51

ESTIMATING WIND
PROFILE PARAMETERS
OVER A MATURING CROP

ESTIMATING WIND PROFILE PARAMETERS OVER A MATURING CROP

by

BRIAN DOUGLAS KALANDA

A Research Paper
Submitted to the Department of Geography
in Fulfillment of the Requirements
for
Geography 4B6

McMaster University
April 1976

ACKNOWLEDGEMENTS

I deeply appreciate the assistance and supervision of Dr. J.A. Davies, not only for this research, but for his positive influence on my academic attitude. Special thanks to Miss C.J. Wood for the preparation of this manuscript, and Mr. W.G. Bailey for his constant encouragement and invaluable assistance. My gratitude extends to friends and colleagues at McMaster University who have freely given me their time upon many occasions.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

The surface aerodynamic properties of vegetation are significant to the combination model through their control over the wind profile and turbulent transfer. These surface properties are the surface roughness length (z_o) and the zero plane displacement (d).

Ideally both z_o and d are determined from wind profiles recorded during neutral equilibrium. However the rarity of this state forces the use of parameter estimates made in near-neutral stability. Further complications may arise from windspeed dependencies. Thom (1971), Monteith (1973), and others have demonstrated such dependencies for leafy, flexible crops. On the other hand, Munro and Oke (1973) found no such dependencies for measurements made over a wheat field. However, the lack of leaves in the mature wheat may account for this disagreement (Munro and Oke, 1973).

This study concerns itself with an analysis of z_o and d from measured wind profiles over a soybean crop. The study encompasses the entire growing season. The emphasis of this study will be towards the expression of z_o and d in terms of existing approaches which utilize crop height. Expressing z_o and d in terms of crop height has two advantages. First, the expensive and time consuming method of obtaining windspeed and temperature profiles is avoided. Secondly, relatively simple, on site estimations of z_o and d can be made.

CHAPTER TWO

WIND PROFILE THEORY

(A) The logarithmic wind profile model

Under restricted conditions the mean windspeed increases logarithmically with height within a few metres of an aerodynamically rough surface. The main restrictions are:

(1) Only the surface boundary layer is considered.

(2) This layer must be thermally neutral so that only the mechanical forces of friction and form drag create turbulence.

(3) The site is flat and horizontally uniform.

(4) Time averaged profiles are considered.

The boundary layer is defined as the air layer in contact with the ground, in which properties are largely determined by exchanges with the underlying surface. The depth of the boundary layer can be related to the fetch or distance of traverse across a uniformly rough surface. An analysis of fetch will be presented in Chapter 3.

Over a stiff, short vegetated surface the logarithmic wind profile can be represented by:

$$u = \frac{u_*}{k} \ln \frac{z}{z_o} \qquad (1)$$

where u = windspeed (ms^{-1})

u_* = friction velocity (ms^{-1})

k = von Karman's constant (dimensionless)

z = height (m)

z_o = surface roughness length (m)

The surface roughness length represents the height at which the windspeed equals zero. When z_o is a significant portion of the height z, equation (1) is re-written as (Sutton, 1953):

$$u = \frac{u_*}{k} \ln \left[\frac{z-z_o}{z_o} \right] \qquad (2)$$

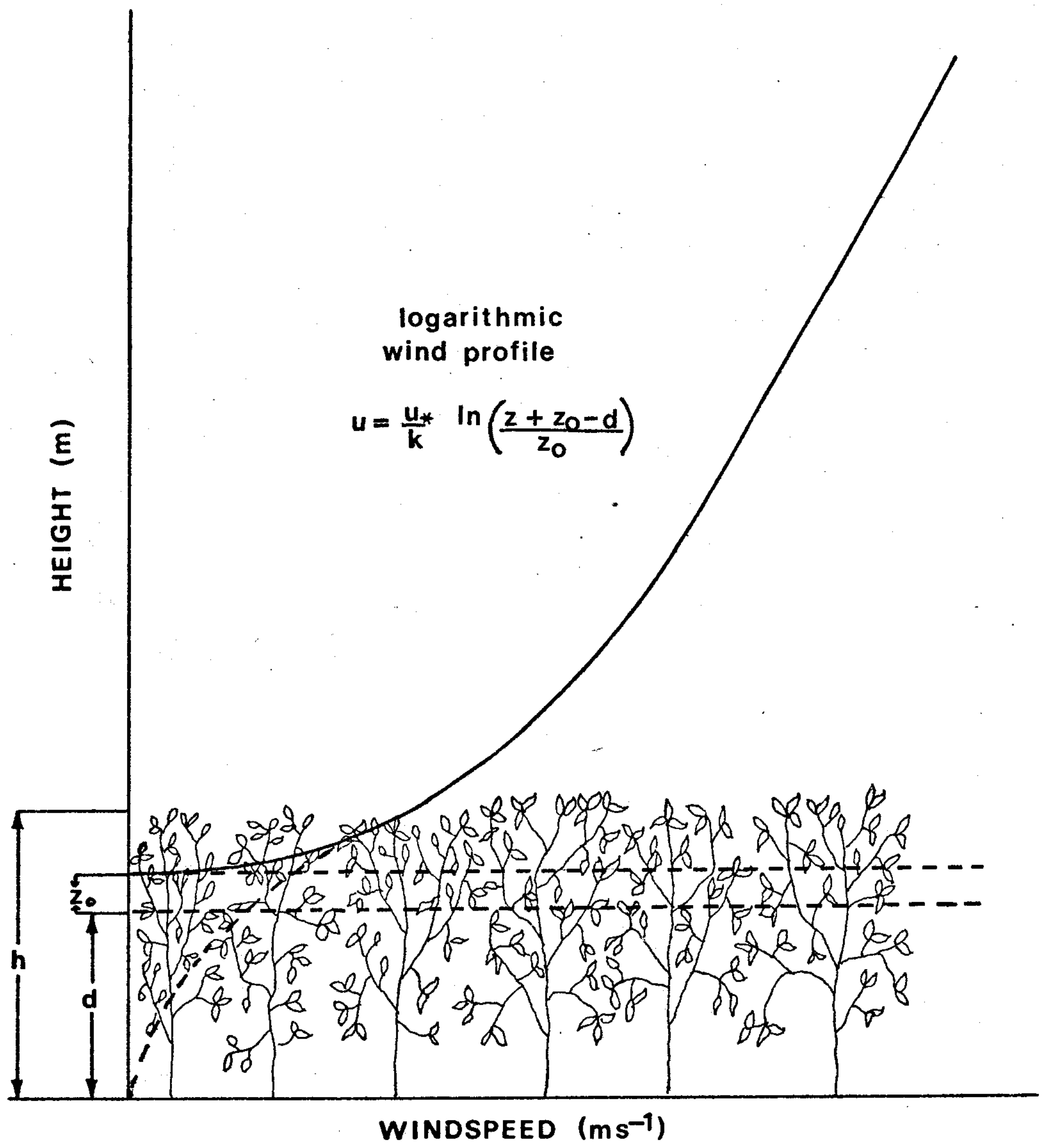
(B) The wind profile over tall vegetation

For most vegetated surfaces the logarithmic wind profile form of equations (1) and (2) is unsatisfactory as disproportionately large z_o values result. A second refinement is required, which accounts for the vertical displacement of the wind profile. This parameter d, is commonly termed the zero plane displacement. When introduced, equation (2) becomes:

$$u = \frac{u_*}{k} \ln \left[\frac{z-d+z_o}{z_o} \right] \qquad (3)$$

Above the height d, the wind profile is logarithmic. Below it, the windspeed is greatly dampened (Figure 1). Thus, the displacement can be regarded as the datum level above which free turbulent exchange occurs and a level for momentum sink (Chang, 1968).

The linear logarithmic shape of a wind profile over



——— logarithmic wind profile
- - - - wind profile within the vegetation
z height of measurement
u wind speed at height z
u_* friction velocity
k von Karman constant
h height of vegetation
z_o roughness length
d zero – plane displacement

FIGURE 1 THE WIND PROFILE OVER TALL VEGETATION a flat, smooth surface becomes curvilinear when the underlying surface has a cover of tall vegetation. The correction required to convert the curvilinear departure to a linear form is the zero plane displacement.

(C) Atmospheric stability

Atmospheric turbulence is the result of mechanical (forced convection) and thermal (free convection) forces. The logarithmic form develops when thermal forces are insignificant compared to mechanical forces. Under superadiabatic conditions (unstable lapse rate), buoyancy disrupts the mechanically produced turbulence. Under inversion conditions (stable lapse rate), turbulent motion is dampened because the gradient of air density is directed upward. In both, the windspeed profile departs from the logarithmic form, thereby altering the values of aerodynamic parameters determined in thermally neutral conditions. Therefore, z_o and d can only be determined effectively in neutral conditions. To accomplish this, a measurement of the relative strengths of the thermal and mechanical forces in the atmospheric layer being considered is required. A suitable criterion is the gradient form of the Richardson number (R_i):

$$R_i = \frac{g}{\theta_v}\left[\frac{\frac{\partial \theta_v}{\partial z} + \Gamma}{\left[\frac{\partial U}{\partial z}\right]^2}\right] \qquad (4)$$

where R_i = gradient form of Richardson number (dimensionless)

g = acceleration due to gravity (ms^{-2})

θ_v = virtual potential temperature (^oK)

T = air temperature (^oC)

and U = windspeed (ms^{-1})

Γ = adiabatic correction factor ($^{o}C\,m^{-1}$)

In practice, partial differentials are replaced by finite gradients and

$$R_i = \frac{g}{\frac{[\theta v_1 + \theta v_2]}{2}} \left[\frac{[\theta v_2 - \theta v_1][z_2 - z_1] + \Gamma}{[U_2 - U_1]^2} \right] \qquad (5)$$

where the subscripts 2 and 1 refer to sensor heights (z_2 and z_1). Only windspeed and temperature profile measurements are required. For unstable, neutral and stable conditions, the Richardson number is less than zero, zero, and greater than zero respectively. Normally the magnitude of the Richardson number increases with height with the forced convection near the ground being replaced by free convection at greater heights.

CHAPTER THREE

SITE, INSTRUMENTATION, and CALCULATION PROCEDURES

(A) Site

(1) Study area

The study was conducted at the Ontario Horticultural Experimental Station near Simcoe, Ontario from June 08 to September 22, 1974. The site was a flat plot (less than 2° slope in any direction from the centre of the field) measuring 121.7 m x 216.4 m. Three buildings were located in a 35 m section along the eastern edge of the field, approximately 92 m from the North-East corner (Figure 2). A trailer (approximately 3 m by 6 m by 3 m tall) that was insulated, air conditioned, and de-humidified provided a controlled environment for measurement recording.

(2) Crop Characteristics

The soybean crop (Glycine Max. L., var. Horosoy '63) was planted on June 06 with a 6° North of West row orientation. Row spacing was 0.53 m. It appeared on June 08 and attained a mean maximum height of approximately 0.74 m $\pm$ 0.075 m by August 18.

Plant height analysis can be destructive or non-destructive (Šestak et al, 1971). Measurements of plant

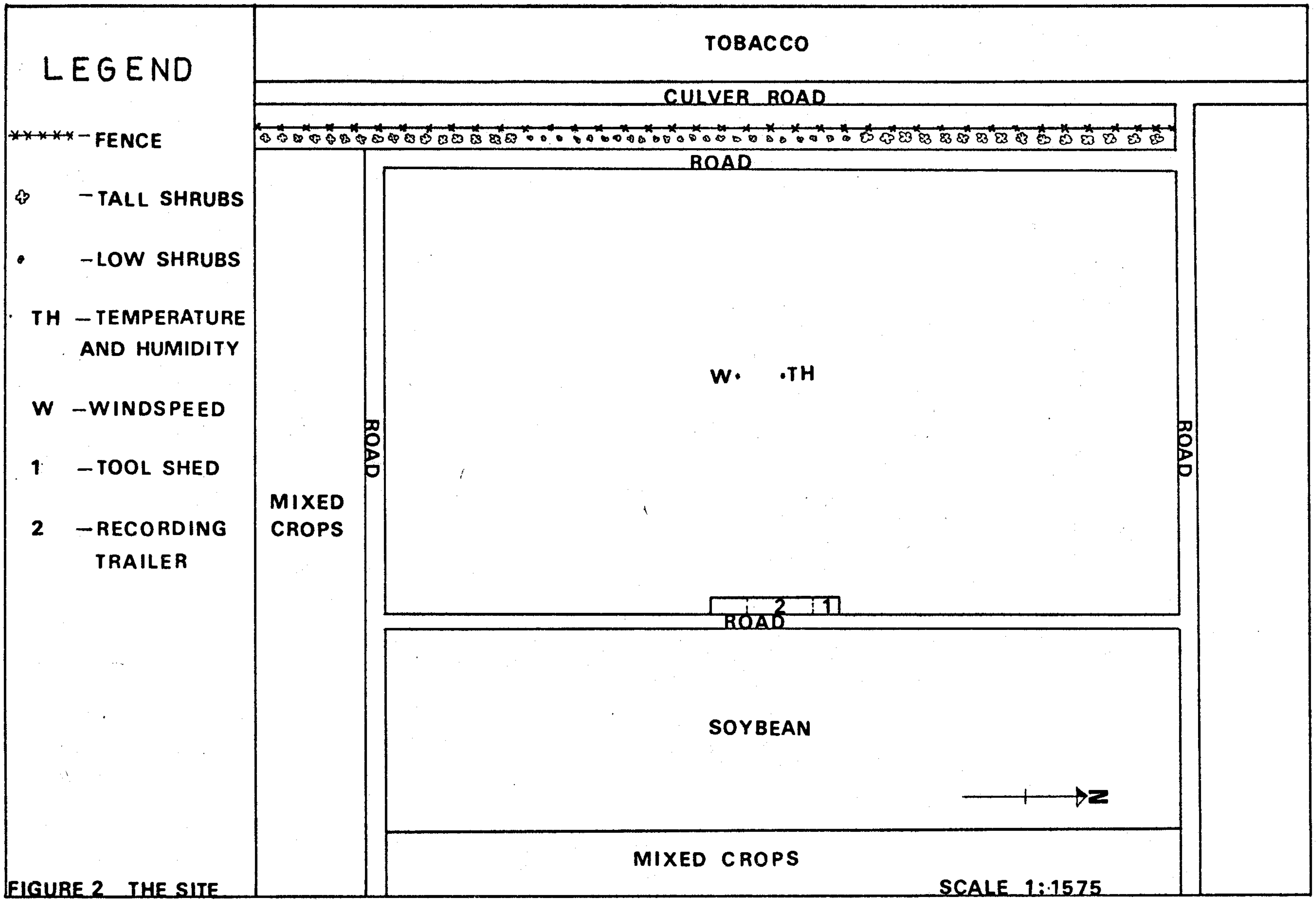


FIGURE 2 THE SITE

height were taken using a metre stick. The random sampling used for destructive analysis involved taking five one metre sections of 10 to 23 plants. The non-destructive analysis involved measuring five randomly selected plants every 50 rows. The mean height plus or minus one standard deviation was taken as representative for that sample. No systematic variation between the destructive and non-destructive methods appeared. A four quadrant height comparison demonstrated general homogeneity for the site. The larger standard deviations for the latter part of the season indicates some general heterogeneity between plants. An eye fit curve (Figure 3) allowed interpolated height estimates over the entire growing season. The curve shape followed the general form presented by Evans (1973).

