$

$$\text{and, } z_0 = (z_f - d)\exp(-Y_d) \tag{4}$$

The term z_m is the height for the mean bulk wind speed expressed as:

$$z_m = \frac{1}{2\bar{U}(z_f)} [\bar{U}_1 \Delta z_1 + 2\sum_2^n \bar{U}_i \Delta z_i + \bar{U}_{n+1} \Delta z_{n+1}] \tag{5}$$

where n is the number of equally spaced layers and Δz is the thickness of the layers. The dimensionless term, Y_d, is given by:

$$Y_d = \ln\left(\frac{z_f - d}{z_0}\right) = \frac{k\bar{U}(z_f)}{u_*} \tag{6}$$

Further details of these equations can be obtained from Molion and Moore (1983), deBruin and Moore (1983) and Azevedo (1985).

Seginer's approach

Seginer (1974) has described another approach for estimating d and z_0 in terms of the mixing length and drag characteristics of the canopy. The above-canopy logarithmic profile (eq. 1) in conjunction with the within-canopy exponential profile (Inoue, 1963; Cionco, 1965) yields:

$$d/h = 1 - [\mathrm{l}(h)/kh] \tag{7}$$

and,

$$\frac{z_0}{h} = \left(1 - \frac{d}{h}\right) \exp\left\{-\left[\frac{2k^3}{\mathrm{l}(h)C_d'A}\right]^{1/3}\right\} \tag{8}$$

where $\mathrm{l}(h)$ is the mixing length $[= k(d\bar{U}/dz)/(d^2\bar{U}/dz^2)] = u_*/(d\bar{U}/dz)$ at the top of the canopy, C_d' is the plant element drag coefficient and A is the plant area density (projected area of plant elements per unit volume occupied by vegetation).

In approaches b and c, above- and within-canopy profiles were used to compute d and z_0 by means of eqs. 2—6 and eqs. 7 and 8, respectively. Wind speeds within the crop canopy were measured with heated thermistor anemometers (details can be found in Bergen, 1971 and Azevedo, 1985). The plant element drag coefficient (C_d') was estimated from within-canopy wind speed data in the manner described by Uchijima and Wright (1964). Values of u_* obtained from the logarithmic profile analysis were used.

RESULTS AND DISCUSSION

Aerodynamic characteristics of sorghum canopies

Roughness parameter and zero-plane displacement

Seasonal variation. Roughness parameter (z_0) and zero-plane displacement (d) were estimated for various stages of crop growth. The logarithmic profile analysis (eq. 1) was used for these computations (relative errors of about 10% in z_0 and d can be expected in this approach). The seasonal variation of z_0 and d under moderate windiness ($0.40\,\mathrm{m\,s^{-1}} < u_* < 0.50\,\mathrm{m\,s^{-1}}$) is shown in Fig. 1a and b. Crop height (h) is also shown in this figure. z_0 and d increased with increasing crop height. However, the rate of increase of these parameters appeared to depend on the stage of crop development. In the vegetative stage of crop growth (before the emergence of the heads which occurred around 25 July in 1982 and 20 July in 1983), z_0 and d increased quite rapidly. During the stage of emergence and growth of the heads, on the other hand, z_0 and d showed a slower rate of increase. As the crops became fully developed ($h \sim 1.30\,\mathrm{m}$), z_0 and d asymptotically approached constant values. Values of z_0 and d were smaller in the sparser canopy (1983).

There is a paucity of information in the literature on z_0 and d for early stages of crop development. Except for Norman (reported in Verma and Barfield, 1979) and Legg et al. (1981), most studies report d and z_0 primarily for fully developed crops. Normalized values of d and z_0 obtained in this study, for early as well as later stages of crop growth, are plotted against h/W (W = row spacing) in Fig. 2a and b. During the vegetative stage, d and