(B) Instrumentation

A mast, on which sensors to measure temperature and humidity were mounted, was located 4 m West of the field centre. An anemometer mast was located 4 m West and 14 m South of the field centre. These 5 m tall masts were guyed with three wires attached to the mast top. Both masts could be rotated so that sensors could face the wind without being obstructed. Mast influence was further minimized by mounting sensors on cross-arms which extended approximately 0.23 m out from the mast. Painting the temperature-humidity mast white reduced possible radiative heating effects. The vertical sensor seperation for both

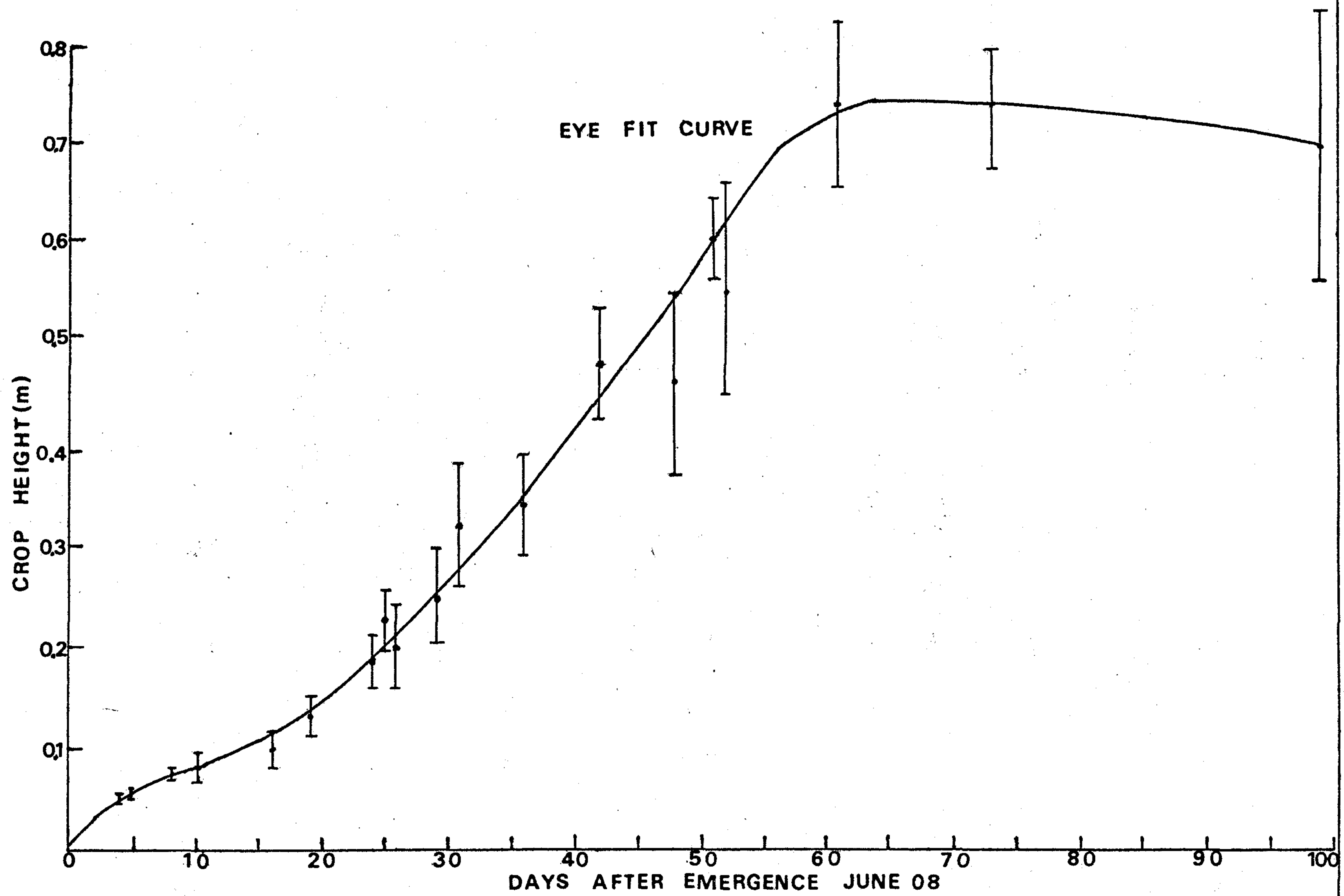


FIGURE 3 CROP GROWTH

systems (0.25 m) was considered sufficient to prevent sensor inter-action (Tanner, 1963). Listed in Table 1 are the anemometer and temperature sensor heights above the ground, that were used in this study. A third possible source of systematic error, that of insufficient sensor height above the surface, will be analyzed in Chapter 4.

(1) Windspeed measurement and recording

Light weight (assembly <7 g) sensitive cup anemometers (C.W. Thornthwaite Associates) were used. The light weight and low friction bearings ensure low stalling speeds (0.1 ms^{-1}) and minimize over run error. Thus, a fast response to windspeed fluctuations results. In this system a shutter-interrupted light beam activates a photo cell which emits electrical impulses at the rate of one pulse per cup revolution. The signal was passed to a digital recorder accurate to 0.0025 ms^{-1} (a slight windspeed dependency exists) in the recording trailer. A one minute interval between recording periods was required to hand record and re-start the registers. After reducing the values to counts per minute, a fitted second order polynomial equation relating counts per minute and windspeed was applied:

$$u = \left(a_o + a_1 c + a_2 c^2\right) f$$

where a_o, a_1, a_2 are polynomial coefficients, c is counts per minute, and f is a relative correction factor.

TABLE 1

Anemometer and Temperature Sensor Heights

Period over Which Heights Applied	Sensor Height above Ground (m)			
	Level 1	Level 2	Level 3	Level 4
June 08 - July 09	0.25	0.50	0.75	1.00
July 10 - July 14	0.40	0.65	0.90	1.15
July 16 - July 28	0.55	0.80	1.05	1.30
July 29 - Aug. 07	0.75	1.00	1.25	1.50
Aug. 08 - Aug. 16	0.90	1.15	1.40	1.65
Aug. 18 - Sept. 22	1.15	1.40	1.65	1.90

For profile measurements, the relative error is more important than the absolute error (Tanner, 1963). Following this, relative calibrations, in the form of cup intercomparisons, were periodically performed. All anemometers were mounted side by side on a horizontal bar (spindles 0.25 m apart). By rotating the sensors' positions with respect to each other, complete intercomparisons were available. Percentage corrections from unity were then applied to the calibration equations. The correction factors are listed in Appendix B.

(2) Temperature measurement and recording

To minimize radiation error and thereby increase accuracy, the sensors were shielded from sunlight and ventilated. The five junction thermopile sensor was constructed from 30 awg copper-constantan thermocouple wire. Junctions were soldered and electrically insulated by heat shrink tubing. The sensor was then potted in polyester resin within a stainless steel tube. The wet and dry bulb probes were approximately 0.20 m and 0.13 m long respectively. The wet bulb probe was covered by wicking which was fed by a water reservoir suspended on the mast cross-arm.

A plexiglass plug was tightly fitted into the back of the T-junction located at the end of the cross-arm. A pair of wet and dry bulb probes were passed through the plug and into the inner shield. By bending the dry bulb probe, both probes were centred in the shield. A spacer held the dry bulb centred, thus avoiding temperature gradients near the wall. The inner shield was a (0.015 m ID) plastic tube that was painted flat black on the inside and wrapped in highly reflective aluminized mylar on the outside. The spherical cap which covered the exposed end further minimized possible radiative inputs. To minimize any unrepresentative air flow caused by the cap, the void spaces between the tube end and the cap equalled the cap's cross-sectional area. Small holes drilled at the downstream end allowed purging of the air with the (0.038 m ID) styrofoam outer shield. The inner shield was tightly fitted inside the T-joint while the outer shield was tightly fitted over the end of the T-joint. Besides wrapping the shield inside and out with aluminized mylar, the exposed end was cut back at a 60° angle to the ground. Both reduce possible radiative effects. Natural ventilation was assisted by a fan (Rotron Mfg. Co., NTO 120) located at the other end of the cross-arm.

Referencing was done against a zero point Frigister housed in a ventilated screen box. This gives a very stable reference temperature for temperature calculations. The thermopile signals were recorded on a magnetic tape recording data logger (Solatron, Farnborough, United Kingdom) housed in the recording trailer. Observations were recorded every five minutes and converted to hourly means. The millivolt readings were converted to temperature

(^{o}C) by second order polynomial calibration equations.

A pre-season calibration was not possible as the data logger was unavailable. A post-season calibration was applied to the entire study period. The temperature sensors were referenced against a platinum resistance thermometer (Rosemount Eng. Co.) over a 0 to 30^{o}C temperature range. The calibration equation for each sensor is listed in Appendix B.

Probe intercomparisons were done in the field. By removing the wicking from the wet bulb probe, the systematic error for all probes as dry bulb probes was determined. By rotating the probes over all reference levels, complete intercomparisons were available. Percentage corrections from unity were then applied to the calibrations. The correction factors are listed in Appendix B.

(3) Observational procedure

The very nature of the turbulent regime causes the length of sampling period to be a critical decision. When the period is too short, the sensor response may be too slow, yielding unrepresentative values. Extended periods can result in secular data trends. Sixty minute sampling periods were utilized in this study to allow sufficient windspeed averaging. This coincides with the hourly mean temperature data.

Wind direction was monitored from a vane on top of the most southern and tallest building. Recording coincided with the Thornthwaite digital windspeed register recording. Wind direction, which was subdivided into sixteen directions, was used to determine the rotation required to have the windspeed and temperature sensors facing into the wind. This was done at the beginning of each observation period. Fetch determinations were also based on these directions. Figure (4) represents the hourly wind directions for the entire study period. The South-West dominance is easily observed.

(C) Data Analysis

(1) Experimental determination of z_o and d

The values of z_o and d can be determined by either graphical or computerized iteration procedures. Both estimate the value of d which linearizes the u versus ln z relationship. Extrapolation of this line to zero windspeed gives estimates of z_o.

(i) Graphic solution

Plotting a neutral equilibrium windspeed profile, that was measured over a vegetated surface, reveals a curvilinear profile (Figure 5). However the extrapolation of curvilinear profiles to zero windspeed, results in z_o values that are so large it loses its significance as a roughness indicator. To obtain realistic values of z_o a value of d is subtracted from each anemometer height. This procedure is continued until the best fit linear

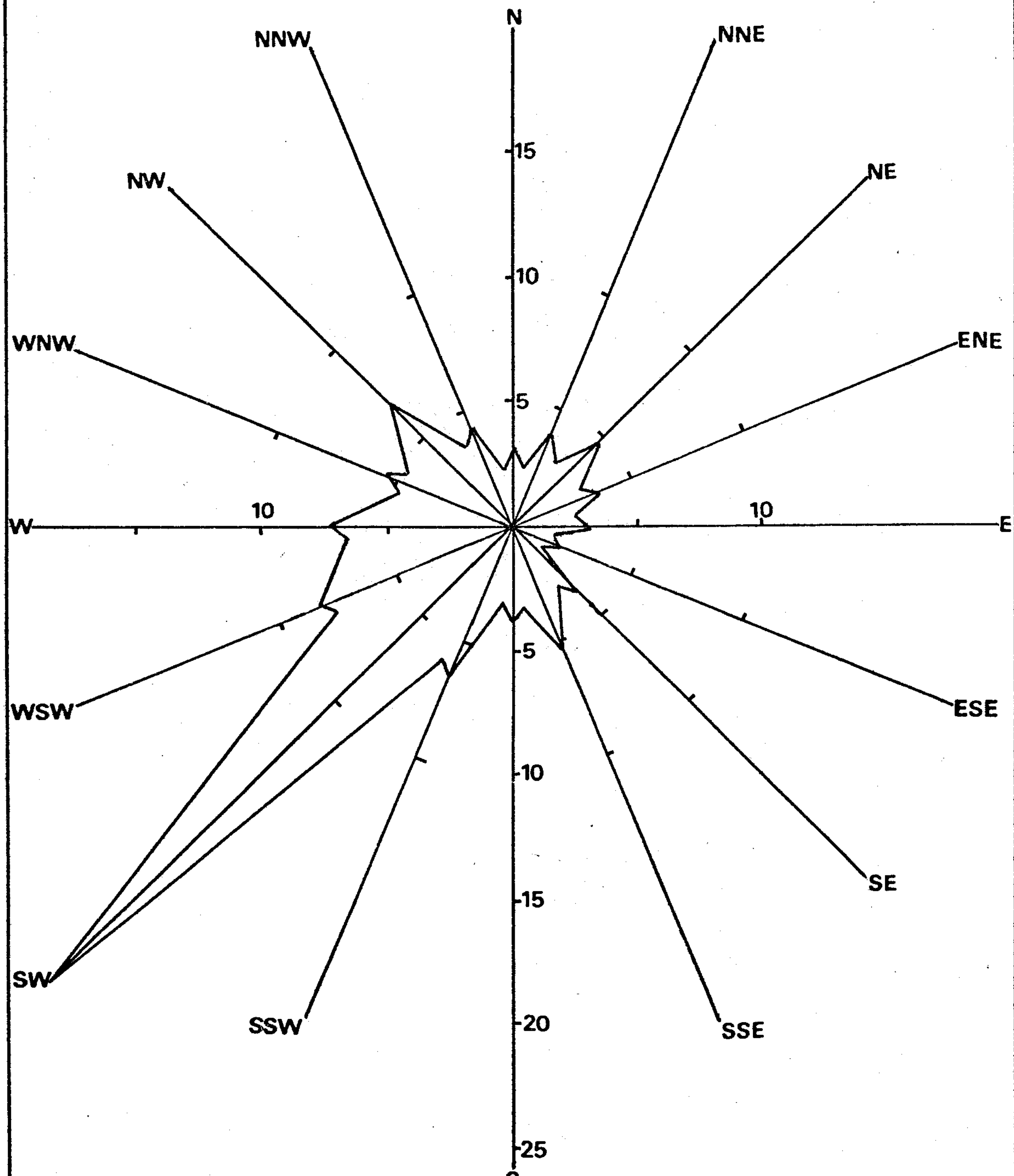


FIGURE 4 WIND ROSE (values in percentages)

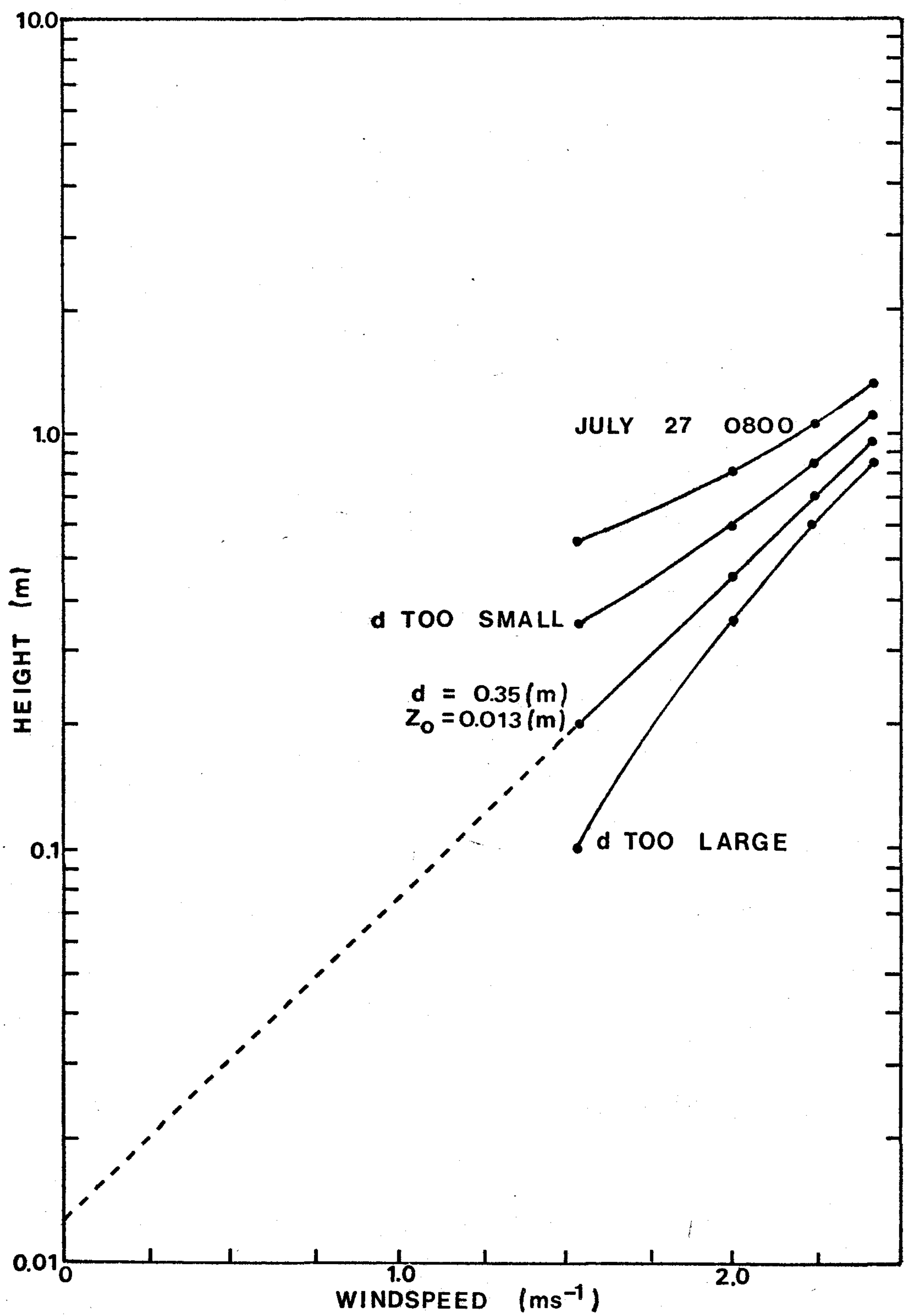


FIGURE 5 GRAPHIC SOLUTION

approximation to the profile is obtained. The extrapolation to zero windspeed gives the z_o estimation. However, this approach is slow and tedious with the accuracy depending upon the capability of the analyst.

(ii) Computerized iteration procedure

With a large data set, the previous approach is impractical and a computerized iteration procedure is used. The anemometer heights (m) and the windspeeds (ms^{-1}) are the only required inputs. Following Lettau (1957) successive trials of d are used to find the d which minimizes the mean square error (variance) of a straight line semi-logarithmic relation. The smaller the variance, the better the profile fits a linear approximation.

(2) Determination of near-neutral equilibrium

Determination of both z_o and d ideally requires thermally neutral conditions. Since truly neutral conditions rarely exist in nature, a near-neutral stability range is used to approximate neutral conditions. The exact stability where near-neutral, forced convection is replaced by free convection, remains a troublesome problem (Priestly, 1959; Tanner, 1963a; Chang, 1968; McIntosh and Thom, 1969, and Oliver, 1971). The height dependency partially explains the variation. General agreement is for a lower or unstable limit of -0.02 to -0.05. McBean and Miyake (1972) working in the four metres above a grass surface established near-neutral limits of $-0.04 \leq \frac{z}{L} \leq 0.01$

where $\frac{z}{L}$ is the Monin-Obukhov dimensionless stability parameter. The lower limit can be equated to within ±6.0% (maximum) of the gradient Richardson number (Dyer and Hicks, 1970) or -0.042 to -0.038. A range of $-0.02 \leq R_i \leq 0.05$ was the criterion applied to this study. This fairly stringent criteria range should effectively minimize the diabatic influence. Applying equation (5) the gradient Richardson number was calculated for all possible pairs of heights (ie: 1-2, 1-3, 1-4, 2-3, 2-4, 3-4). The level 3-level 4 ($R_{i\,3-4}$) permutation ideally represents the maximum Richardson number of the atmospheric layer under consideration. As such, it best exemplifies the stability of the layer. Therefore it will be used to represent the stability classification. For consistency this was applied throughout the study period. Although the height of this layer changed in absolute terms, the continual sensor adjustment meant constant referencing to the 1.0 to 1.5 m atmospheric layer immediately above the canopy.

Although $R_{i\,3-4}$ was chosen as representative of the measured layer, all permutations were considered. This was necessary for two reasons:

(i) The occasional occurence of near zero and negative windspeed gradients. The importance of windspeed gradients in equation (5) ($1/(\Delta u)^2$) resulted in disproportionately large values for these permuations.

(ii) During turn-over between unstable and stable conditions, R_{i3-4} may remain within the excepted range while lower permutations do not.

(3) Fetch

A simple test for adequate fetch is the satisfactory measurement of logarithmic profiles above a vegetated surface during periods of near-neutral stability (Lemon, 1965). Two assumptions are inherent in such a determination. First, that the anemometers are sensitive enough to detect the upper equilibrium boundary layer limit. Secondly, that this height is relatively constant. Employing similar anemometry, Munro and Oke (1975) were able to define this upper limit using only ten minute recording periods. Therefore both conditions should be satisfied in this study. Figure(6) shows three profiles which were directed across the minimum field fetch. The logarithmic form indicated that they were within the equilibrium boundary layer. Thus, adjusted profiles can be expected for any wind direction during conditions of near-neutral stability.

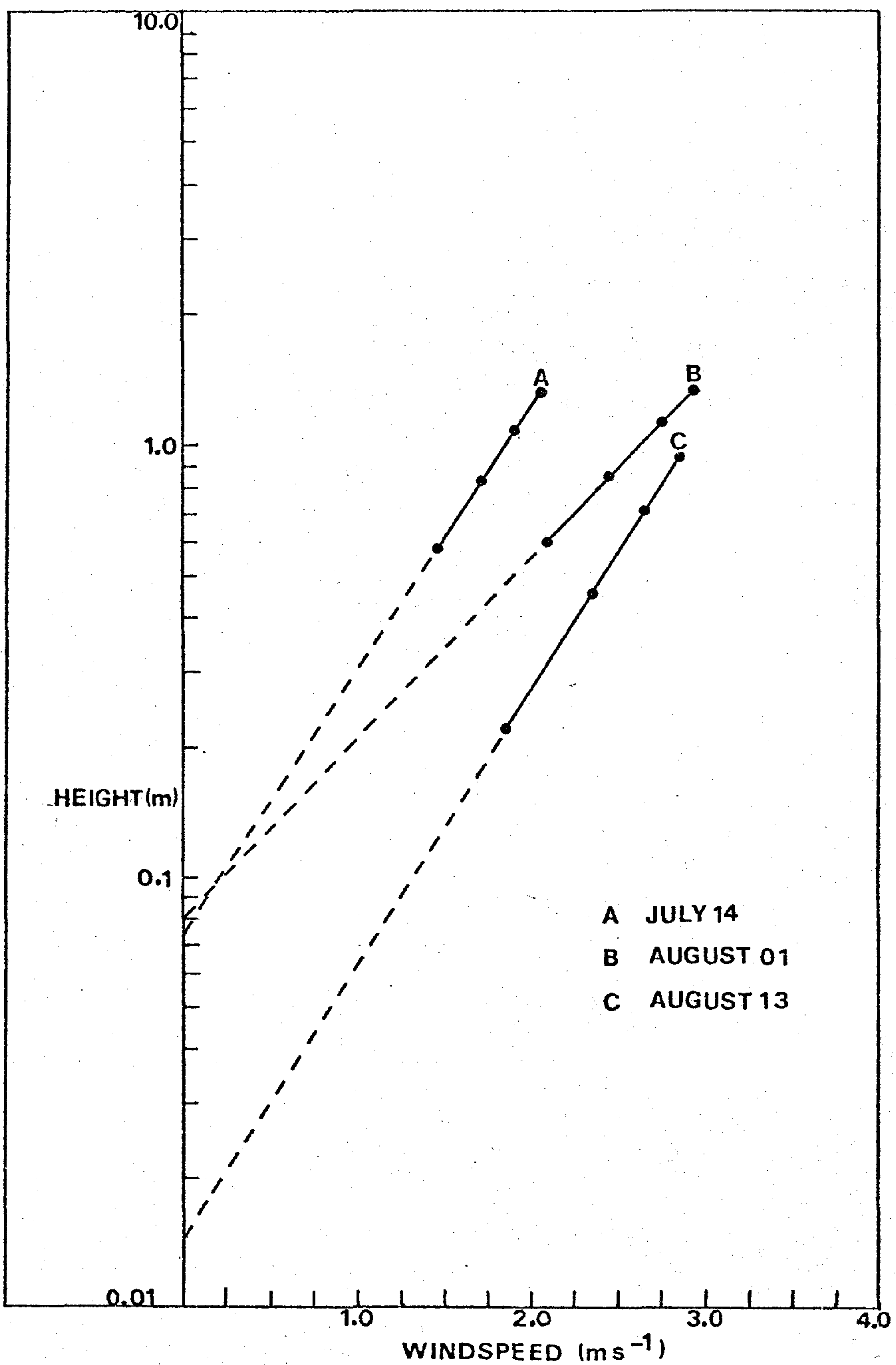


FIGURE 6 ADJUSTED WIND PROFILES

CHAPTER FOUR

RESULTS

(A) Sensitivity of z_o and d to errors in windspeed measurement

Following Tanner (1963), zero plane displacement and surface roughness were determined by Lettau's iterative procedure. This method is very sensitive to small errors in windspeed measurements. Figures (7a) and (7b) represent two examples of this sensitivity. The velocity of the lowest anemometer was allowed to change by ±2%. In the first example, (July 1, 1400 hrs.-Figure 7a), the 2% overestimation and the 2% underestimation both reduced z_o. The 2% underestimation also produced a marked error in the zero plane displacement (0.0036 m to 0.066 m). In the iterative method, an increase in d forces a decrease in z_o. Consequently, z_o was decreased by 46%. Since the unaltered profile was linear, the 2% overestimation forced the slope to increase and hence forced z_o to decrease by 30%. In the second example, (August 18, 1700 hrs.-Figure 7b), the 2% overestimation reduced d by 61% which forced a 157% increase in z_o. The 2% underestimation increased d by 43% and decreased z_o by 69%. Results similar to the August 18 example were found by Tanner (1963) and Allen (1972).