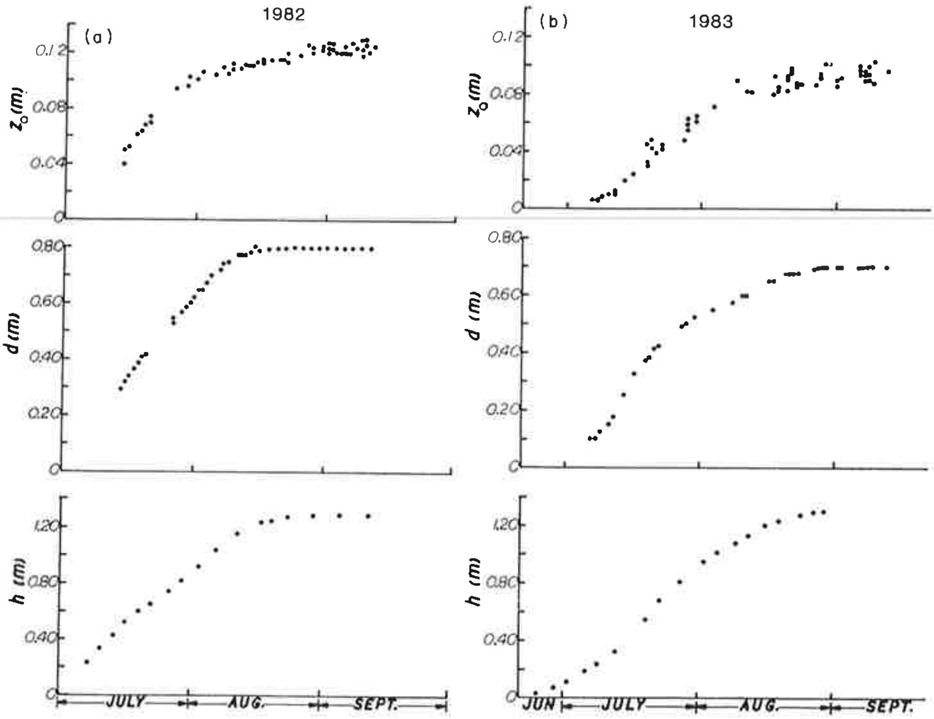


Fig. 1. (a) Variation of the roughness parameter (z_0), zero-plane displacement (d) and crop height (h) throughout the 1982 growing season. z_0 and d data were obtained under moderate windiness. (b) Variation of the roughness parameter (z_0), zero-plane displacement (d) and crop height (h) throughout the 1983 growing season. z_0 and d were obtained under moderate windiness.

z_0 increased relatively more rapidly than did the crop height, reaching maximum values at the time of the emergence of the heads. These results are in general agreement with those of Norman (reported in Verma and Barfield, 1979). During the period of emergence and growth of the heads ($0.95 < h/W < 1.60$ in 1982 and $0.80 < h/W < 1.45$ in 1983) the rate of increase of d was smaller than that of h so that the ratio d/h decreased with time. For the same time periods, z_0/h appeared to decrease in 1982, but remained approximately constant in 1983.

At full crop development ($h/W \sim 1.71$), z_0/h under moderate windiness reached about 0.096 and 0.076, on average, in 1982 and 1983, respectively. Corresponding values of d/h were about 0.61 and 0.54, respectively. These values are within the range of results reported in the literature. Values of z_0/h and d/h were smaller in 1983, probably because the canopy was sparser (the plant area index, PAI, was 5.2 in 1982 and 3.8 in 1983).

Values of d/h and z_0/h obtained under moderate windiness by the mass conservation approach and Seginer's approach are compared against those