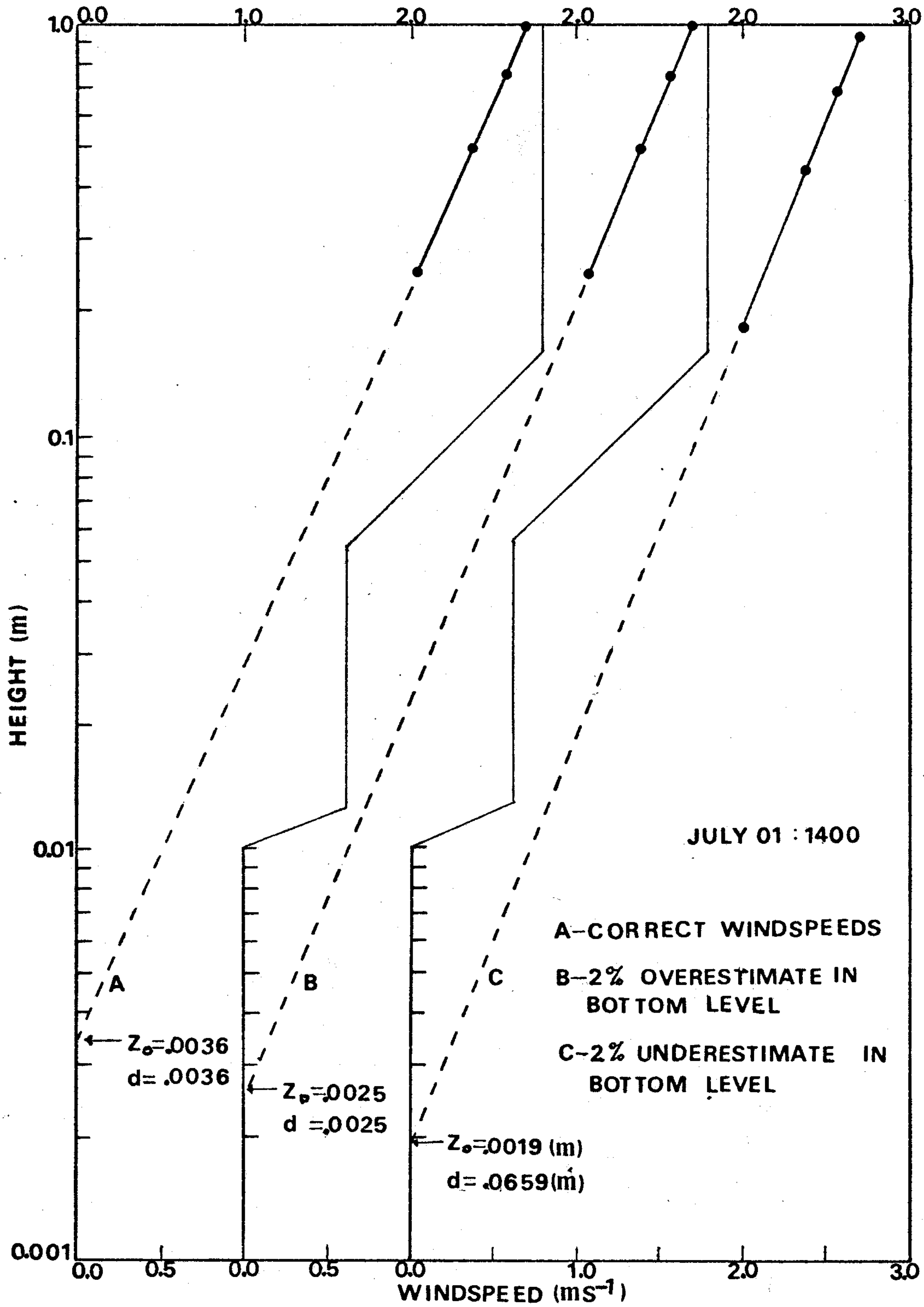


FIGURE 7a SENSITIVITY OF Z_o TO ERRORS IN WINDSPEED MEASUREMENT

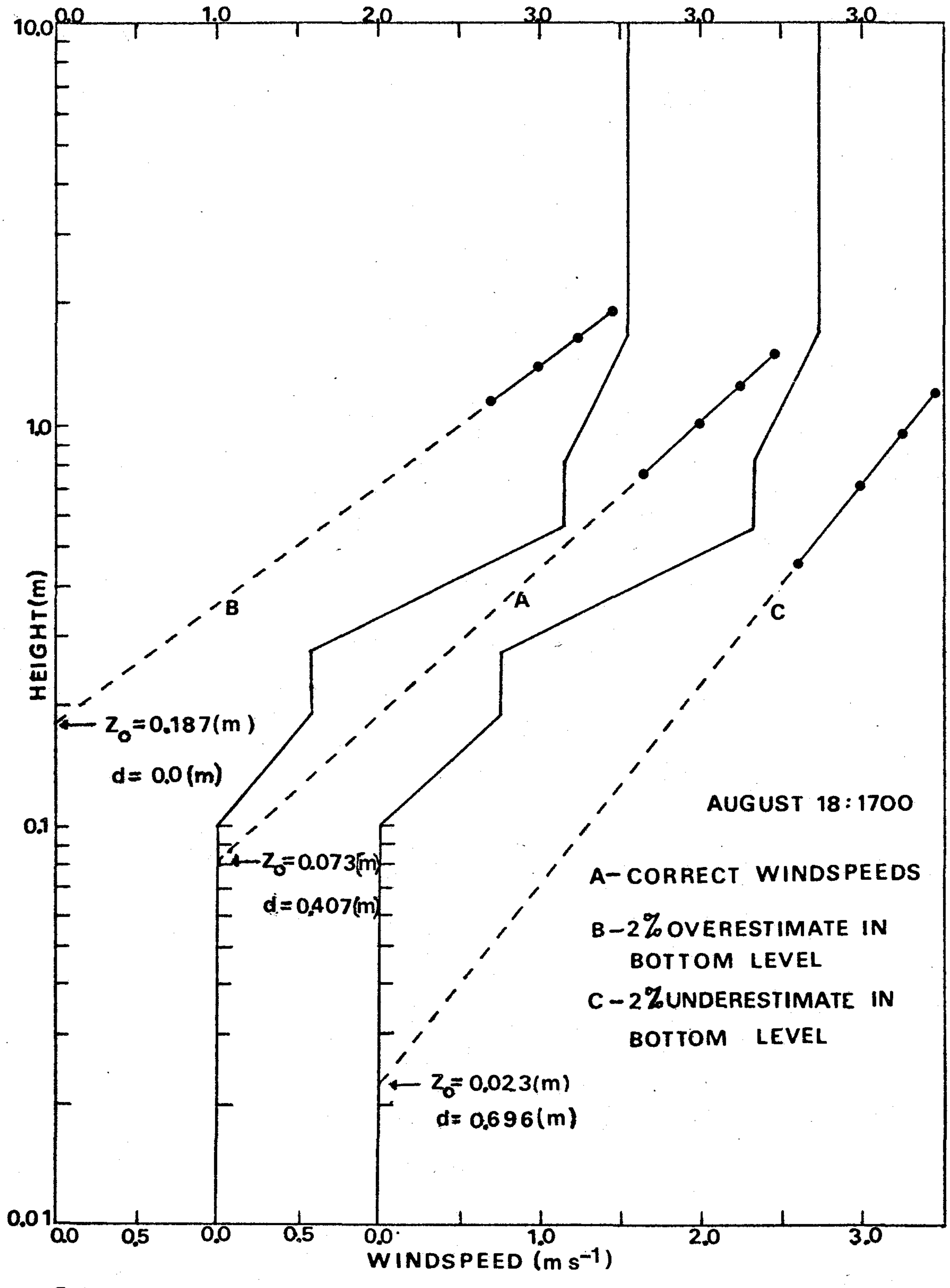


FIGURE 7b SENSITIVITY OF Z_o TO ERRORS IN WINDSPEED MEASUREMENT

(B) Dependency of z_o and d on windspeed

To investigate the possibility of z_o and d windspeed dependencies, values derived from hourly profiles were plotted against mean profile windspeed (rounded to the nearest 0.1 ms^{-1}). Two periods were investigated. For both, the crop height change was limited to 0.05 m. This was chosen as the best of a trade off between minimizing crop height change, and thereby the expected variability in z_o and d, and attaining as large a sample size as possible. The two periods, (June 29 to July 5, and August 9 to 23), allow analysis of both early and mature growth stages (Figures 8-11). The large scatter apparent for both z_o and d for both periods indicates a random variation with windspeed. The apparent linearity in Figure (9) may be some what misleading as the smaller scatter can be explained by the smaller magnitude of the z_o values. Relative changes of up to 500% (windspeed = 4.0 ms^{-1}) occur within this data set. As such, the range is too small to base confident estimates on and hence will be excluded from further analysis. The random variation with windspeed infers neither a windspeed dependence or independence for z_o and d. The randomness only indicates that a windspeed variation for z_o and d was impossible to discern.

Subsequent analysis of a wind direction dependency revealed a definite difference in z_o and d values obtained from along-row and across-row wind directions. This will be discussed in more detail in the following chapter. Elimination of the less frequent along-row values (circled

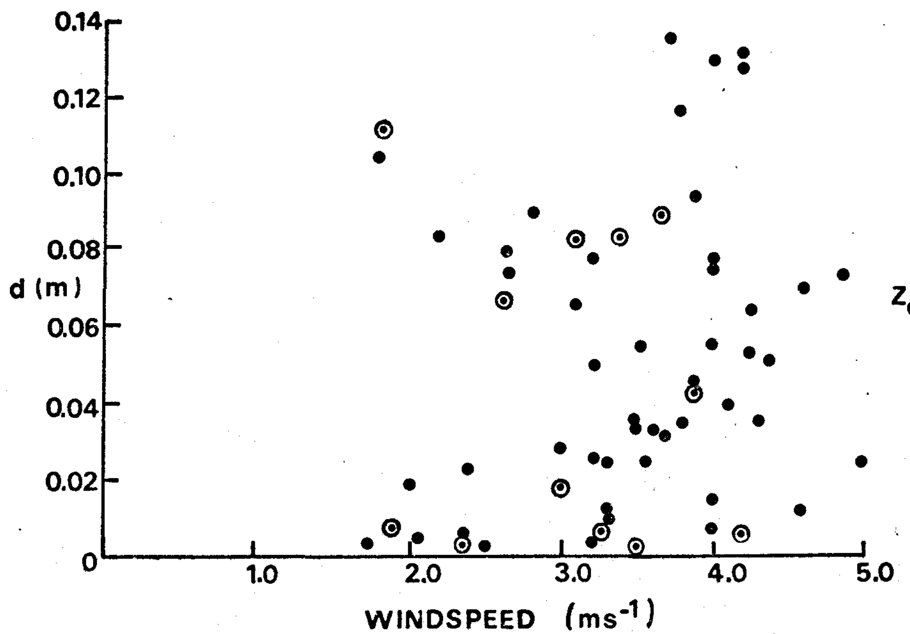


FIGURE 8 DEPENDENCE of d on WINDSPEED

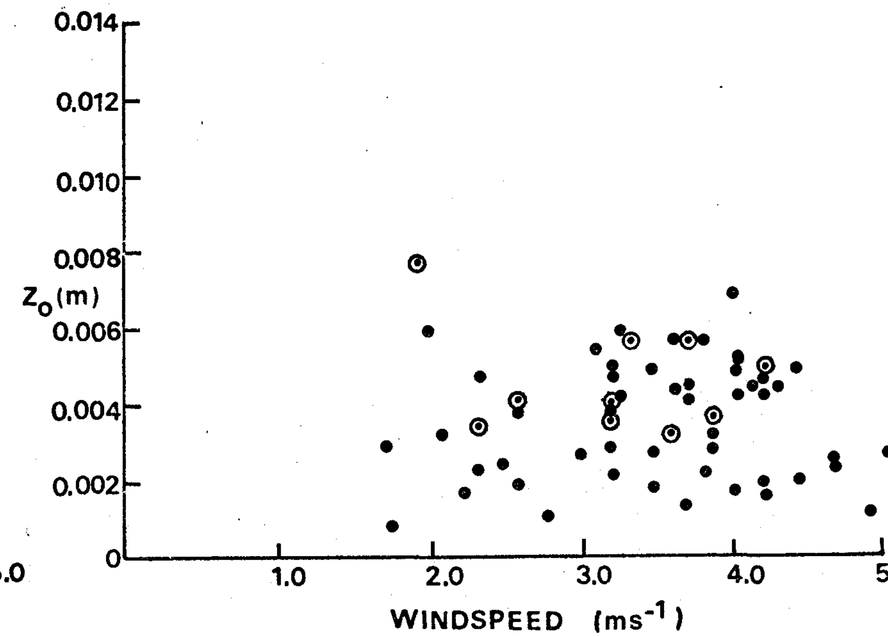


FIGURE 9 DEPENDENCE of Z_o on WINDSPEED

VALUES FROM JUNE 29 TO JULY 05

⊙ VALUES FROM ALONG-ROW WIND PROFILES

• VALUES FROM ACROSS-ROW WIND PROFILES

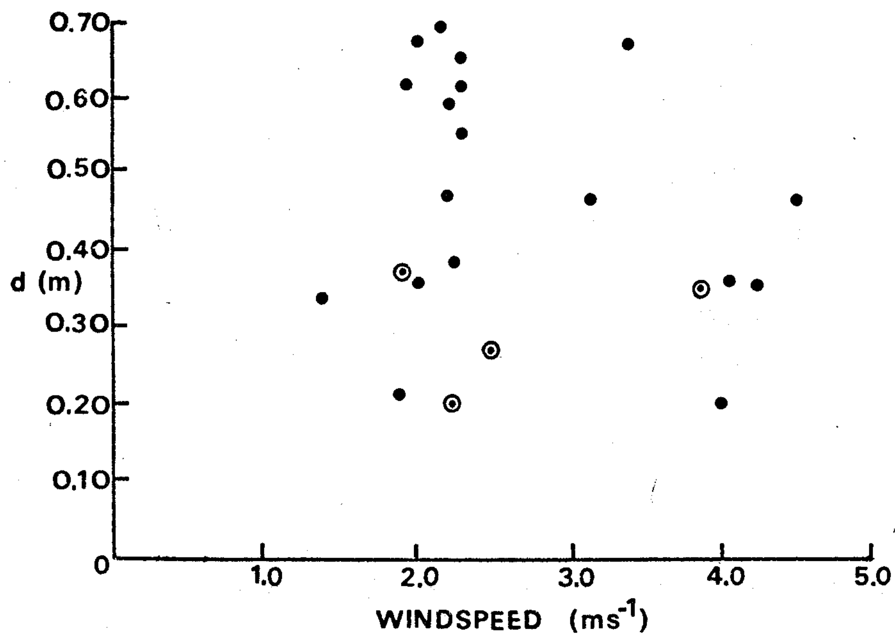


FIGURE 10 DEPENDENCE OF d ON WINDSPEED

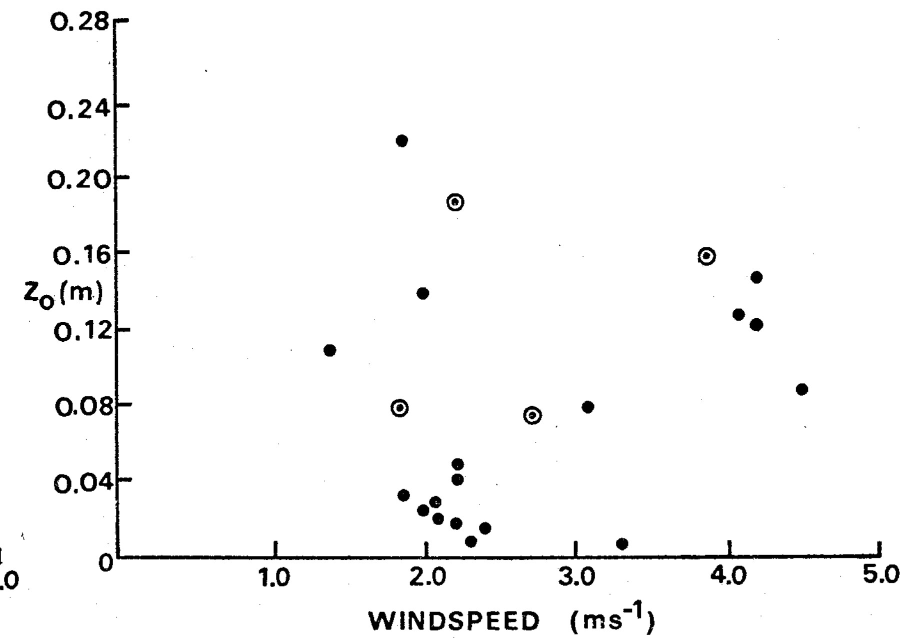


FIGURE 11 DEPENDENCE OF Z_o ON WINDSPEED

VALUES FROM AUGUST 09 TO AUGUST 23

⊙ VALUES FROM ALONG-ROW WIND PROFILES

• VALUES FROM ACROSS-ROW WIND PROFILES

in Figures 8-11), did not improve the scatter to the extent that a windspeed dependency could be determined.

Three other factors may account for the scatter:

(i) An undefinable windspeed dependence.

(ii) A natural variation in the windspeed profiles which is induced by the fairly rough surface. This is undefinable.

(iii) The extreme sensitivity of Lettau's iterative method for calculating z_o and d to possible windspeed error. Cup anemometers by design, constantly average the expected turbulent eddy velocities. However, any combination of the anemometers may be subjected to a windspeed burst or lull that does not occur at other levels. The use of sixty minute averaging periods minimizes the possibility of a given profile level possessing an atypical averaged windspeed, but may not negate it. Assuming random frequency and height occurence for these pulses and realizing the sensitivity of the iterative model, a large scatter for both z_o and d can be expected. The random nature of the bursts and lulls negates the possibility of isolating such an effect.

The adopted approach assumes no windspeed dependency. Not because it does not exist, but because it could not be determined. This contradicts many other leafy canopy studies (Rider, 1954; Thom, 1971; Monteith, 1973). However no other alternative is possible. The application of existing dependency trends would be highly subjective as wide discrepencies exist (Monteith, 1973).