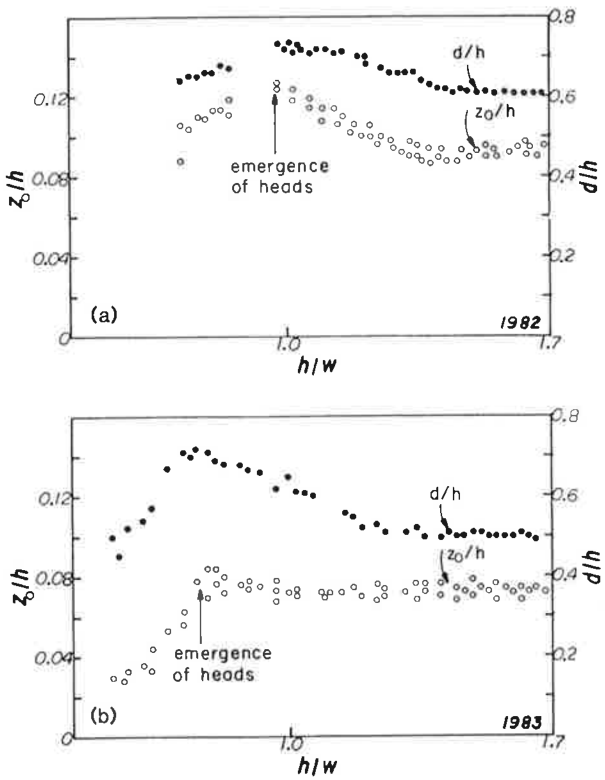


Fig. 2. Seasonal variation of the normalized roughness parameter (z_0/h) and zero-plane displacement (d/h) under moderate windiness. h = crop height and w = row spacing.

obtained by the logarithmic profile analysis in Fig. 3a and b. Values of d/h obtained with both alternative approaches were slightly lower than those obtained with the logarithmic profile analysis. This discrepancy may be due to the fact that the logarithmic profile analysis uses the above-canopy wind speed profile only whereas the other two approaches employ both above- and within-canopy wind speed data. The lowest values of d/h were obtained by means of Seginer's approach. This underestimation probably occurred because the mixing length computed for the top layer of the canopy in this approach is assumed to be constant throughout the canopy. Values of z_0/h obtained with the mass conservation and Seginer approaches were somewhat higher than those obtained with the logarithmic profile analysis for reasons that are discussed above.

Wind speed dependence. Wind speed dependence of d and z_0 is shown in Figs. 4 and 5, respectively. Values of d/h and z_0/h at full crop development, obtained by means of the mass conservation approach, are shown in these figures. In both years, a decrease of d was observed with increasing wind

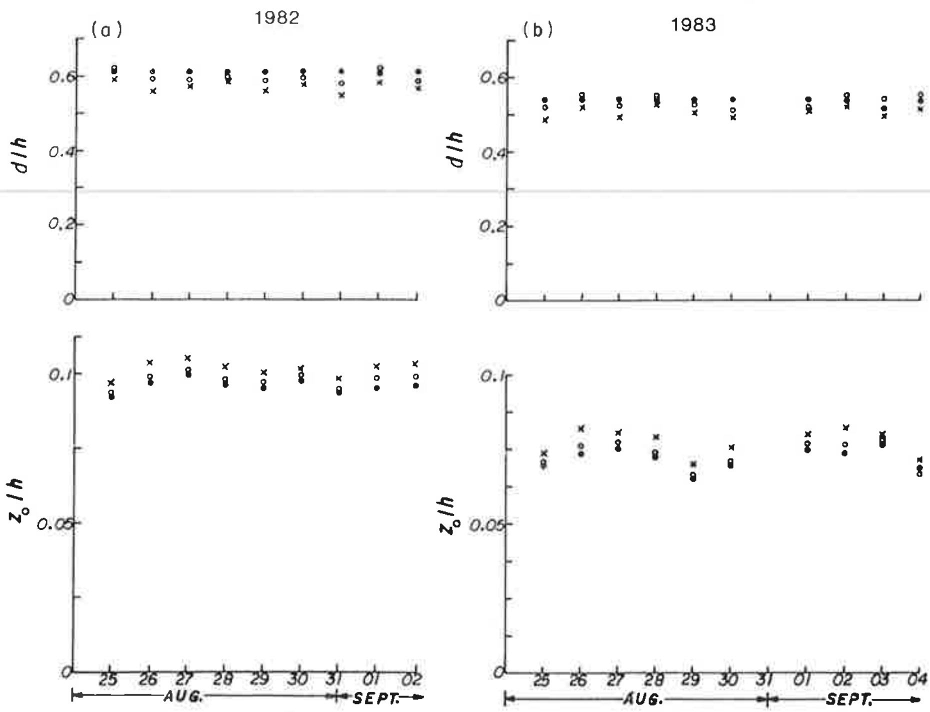


Fig. 3(a). Comparison of three methods (●, logarithmic profile analysis; ○, mass conservation approach; and ×, Seginer's approach) of estimating d and z_0. Data were obtained under moderate windiness at full crop development during 1982. (b) Comparison of three methods (as for (a)) of estimating d and z_0. Data were obtained under moderate windiness at full crop development during the 1983 season.

speed, probably as a result of bending of the plants. A similar reduction of d with increase in wind speed has been reported by Rauner (1976), Uchijima (1976), Bache and Unsworth (1977) and Molion and Moore (1983).

In 1982, d/h decreased from 0.61 at low wind speed ($u_* < 0.30\,\mathrm{m\,s^{-1}}$) to 0.48 at high wind speed ($u_* > 0.60\,\mathrm{m\,s^{-1}}$). In the sparser canopy (1983), the corresponding d/h values were 0.55 (low wind speed) and 0.42 (high wind speed), respectively. These variations may be represented by linear regressions of the form: $d/h = 0.65 - 0.23u_*$ in 1982 and $d/h = 0.55 - 0.2u_*$ in 1983.

In 1982, z_0/h decreased from 0.13 at low wind speed ($u_* < 0.30\,\mathrm{m\,s^{-1}}$), to 0.08 at high wind speed ($u_* > 0.60\,\mathrm{m\,s^{-1}}$). In the sparser canopy (1983) the corresponding z_0/h values were 0.13 (low wind speed) and 0.05 (high wind speed), respectively. These variations may be represented by exponential functions of the form: $z_0/h = 0.68u_*^{-0.345}$ for 1982 and $z_0/h = 0.035u_*^{-0.8}$ for 1983. The wind speed dependence of z_0/h presented here may be attributed to the flexibility of the sorghum leaves, which became more streamlined at high winds, thereby reducing z_0. The greater dependence on

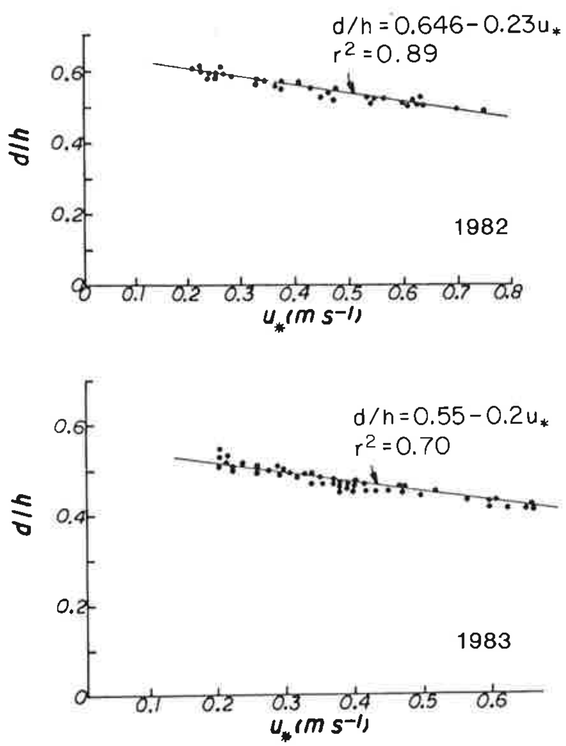


Fig. 4. Dependence of the zero-plane displacement (d) on friction velocity (u_*) at full crop development.

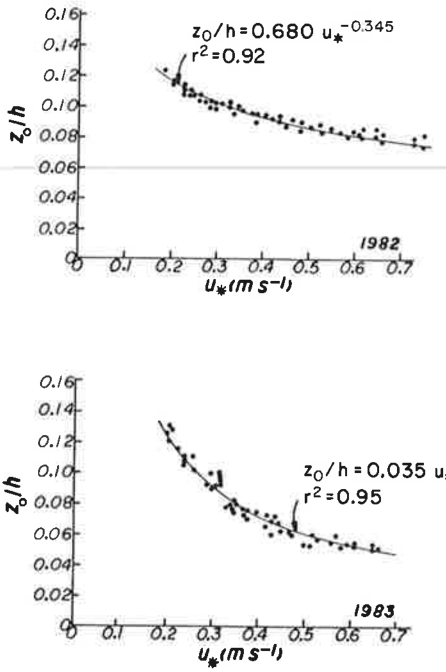
wind speed observed in 1983 was probably due to enhancement of fluttering and waving effects of the winds in the sparser canopy. These results agree with those of Thom (1971), Businger (1975), Hicks (1976), Saugier and Ripley (1978), Aase and Siddoway (1980), Legg et al. (1981) and Molion and Moore (1983). Oliver (1971), Munro and Oke (1973), Legg and Long (1975), Leuning and Attiwill (1978) and Baldocchi et al. (1983), however, reported no dependence of z_0/h on wind speed.