(C) Analysis of lowest anemometer level

Table 2 lists the lowest anemometer levels and the minimum spacing between this sensor and the mean crop height. Ideally the lowest sensor should be at least five times the average roughness length (Tanner, 1963). However a clearance of just over three times the roughness length has also been used successfully (Munro, 1970). If this spacing is not achieved, the sensor may be in a transition zone between the canopy and the boundary layer. As such, the profile will not be representative of the surface boundary layer conditions. If this results in non-logarithmic profiles, systematic errors in z_o and d shculd be evident. Subsequent analysis of the roughness length revealed that the minimum spacing requirement may have been violated on three days (July 27, July 28, and August 05). To examine these situations, the data was checked for systematic trends in the Richardson number and calculated values of d and z_o. A three level analysis (lowest level dropped) was also attempted. Neither the Richardson number nor the calculated d and z_o values revealed any systematic trends. The results of the three level analysis were also inconclusive. Consequently, the profiles could not be excluded from the analysis.

TABLE 2

Lowest Anemometer Level

Period	Height of Lowest Level (m)	Maximum Crop Height for Period (m)
June 08-July 09	0.25	0.18
July 10-July 14	0.40	0.25
July 16-July 28	0.55	0.49
July 29-August 07	0.75	0.67
August 08-August 16	0.90	0.73
August 16-August 23	1.15	0.75

CHAPTER FIVE

ALTERNATIVE METHODS OF ESTIMATING z_o AND d

Profile analysis methods for determining z_o and d are time consuming and costly. Differences in the derived z_o and d values can lead to scattered results. As such, individual values cannot be confidently accepted as typical of that surface. Results are rarely obtainable on a continual daily basis. Therefore, expressing z_o and d in terms of more readily measured values has obvious merit. Estimates can be obtained by expressing z_o and d in terms of crop height using simple linear regression techniques. This procedure assumes that the data is linearly representable. A statistical analysis of the procedures to be outlined below, will be presented in Chapter 6.

(A) Zero plane displacement

(1) Comparison with other workers

Figure (12) represents the individual hourly profile values over the entire study period. A large scatter is clearly evident. The strength of the fitted relation (correlation coefficient = 0.835) should allow reasonable estimation of d by mean crop height (h). Three other regression equations are also shown:

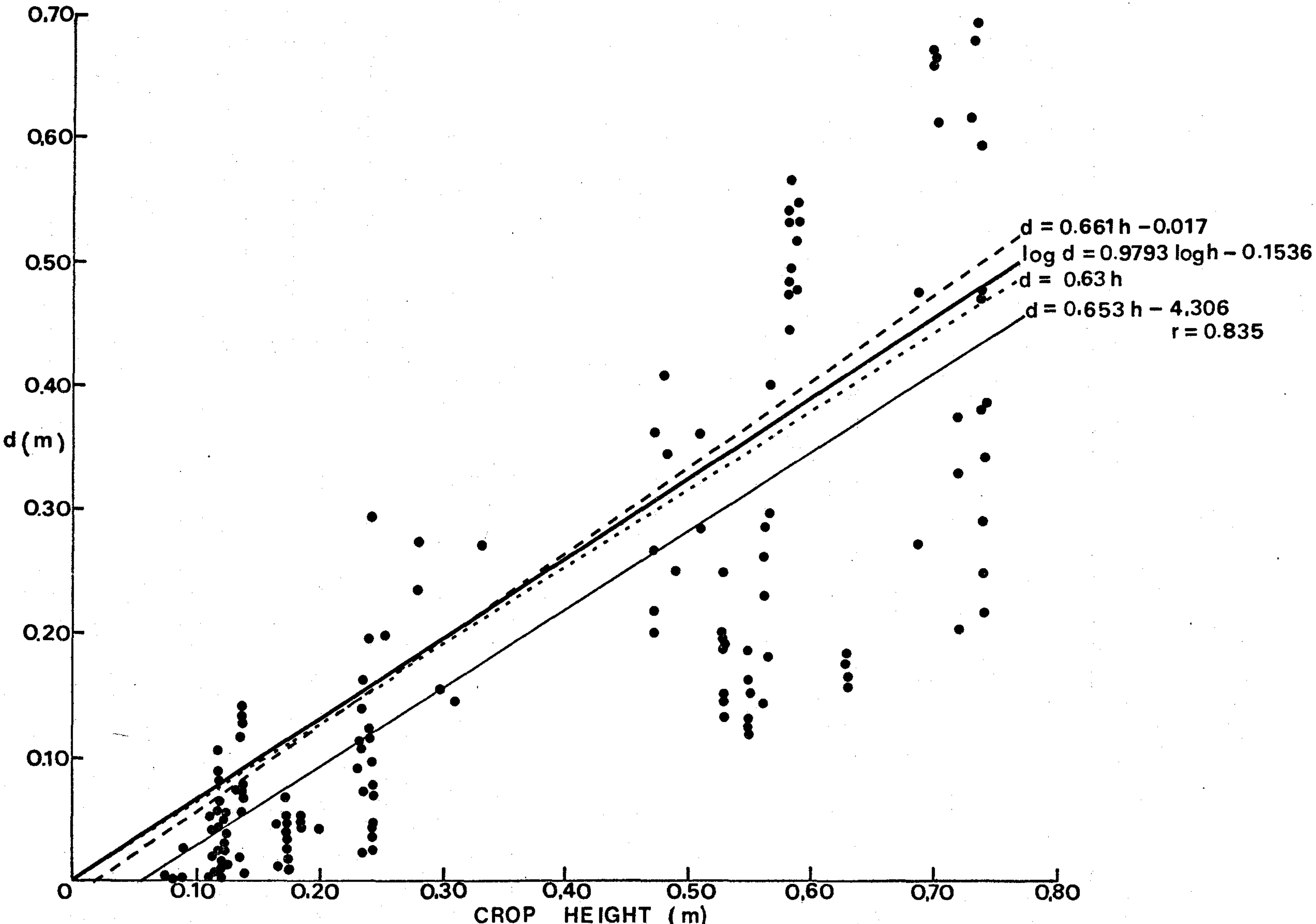


FIGURE 12 THE RELATIONSHIP BETWEEN d AND CROP HEIGHT FOR ALL HOURLY VALUES

$$d = 0.63h \qquad \text{(Monteith, 1973)} \qquad (6)$$

$$\log d = 0.9793 \log h - 0.1536 \qquad \text{(Stanhill, 1969)} \qquad (7)$$

$$d = 0.661 - 0.017 \qquad \text{(Allen, 1972)} \qquad (8)$$

Equations (6) and (7) are basically equivalent (Figure 12) and were derived for multi-crop representation. Equation (8) was derived only for a grass surface but its results agree remarkably well with those from equations (6) and (7). The consistent underestimation of the obtained relation appears to indicate displacement values slightly less than those for most investigated surfaces.

(2) Wind direction dependency

The individual hourly profiles were sub-divided into along-row and across-row wind profiles. To be classified as along row, the wind direction at the beginning or end of the hour had to lie within 254° to 299°, or 74° to 119°. Because the rows were planted with a 6° North of West orientation, the along row criteria were also changed by 6° to maintain an even distribution about the true along row direction. These limits were subjectively chosen and represent 23° ranges from true along row flow. The total range (46°) encompasses winds ranging from ESE to ENE and WSW to WNW. It was felt that these limits should encompass the profiles that were subjected to the greatest along row influences. For accuracy, the hourly wind directions recorded at the Atmospheric Environment Service meteorological observation station (500 m from the site), were used. The increased accuracy (to the nearest degree) justified their use. Fifty of the 137 near-neutral profiles fell into this category.

Figures (13) and (14) represent the across-row and along row profiles respectively. The difference between the two fitted relations is easily discerned. The across-row profiles are in good agreement with equations (6-8). This relation is also stronger than the relation in Figure (12). Values derived from the along-row relation are considerably smaller for a given crop height (Table 3). The lower values indicate greater canopy penetration by the wind. The negative y intercepts do not represent the crop height at which the zero plane displacement becomes important. The obtained value is only the intercept associated with the slope of the best fit line.

The change over from across-row to along-row profiles was considered to be very abrupt. More realistically, a progressive deterioration would occur. However, the determination of such a deterioration would be very complex. The determination is complicated by unevaluated windspeed dependencies and the natural variation of the parameters over an aerodynamically rough surface. Consequently, such a deterioration could not be accurately evaluated. The large sample of near-neutral profiles allowed further manipulation of the data. In an attempt to represent the data better, four other approaches were

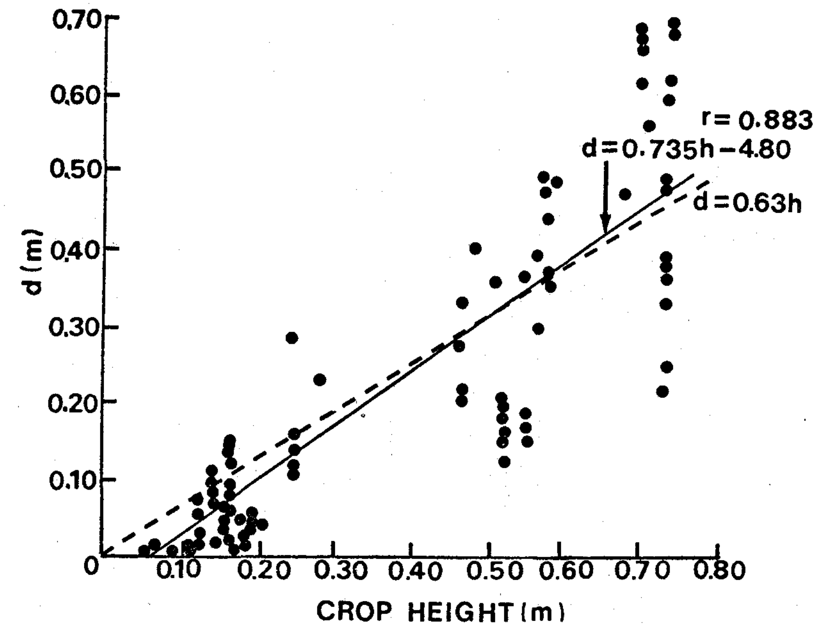


FIGURE 13 ACROSS-ROW WIND PROFILES

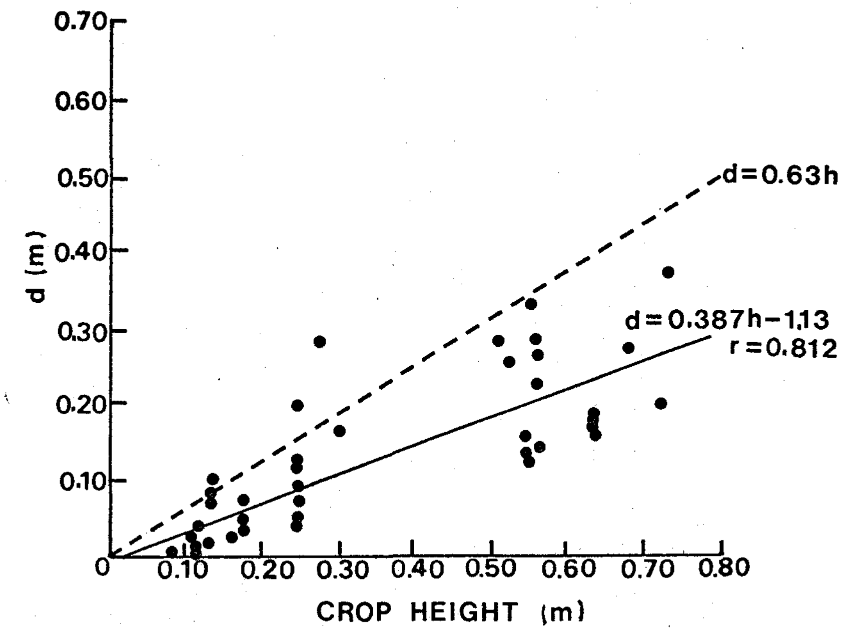


FIGURE 14 ALONG-ROW WIND PROFILES

THE RELATIONSHIP BETWEEN d AND CROP HEIGHT (h)

TABLE 3

Comparison of Along and Across-Row Zero Plane Displacement Values

Crop Height (m)	Along Row d (m)	Across Row d (m)
0.10	0.027	0.026
0.20	0.066	0.099
0.30	0.105	0.173
0.50	0.182	0.320
0.70	0.260	0.467

investigated.

(3a) Daily average profiles

Values of d (and z_o) are rarely required on more than a daily basis. Average daily windspeed profiles were obtained by calculating the mean windspeed profile from all near-neutral profiles for a given day. Average, daily d (and z_o) values are then derived by the iterative procedure. The results are presented in Figure (15). Although a fairly large scatter existed, the fitted relation is in good agreement with equations (6-8). Because of its simplicity only equation (10) is shown. This method also provides a slightly stronger correlation ($r = 0.757$) than the fitted relation of Figure (12). Considering the pooled data approach, this method should provide a viable alternative for studies where wind direction influence is minimum at most.

(3b) Average and mean methods based on crop height intervals

One assumption inherent in the procedure so far discussed is the validity of the estimated crop height as representative for a given day. The large standard deviations apparent in Figure (3) makes this assumption highly suspect. More realistic comparisons may result from the use of 0.05 m crop height intervals. The selection of this increment was based on four considerations:

(1) To allow a maximum number of samples in each 0.05 m interval for averaging purposes.

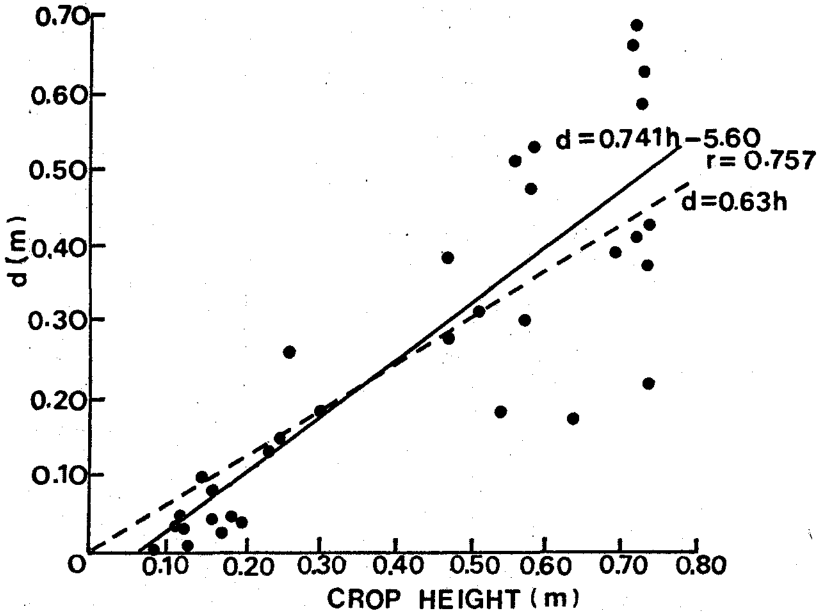


FIGURE 15 AVERAGE DAILY PROFILE d VALUES

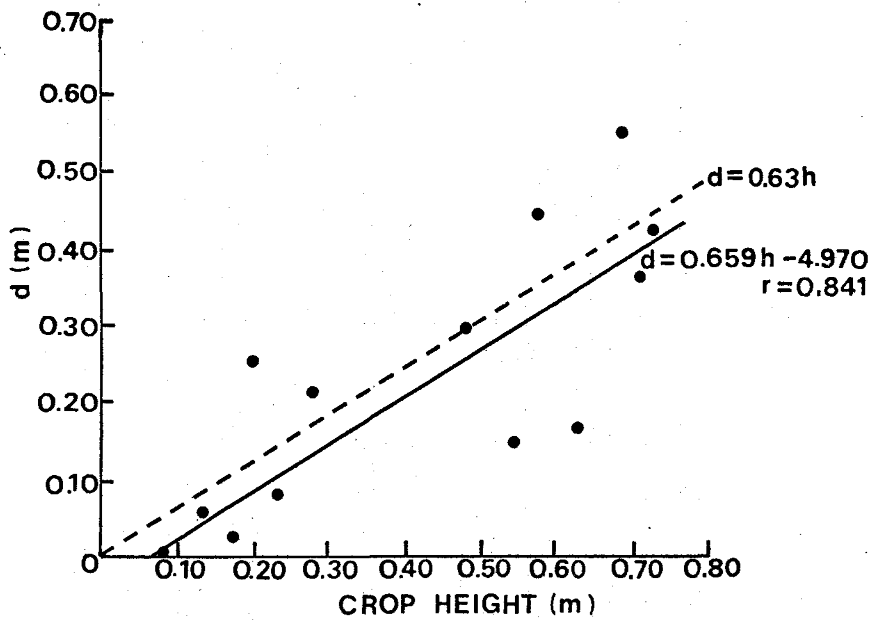


FIGURE 16 AVERAGE PROFILE d VALUES

averages based on 0.05 (m) crop height intervals

(2) To obtain a maximum number of increment periods.