Crop drag coefficient

The crop drag coefficient (C_d) was calculated using the following equation:

$$C_d = (u_* / \bar{U}_R)^2 \tag{9}$$

where $\bar{U}_R$ is the mean wind speed at a reference level (1.5 m). Values of C_d at full crop development are plotted against friction velocity in Fig. 6. In both years, C_d decreased with increasing friction velocity. In 1982, C_d decreased from 0.10 at low wind speed to 0.046 at high wind speed, with a



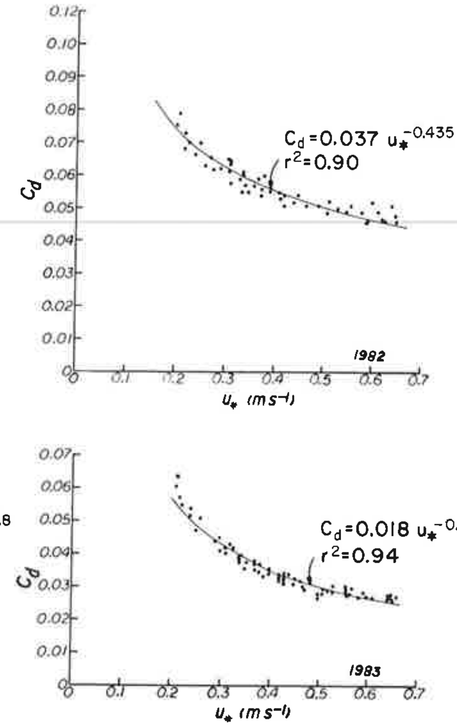


Fig. 5. Dependence of the roughness parameter (z_0) on friction velocity (u_*) at full crop development.

Fig. 6. Dependence of the crop drag coefficient (C_d) on friction velocity at full crop development.

mean value of 0.055 under moderate windiness. Correspondingly, C_d varied in 1983 from 0.064 to 0.026, with a mean value of 0.035. These variations may be represented by the relationships: $C_d = 0.037 u_*^{-0.435}$ in 1982 and $C_d = 0.0177 u_*^{-0.743}$ in 1983. The effect of wind speed on C_d depends on the flexibility of the canopy elements. It appears that at high winds, the canopy is distorted and becomes aerodynamically smoother. A decrease in C_d with increasing wind speed has been reported by several researchers (Denmead, 1964, for corn; Uchijima, 1976, for corn and rice and Ripley and Redman, 1976, for grassland). On the other hand, results reported by denHartog and Shaw (1975) for corn, Garratt (1977) for scattered trees and shrubs, Leuning and Attiwill (1978) for a eucalyptus forest and Legg et al. (1981) for beans and potatoes show no dependency of C_d on wind speed.

Values of C_d were smaller in 1983. An increase in the porosity of the vegetation, caused by the reduction in plant density, allowed a better penetration of air flow through the canopy. The effect of porosity of vegetation on the crop drag coefficient has been studied by Thom (1971), Bergen (1975), Jarvis et al. (1976) and Seginer et al. (1976).

The values of C_d reported in the literature include: 0.0231—0.0335 for sorghum ($h \sim 1.03$—1.28 m, $z_R = 1.5$ m) and 0.0225—0.0256 for millet ($h \sim 0.75$—0.80 m, $z_R = 1.1$ m) (Verma et al., 1976); ~ 0.025 for scattered trees and shrubs ($z_R = 17.5$ m) (Garratt, 1977); 0.022 for beans and 0.014 for potatoes ($z_R = 2$ m) (Legg et al., 1981); and 0.027—0.035 for soybean crops ($z_R < d + 1.0$ m) (Baldocchi et al., 1983). Much smaller values of C_d have been observed over water surfaces. Pond et al. (1974) reported $C_d = 0.00148$ at a reference level of 10.0 m over the ocean surface.