(3) To minimize the magnitude of the increment as a larger increment creates a larger variation of d (and z_o) within that interval.

(4) To have a crop height interval that should allow realistic and valid crop height estimates.

Three approaches were possible:

(i) Mean windspeeds over the entire study period were calculated for each 0.05 m crop height interval. The profiles and the obtained d (and z_o) values represent the averages for each interval (Figure 16).

(ii) Mean d (and z_o) values, based on the average daily profiles, were calculated. These represent mean daily values for each interval (Figure 17).

(iii) This approach involved calculating means of the individual hourly profile d (and z_o) values for each interval. These represent mean values for each interval (Figure 18).

Only near-neutral profiles were examined. The first method required interfacing the 0.05 m intervals with changes in the anemometer heights. For consistency all other approaches used the same periods. The results were very similar (Figures 16-18). The fitted relations of the second and third methods were the strongest. With the exception of one point (h = 0.63 m, d = 0.167 m) the scatter of the second approach is quite small. The five hourly profiles which made up the daily profile and hence the 0.05 m interval mean daily value, were all along-row profiles.

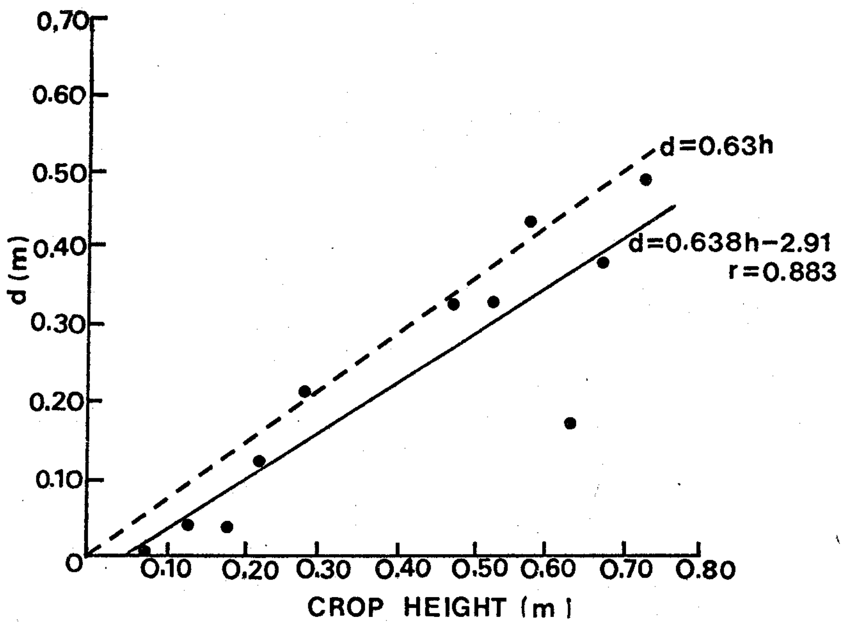


FIGURE 17 MEAN DAILY PROFILE d VALUES

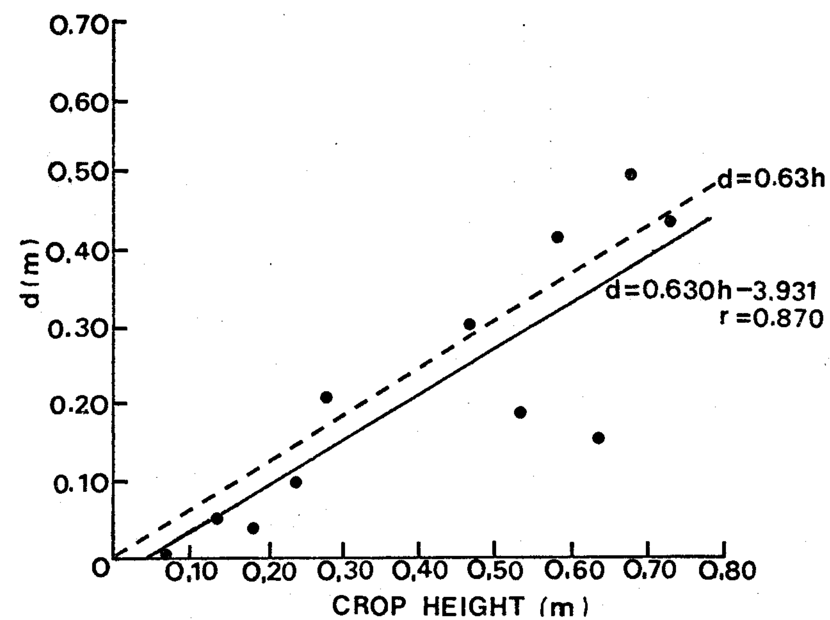


FIGURE 18 MEAN d VALUES

values based on 0.05 (m) crop height intervals

This was the only mean daily point, of the second method, at which this occured.

Although these approaches could be confidently applied to a study where row influence was minimal at most, this influence cannot be ignored in this investigation.

(4) Mean and average d for along and across-row winds

Following the same procedure, mean and average profile values were seperately calculated for the along and across-row profile sample sets (Figures 19-22). The fitted relations were very similar and in good agreement with Figures (13) and (14). The relations derived by the mean method were slightly stronger. This was somewhat surprising. The average profile method minimizes the use of the sensitive iteration procedure. By using mean windspeeds any minor errors in the windspeed measurements should have been reduced. Thus, the sensitivity of the iteration procedure would be reduced and a smaller scatter would be expected to result. The less frequent use of the iteration procedure also makes this method more efficient. The 95% confidence limits indicated for the fitted relations of Figures (21) and (22), demonstrate that the fitted relations of the two methods are indistinguishable. Apparently taking the mean of the individual hourly profile values reduces the variability in a given crop height interval (as indicated by the stronger correlation

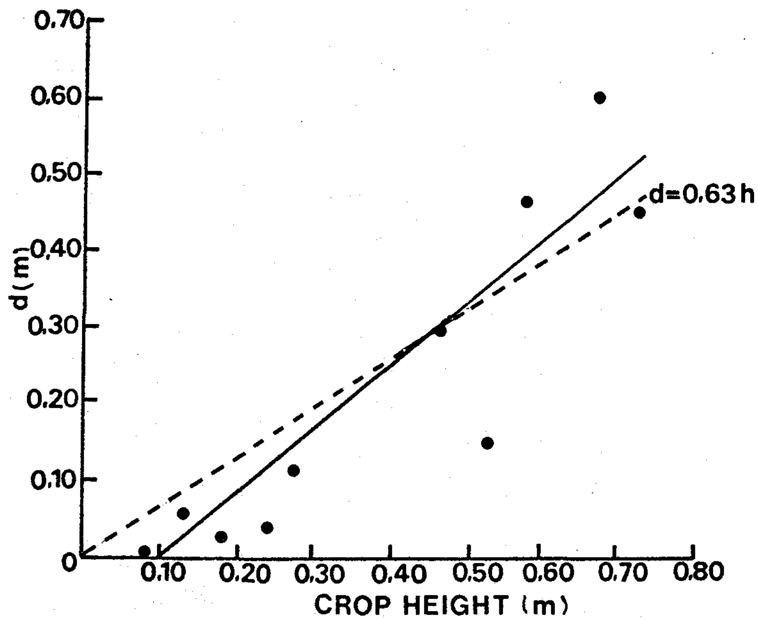


FIGURE 19 AVERAGE ACROSS-ROW d

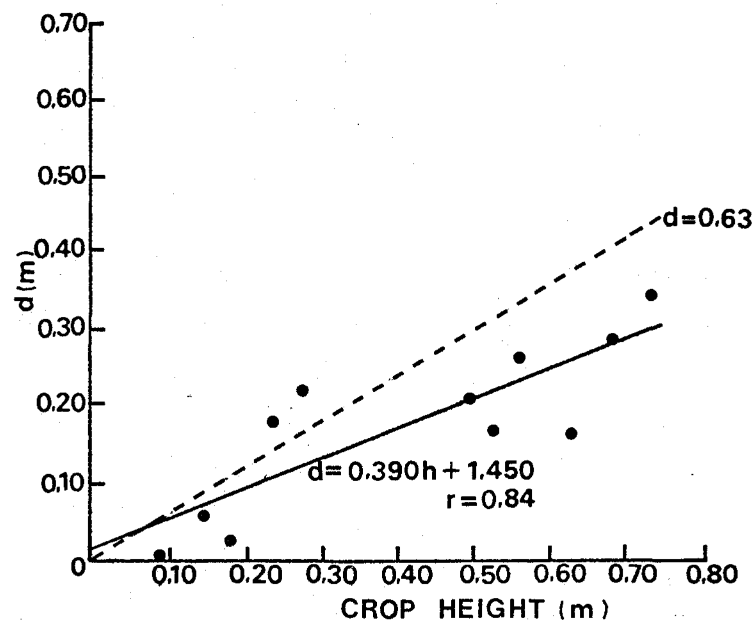


FIGURE 20 AVERAGE ALONG-ROW d

values based on 0.05(m) crop height intervals

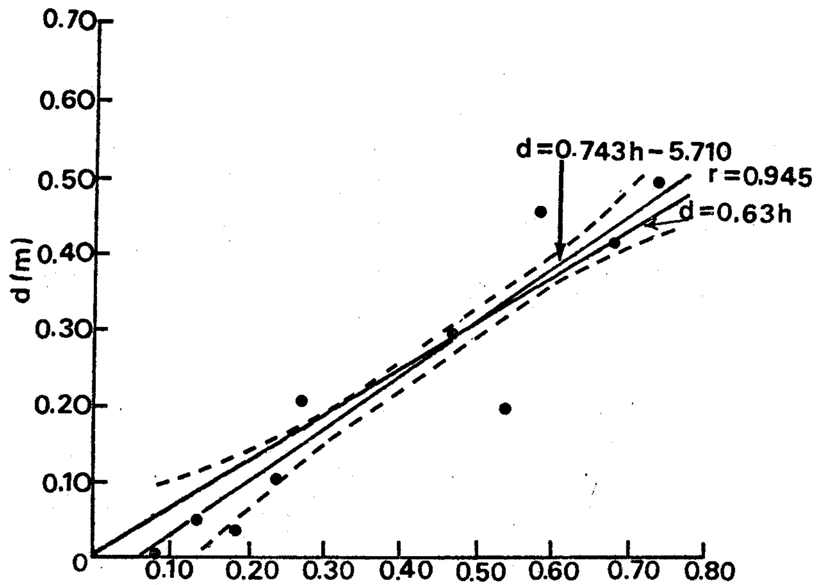


FIGURE 21 MEAN ACROSS-ROW d VALUES

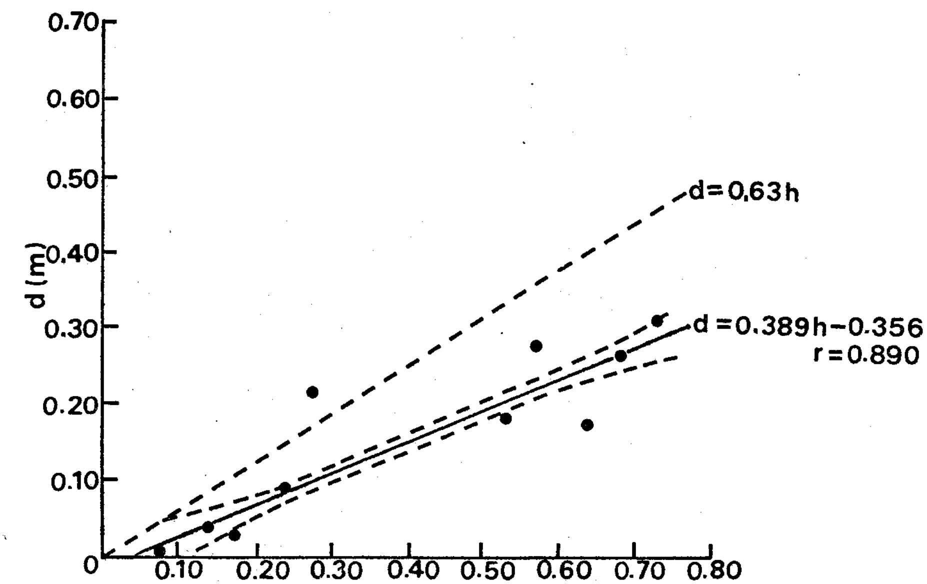


FIGURE 22 MEAN ALONG-ROW d VALUES

values based on 0.05 m crop height intervals

--- 95% confidence limits for : $d = 0.743h - 5.710$

$d = 0.389h - 0.356$

coefficient), more effectively. Although the average profile method is more efficient and produces representative values, it cannot be statistically evaluated for linearity. However both the meaned daily average and mean approaches can be evaluated for linearity. The importance of this will be discussed in Chapter 6.

The values of the y intercepts reflect the slope of the fitted relations as the steeper the slope, the larger (more negative) the intercept value. It is doubtful that they can be physically related to crop growth.

(B) Surface roughness

(1) Comparison with other workers

Individual, hourly profile values for the entire study period are presented in Figure (23). The large scatter is reflected in the weak strength of the fitted relation (correlation coefficient = 0.656). Also shown in Figure (23) are four other regression equations:

$z_o = 0.13\ h$ (Monteith, 1973) (9)

$\log z_o = 0.997 \log h - 0.883$ (Tanner and Pelton, 1960) (10)

$\log z_o = \log h - 0.98$ (Sziecz et al, 1969) (11)

$z_o = 1.25\ h - 0.002$ (Allen, 1972) (12)

Equations (9) and (10) are indistinguishable. Only equation (12) (grass surface) is surface specific. Although the fitted relation of Figure (23) is in good agreement with the results of other workers, the weak correlation will not allow confident estimations of z_o.