SUMMARY AND CONCLUDING REMARKS

The aerodynamic characteristics of grain sorghum were evaluated from wind speed profiles measured above and within the canopy. Three methods (the logarithmic profile analysis, the mass conservation approach and Seginer's approach) were employed to evaluate the roughness parameter (z_0) and the zero-plane displacement (d). The three methods provided values in reasonable agreement.

Information on d and z_0 was developed for various stages of crop growth. During the vegetative stage, d and z_0 increased more rapidly than did the crop height (h), reaching a maximum at the time of emergence of the heads. During the period of emergence and growth of the heads, the rate of increase of d was smaller than that of h. Values of z_0/h at this stage appeared to decrease in 1982, but remained approximately constant for the sparser crop in 1983.

At full crop development under moderate windiness, d/h reached about 0.61 and 0.54, on average, in 1982 and 1983, respectively. Corresponding values of z_0/h were about 0.096 and 0.076, respectively. Mean crop drag coefficient (C_d) was 0.055 in 1982 and 0.035 in 1983.

ACKNOWLEDGEMENTS

This study was supported by the Coordenacao de Aperfeicoamento de Pessoal de Nivel Superior, Brazil and by the Atmospheric Sciences Division of the National Science Foundation under Grant ATM-8205431. Messrs. H.D. Earl and Dale Sandin provided valued assistance in maintenance of instruments and data acquisition systems. Mr. James Hines assisted in data computation. We thank Dr. John M. Norman and Dr. Roger H. Shaw for many helpful suggestions and Dr. Norman J. Rosenberg and Dr. Kenneth G. Hubbard for their reviews of this paper. Our thanks to Mrs. Roberta Sandhorst for the stenographic work.

REFERENCES

Aase, J.K. and Siddoway, F.H., 1980. Stubble height effects on seasonal microclimate, water balance, and plant development of no-till winter wheat. Agric. Meteorol., 21: 1—20.

Azevedo, P.V., 1985. Characteristics of air flow within and above grain sorghum canopies.

Ph.D. Dissertation and Center for Agricultural Meteorology and Climatology Progress Report 85-1, University of Nebraska-Lincoln, 266 pp.

Bache, D.H. and Unsworth, M.H., 1977. Some aerodynamic features of a cotton canopy. Q. J. R. Meteorol. Soc., 103: 121–134.

Baldocchi, D.D., Verma, S.B. and Rosenberg, N.J., 1983. Characteristics of air flow above and within soybean canopies. Boundary-Layer Meteorol., 25: 43–54.

Bergen, J.D., 1971. An inexpensive heated thermistor anemometer. Agric. Meteorol., 8: 395–405.

Bergen, J.D., 1975. An approximate analysis of the momentum balance for the airflow in a pine stand. In: D.A. de Vries and N.H. Afgan (Editors), Heat and Mass Transfer in the Biosphere. Scripta Book Co., Washington, pp. 287–298.

Businger, J.A., 1975. Aerodynamics of vegetated surfaces. In: D.A. de Vries and N.H. Afgan (Editors), Heat and Mass Transfer in the Biosphere. Scripta Book Co., Washington, pp. 139–163.

Cionco, R.M., 1965. A mathematical model for air flow in a vegetative canopy. J. Appl. Meteorol., 4: 517–522.

deBruin, H.A.R. and Moore, C.J., 1983. Zero-plane displacement and roughness length for tall vegetation, derived from a simple mass conservation hypothesis. Presented at the Forest Environment Measurements Conference, Oak Ridge, TN.

denHartog, G. and Shaw, R.H., 1975. A field study of atmospheric exchange processes within a vegetative canopy. In: D.A. de Vries and N.H. Afgan (Editors), Heat and Mass Transfer in the Biosphere. Scripta Book Co., Washington, pp. 299–309.

Denmead, O.T., 1964. Evaporation sources and apparent diffusivities in a forest canopy. J. Appl. Meteorol., 3: 383–389.