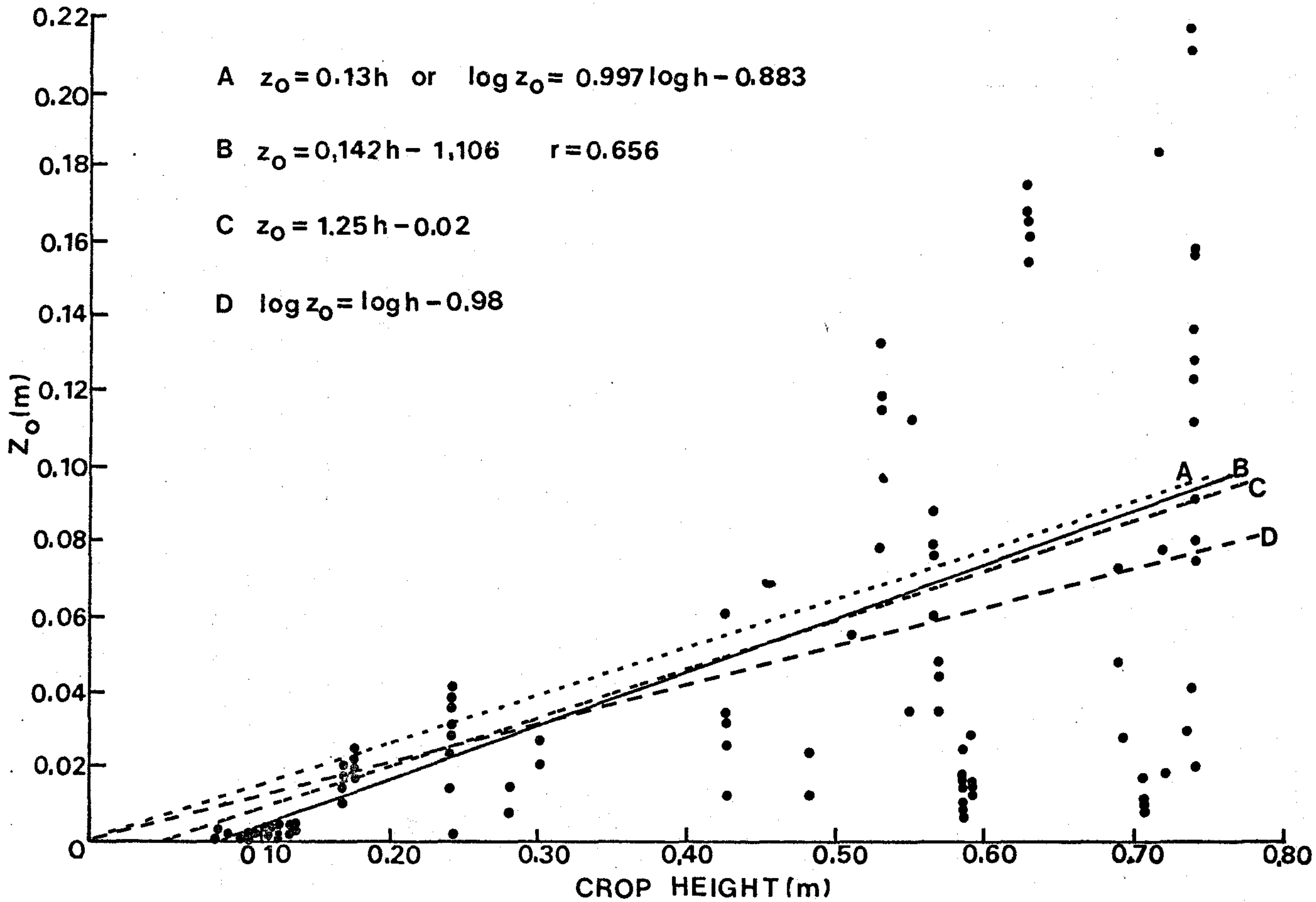


FIGURE 23 THE RELATIONSHIP BETWEEN Z_o AND CROP HEIGHT (h)

(2) Wind direction dependency

The surface roughness calculation is based on the value of d. Since d exhibited a wind direction dependency, z_o should also be sub-divided into along and across-row profiles (Figures 24 and 25). The along-row profiles exhibit a much smaller scatter than the across-row profiles and hence a stronger correlation coefficient. This result was surprising considering the strength of the across-row correlation coefficient ($r^2 = 0.78$) for d, compared to the along-row correlation coefficient ($r^2 = 0.66$). A possible explanation is the greater sensitivity of z_o compared to d for a small change in the windspeed at the lowest sensor level. This sensitivity was verified by the second example of the sensitivity to errors in windspeed test as a given relative change in d resulted in a larger relative change in z_o. The variability in d and hence z_o, would also be enhanced by a windspeed dependency and the natural variation of the wind profiles over an aerodynamically rough surface.

The across-row fitted relation is in good agreement with equation (11). However the weak correlation coefficient ($r^2 = 0.336$) does not allow confident estimation. The consistently smaller d values for the along-row profiles is reflected by the large z_o values for these profiles. Similar to the fitted relation of Figure (11), the fitted relation of Figure (25), greatly differs from the values predicted for a given crop height by other workers

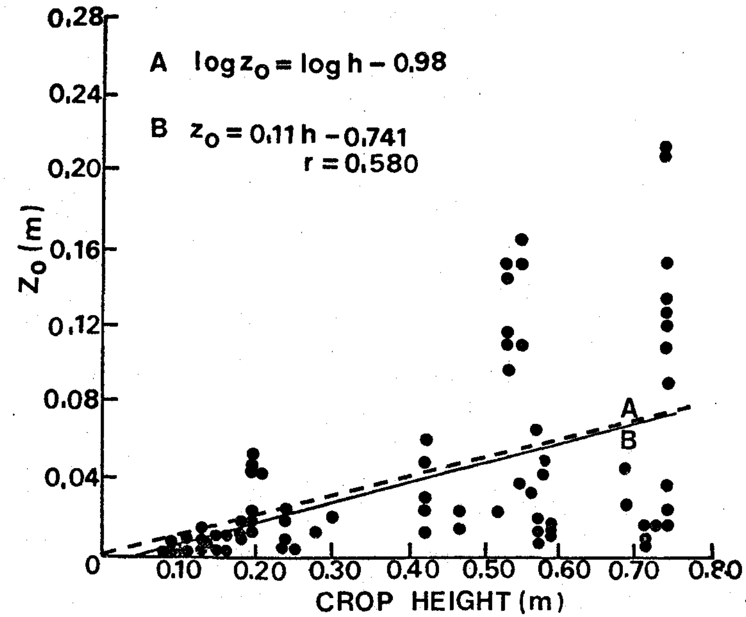


FIGURE 24 ACROSS-ROW WIND PROFILES

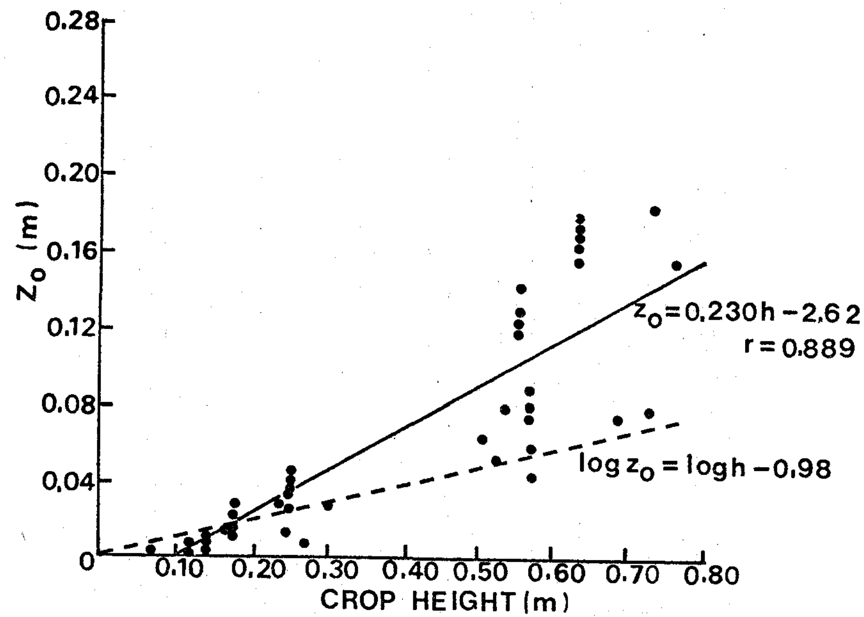


FIGURE 25 ALONG-ROW WIND PROFILES

THE RELATIONSHIP BETWEEN Z_0 AND CROP HEIGHT (h) (equations 9-12). This clearly demonstrates the row influence on these aerodynamic parameters.

(3) Average and mean methods based on crop height intervals

The questionable validity of the estimated crop height for a given day is also applicable to z_o estimates. Following the previously described methodology, mean and average z_o values were calculated for the same 0.05 m crop height intervals used in estimating the zero plane displacement (Figures 19-22). The fitted relations of the two methods are nearly identical for the across and along-row situations (Figures 26-29). Again the mean method provided better scatter reduction as evidenced by the stronger correlation coefficients. Therefore, more confident estimates can be made. As expected the good agreement with equation (15) is maintained for the across-row situation. However the strength of the across-row fitted relation for the mean method is still only fair. The ability to reasonably estimate the along-row profiles, but not the across-row profiles, may be related to the shape of the structure encountered. The along-row winds encounter a series of evenly spaced canyon-like features, while the across-row winds encounter an infinite number of ridges, troughs, depressions and hills. Assuming this overly simplified approach to be basically realistic, the across-row profiles encounter a more variable surface. Under ideal conditions of infinite fetch, this should be negligable.