Garratt, J.R., 1977. Aerodynamic roughness and mean monthly surface stress over Australia. Commonwealth Scientific and Industrial Research Organization (CSIRO), Paper No. 29, Australia, pp. 19.

Hicks, B.B., 1976. Wind profile relationships from the "Wangara" Experiment. Q. J. R. Meteorol. Soc., 102: 535–551.

Inoue, E., 1963. On the structure of airflow within crop canopies. J. Meteorol. Soc. Jpn. Ser. 2, 41: 317–326.

Jarvis, P.V., James, G.B. and Landsberg, J.J., 1976. Coniferous forest. In: J.L. Monteith (Editor), Vegetation and the Atmosphere. Vol. 2, Academic Press, pp. 171–236.

Legg, B.J. and Long, I.F., 1975. Turbulent diffusion within a wheat canopy. II. Results and interpretation. Q. J. R. Meteorol. Soc., 101: 611–628.

Legg, B.J., Long, I.F. and Zemrock, P.J., 1981. Aerodynamic properties of field bean and potato crops. Agric. Meteorol., 23: 21–43.

Leuning, R. and Attiwill, P.M., 1978. Mass, heat and momentum exchange between a mature eucalyptus forest and the atmosphere. Agric. Meteorol., 19: 215–241.

Molion, L.C.B. and Moore, C.J., 1983. Estimating the zero-plane displacement for tall vegetation using a mass conservation method. Boundary-Layer Meteorol., 26: 115–125.

Munro, D.S. and Oke, T.R., 1973. Estimating wind profile parameters for tall dense crops. Agric. Meteorol., 11: 223–228.

Oliver, H.R., 1971. Wind profiles in and above a forest canopy. Q. J. R. Meteorol. Soc., 97: 548–553.

Pond, S., Fissel, D.B. and Paulson, C.A., 1974. A note on bulk aerodynamic coefficients for sensible heat and moisture fluxes. Boundary-Layer Meteorol., 6: 333–339.

Rauner, J.L., 1976. Deciduous forests. In: J.L. Monteith (Editor), Vegetation and the Atmosphere. Vol. 2, Academic Press, pp. 241–264.

Ripley, E.A. and Redmann, R.E., 1976. Grassland. In: J.L. Monteith (Editor), Vegetation and the Atmosphere. Vol. 2, Academic Press, pp. 379–398.

Rosenberg, N.J. and Brown, K.W., 1974. "Self-checking" psychrometer system for gradient and profile measurements near the ground. Agric. Meteorol., 13: 215–226.

Saugier, B. and Ripley, E.A., 1978. Evaluation of the aerodynamic method of determining fluxes over mature grassland. Q. J. R. Meteorol. Soc., 104: 257—270.
Seginer, I., 1974. Aerodynamic roughness of vegetated surfaces. Boundary-Layer Meteorol., 5: 383—393.
Seginer, I., Mulhearn, P.J. and Funnigan, J.J., 1976. Turbulent flow in a model plant canopy. Boundary-Layer Meteorol., 10: 423—453.
Thom, A.S., 1971. Momentum absorption by vegetation. Q. J. R. Meteorol. Soc., 97: 414—428.
Uchijima, Z., 1976. Maize and rice. In: J.L. Monteith (Editor), Vegetation and the Atmosphere. Vol. 2, Academic Press, New York, pp. 33—64.
Uchijima, Z. and Wright, J.L., 1964. An experimental study of air flow in a plant air layer. Bull. Inst. Agric. Sci. Jpn. Ser. A, 11: 18—65.
Verma, S.B. and Barfield, B.J., 1979. Aerial and crop resistances affecting energy transport. In: B.J. Barfield and J.F. Gerber (Editors), Modification of the Aerial Environment of Plants. Am. Soc. Agric. Eng., St. Joseph, MI, pp. 230—248.
Verma, S.B., Rosenberg, N.J., Blad, B.L. and Baradas, M.W., 1976. Resistance—energy balance model for predicting evapotranspiration: Determination of boundary layer resistance and evaluation of error effects. Agron. J., 68: 776—782.
Webb, E.K., 1965. Aerial Microclimate. Meteorological Monographs. Vol. 6, No. 28, Chapter 2, pp. 27—58.