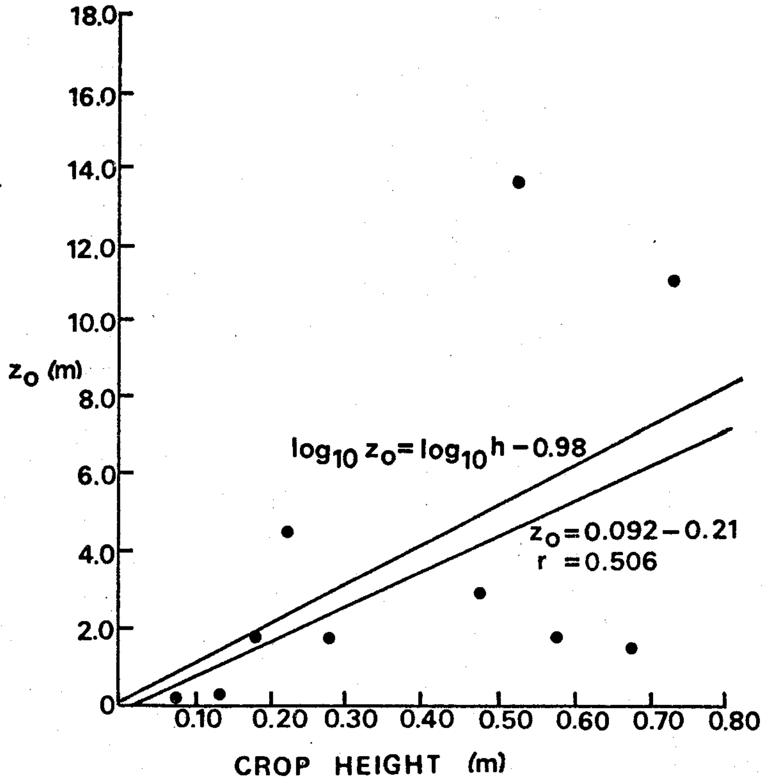


FIGURE 26 AVERAGE ACROSS-ROW Z_o

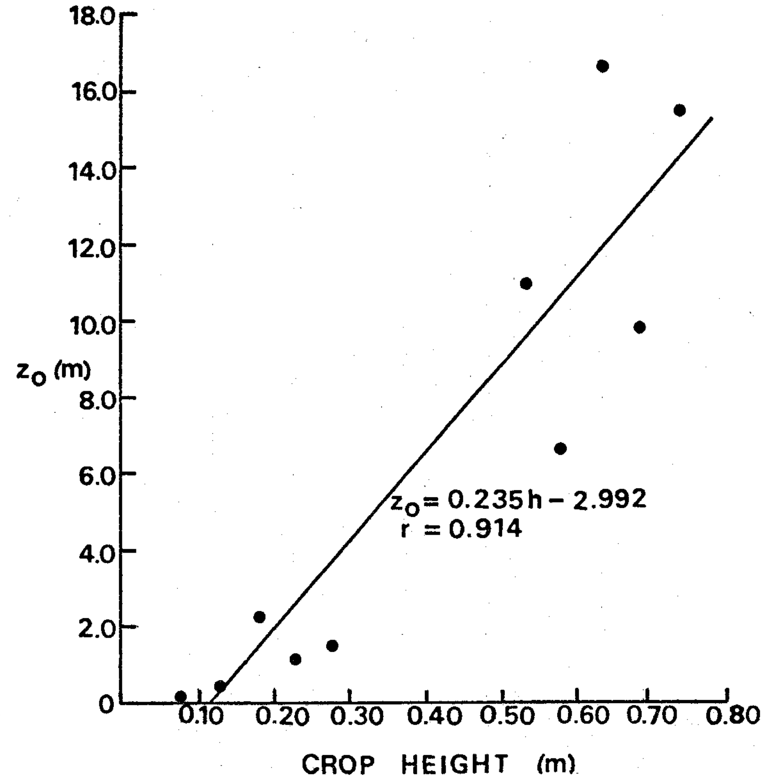


FIGURE 27 AVERAGE ALONG-ROW Z_o

values based on 0.05 m crop height intervals

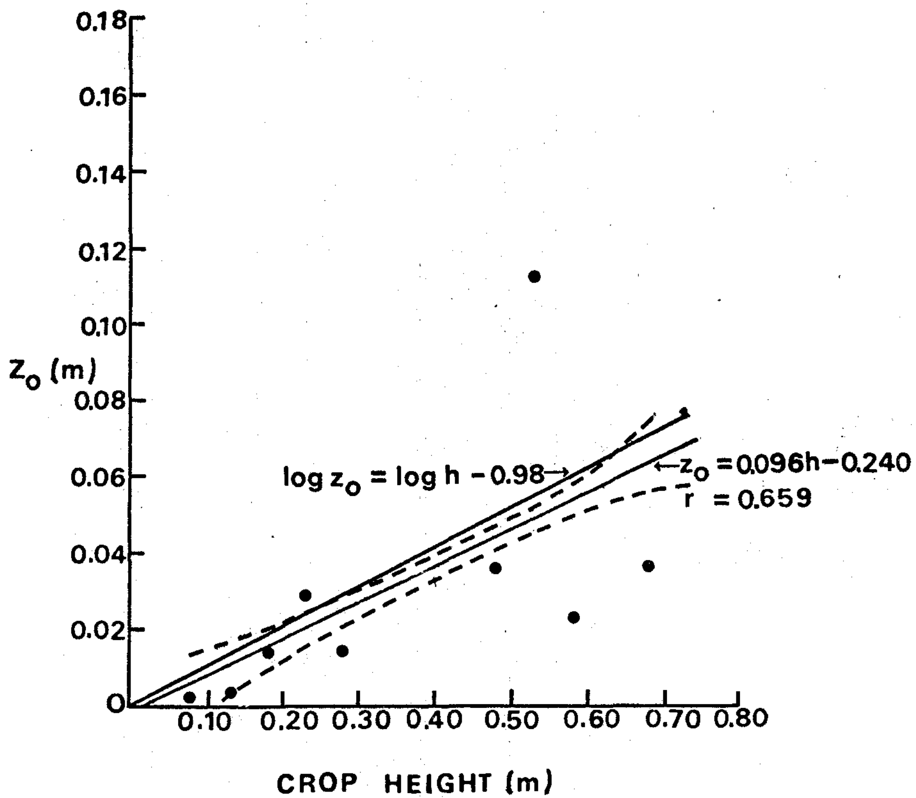


FIGURE 28 MEAN ACROSS-ROW z_o

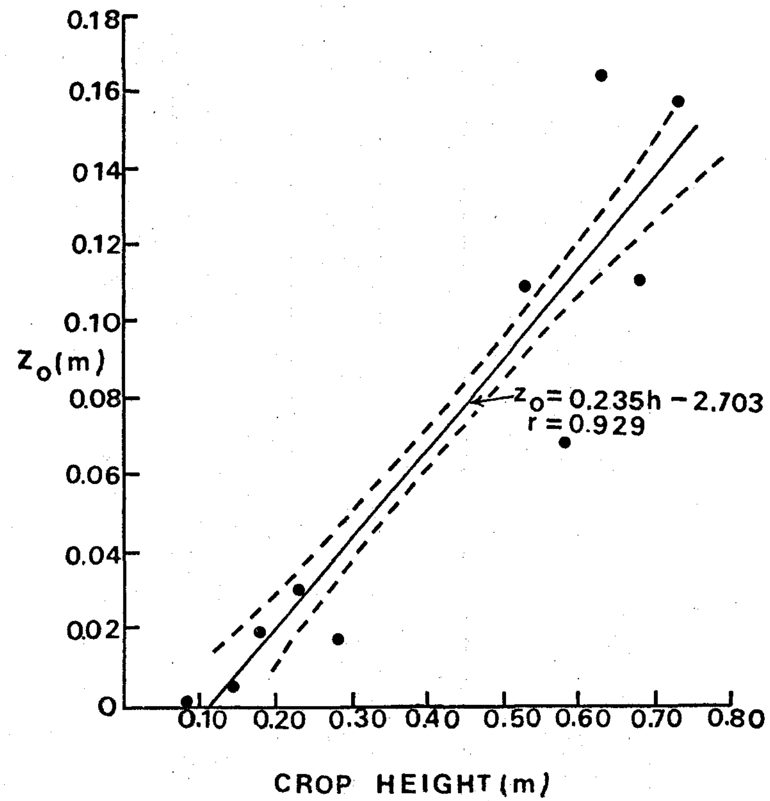


FIGURE 29 MEAN ALONG-ROW z_o

- - - 95% confidence limits

values based on 0.05 m crop height intervals

However for a field of limited fetch, as is the case here, this may not be completely true. Therefore, the windspeed profiles may vary and hence so may z_o. As previously shown, the strong correlation obtained for the zero plane displacement indicates that this parameter is less sensitive than z_o to such variations.

However, the ability of these approaches to allow confident estimations of the along row z_o values does indicate that these are useful alternatives for the estimation of z_o. The results are particularly encouraging considering the possible existence of a windspeed dependency.

CHAPTER SIX

STATISTICAL ANALYSIS

The use of linear regression techniques assumes that the data can be linearly represented. To test this assumption an analysis of variance, with replication, was applied (Freund, 1967; Wonnacott and Wonnacott, 1972). Replication is defined here as the multiple occurance of dependent variable values for a given independent variable. The greater the number of replication samples, the more confidently can the analysis be applied. Replication is accomplished in this study by the use of mean z_o and d values based on the 0.05 m crop height intervals. Only the mean method can be tested. The average profile method eliminates replication as only one profile per interval existed. The following analysis demonstrates that this could be a major drawback of the method.

The following data sets and their respective fitted linear relations were tested:

(1) The mean pooled (along and across-row) values of the zero plane displacement (Figure 18).

(2) The mean along and across-row zero plane displacemeant data sets (Figures 21 and 22).

(3) The mean along and across-row surface roughness length data sets (Figures 28 and 29).

(4) The meaned average daily profile sample set (Figure 17).

Two null hypotheses were tested. First, that the estimated slope is equal to zero (H_o: $\beta = 0$), and secondly that the derived linear regression line represents the data set (H_o).

The computational formulas and analysis procedures are outlined in Appendix D. The null hypothese are tested by comparing the calculated variance ratio to values in a standard F table. If the calculated variance ratio exceeds the F table value, the null hypothesis is rejected. Results are summarized in Table. 4.

The first null hypothesis was disproven in each analysis as the calculated variance ratio always exceeded the $F_{0.01}$ value. The second null hypothesis (data linearly representable) was also disproven for each analysis. This is a very significant result as it implies (99% confidence) that the data is not linearly representable. Therefore, the fitted linear relations misrepresent their respective data sets. The non-linearity is not contradictory to the slope hypothesis. The z_o and d values increase with crop height but only in a non-linear manner. The determination of these non-linear relations is beyond the scope of this analysis.

The use of non-linear equations to represent the data raises many problems. If the non-linear relations are site specific, they many not be applied to other Soybean canopies or similar surfaces. However if they are not site

TABLE 4

Results of Analysis of Variance Test

Data Set Tested	Slope Mean Square / Residual Mean Square	$F_{0.01}$*	Lack of Fit SS / Pure Error SS	$F_{0.01}$*
Pooled d (Figure 15)	567.50	6.85	26.90	2.56
Across-row d (Figure 18)	62.70	6.85	14.44	2.66
Along-row d (Figure 19)	48.25	7.30	9.71	2.99
Across-row z_o (Figure 28)	206.98	6.85	17.29	2.66
Along-row z_o Figure 29)	161.44	7.30	181.91	2.99
Daily average profile d (Figure 14)	80.29	7.43	4.03	3.26

(* - F values taken from Freund, 1967)

specific, they may prove to be valuable tools for determining z_o and d over such surfaces. Short term studies or investigations where near-neutral conditions are less frequent may be unable to confidently analyze the derived data for this linearity question. The problem then arises whether linear or non-linear relations should be applied. Verification of the obtained results is clearly desirable. If other analyses arrive at similar non-linear conclusions, then this approach would be necessary.

The apparent uniqueness of the non-linear conclusion may indicate that the mean method does not represent the data. However, the mean method allows greater replication and hence more confident predictions. Because the means are calculated from the individual, hourly profile data sets, the results should accurately represent these data sets as well.

Since previous workers do not include an analysis of variance (Szeicz et al, 1969; Stanhill, 1969; Tanner and Pelton, 1960) their derived linear relations may also be highly suspect. The strength of the fitted linear relations and their good agreement with these other studies is puzzling in light of the non-linearity findings. It may be conjectured that the linear relation is a good approximation for the non-linear data sets. However, this is a very speculative and qualitative statement that cannot be substantiated.

Because the averaging method negates the possibility of replication, it cannot be confidently analyzed in this fashion. However, in light of the non-linearity of the mean method and the similarity in the fitted relations obtained by the mean and average methods, the non-linearity would likely exist for this method as well.

CHAPTER SEVEN

CONCLUSIONS

This study sought to obtain and evaluate alternative approaches for estimating z_o and d using a simple crop parameter. Methods applicable to studies where a wind direction dependency may or may not exist, are presented.

In light of the statistical implications of non-linearly representable data, the fitted relations cannot be justifiably used to estimate z_o and d. The unsubstantiated use of the linear regressions derived in other studies may lead to inaccurate results. This applies to both previous and future studies. The inability of the presented analysis to either validate or invalidate the existence of a wind-speed dependency and the simplified, subjective approach to the wind direction dependency may partially or fully account for the non-linear relations required for this study.

Despite the difficulties, some positive results were obtained. The wind direction dependency of the profiles is very apparent. However, consideration of this may be particularly difficult in studies involving row structured canopies where near-neutral profiles are less frequent. For studies where this is minimal at most and the data are linearly representable, methods of obtaining confident estimates of the zero plane displacement were presented. The greater scatter that appears to exist for z_o in this study make it more difficult to obtain confident estimates of the surface roughness length.

It is apparent from this study that a strong correlation coefficient can be very misleading. Consequently, future analyses should include a statistical analysis along these lines if possible. An evaluation of both windspeed and wind direction dependencies are also warranted. Improvement in the estimating ability of z_o and d in terms of simple crop parameters will depend on the success of these analyses. In this way, a better understanding of these basic yet complex wind profile parameters, might be gained.

APPENDIX A

NOTATION

Upper Case Roman

L	stability length scale	m
R_i	gradient Richardson number	dimensionless
T	temperature, not corrected for adiabatic lapse rate	C

Lower Case Roman

a	polynomial regression coefficient, order denoted by numerical subscript	
c	number of anemometer cup revolutions	rpm
d	zero plane displacement	
f	relative correction factor	
g	gravitational acceleration	ms^{-2}
k	von Karman's constant	dimensionless
r	correlation coefficient	
u	windspeed, subscript refers to a height above the surface	ms^{-1}
u_*	friction velocity	"
z	height above the surface	m

z_o	wind profile roughness length	m
z/L	stability parameter	dimensionless

Greek

Γ	adiabatic correction factor	$C\,m^{-1}$
θ_v	virtual potential temperature	K

APPENDIX B

(1) Windspeed calculation

The polynomial regression equation used to convert to windspeed was:

$$u = (11.44069 + 2.57227c - 0.00043c^2)f$$

where

u is windspeed (ms^{-1})

c is counts per minute

f is the relative correction factor

The relative correction factors and the period to which they applied are listed in Table B1. Levels 1-4 refer to the lowest to highest anemometer heights inclusive.

(2) Temperature calculation

The polynomial regression equations used to convert measurements to temperature (^oC) were of the form:

$$T = (a_o + a_1mv + a_2mv^2)f$$

where

a_o, a_1, a_2 are calibration coefficients

mv is the sensor signal

f is the relative correction factor

The values for these are listed in Table B2. Levels 1-4 refer to the lowest to highest dry bulb (T) and wet bulb (TW) sensors inclusive.

TABLE B1

Anemometer Correction Factors

Period	Level 1	Level 2	Level 3	Level 4
June 08-July 09	1.0036	0.9964	-	0.9894
July 10	1.0036	0.9964	0.9894	1.0627
July 11-August 04	1.0036	0.9964	1.0627	0.9894
August 05-September 03	1.0015	0.9986	1.0630	0.9853
September 04-September 22	1.0052	0.9949	1.0584	0.9851

(all values expressed as percentage difference from unity)

TABLE B2

Temperature Calibration Coefficients and Correction Factors

Sensor	a_o	a_1	a_2	f*
T1	0.62416	5.15131	-0.03436	0.9858
T2	0.06075	5.18926	-0.02990	1.0005
T3	0.05760	5.20112	-0.03267	1.0000
T4	0.02090	5.18487	-0.02801	1.0034
TW1	-0.01318	5.24361	-0.03461	0.9999
TW2	0.29168	5.21092	-0.03257	0.9961
TW3	0.05354	5.21848	-0.03549	0.9998
TW4	0.06499	5.16983	-0.02716	1.0011

* all values expressed as difference from unity

APPENDIX C

Statistical analysis procedure

The analysis of variance test is summarized in the following table:

Regression Equation: $\hat{Y} = \hat{\alpha} + \hat{\beta} X$

Source of Variance	Degrees of Freedom	Sum of Squares (SS)	Mean Square
(1) Mean	1	$(n\bar{\bar{y}})^2$	$\frac{SS}{1}$
(2) Slope	1	$\hat{\beta}^2 \Sigma (x_i - \bar{\bar{x}})^2$	$\frac{SS}{1}$
(3) Residual	n-2	3a+3b	$\frac{SS}{n-2}$
(3a) Lack of Fit	r-2	$\Sigma n_i (\bar{y}_i - \hat{Y})^2$	$\frac{SS}{r-2}$
(3b) Pure Error	n-r	$\Sigma\Sigma (y_{ij} - \bar{\bar{y}})^2$	$\frac{SS}{n-r}$
Total	n	1+2+3	$\frac{SS}{n}$

where:

$\bar{y}_i$ is the mean of each interval's dependent variables (y_{ij})

$\bar{\bar{y}}$ is the grand mean of all dependent variables

$\bar{\bar{x}}$ is the grand mean of all independent variables

n is the total number of samples

r is the total number of 0.05 (m) intervals

n_i is the number of replications in a given interval

Computational formulas used:

(1) Mean SS $= \frac{(\Sigma\Sigma y_{ij})^2}{n}$

(2) Slope SS $= \hat{\beta}^2 \sum_{i=1}^{r} n_i (x_i - \bar{\bar{x}})^2$

(3) Residual SS $=\sum_{i=1}^{r} \hat{\sigma}_i^2 \cdot n_i$

(4) Lack of Fit SS $=\sum_{i=1}^{r} n_i(\bar{y}_i - \hat{Y}_i)^2$

(5) Pure Error SS = Residual SS-Lack of Fit SS

To test hypothesis 1 (H_o: $\beta = 0$):

$$F = \frac{\text{Slope Mean Square}}{\text{Residual Mean Square}}$$

where F is the variance ratio with the degrees of freedom defined by the numberator and denominator. If the calculated variance ratio exceeded $F_{0.01}$ (from F tables), the null hypothesis was rejected. To test null hypothesis 2 (H_o-linear representable data):

$$F = \frac{\text{Lack of Fit Mean Square}}{\text{Pure Error Mean Square}}$$

If the calculated variance ratio exceeded $F_{0.01}$, the null hypothesis was rejected.

REFERENCES

Allen, C.D., 1972: Surface Control on the Energy Balance and Combination Model Components. M.Sc. Thesis, McMaster University, Hamilton.

Chang, J., 1968: Climate and Agriculture. Aldine Publishing Co., Chicago.

Dyer, A.J., and B.B. Hicks, 1970: Flux-Gradient Relationships in the Constant Flux Layers. Quart. J. R. Meteor. Soc., 96, 715-731.

Evans, G.C., 1973: The Quantitative Analysis of Plant Growth. Univ. of Calif. Press, 17 p.

Freund, J.E., 1967: Modern Elementary Statistics, 3rd ed., Prentice-Hall, Englewood Cliffs, N.J.

Lemon, E., 1965: Micrometeorology and the Physiology of Plants in Their Natural Environment in Plant Physiology. F.C. Steward, ed., IVA, Academic Press, New York, 203-227 pp.

Lettau, H.H., 1957: Computation of Richardson numbers, classification of wind profiles, and determination of roughness parameters in Exploring the Atmosphere's First Mile. H.H. Lettau and B. Davidson ed., Pergamon, London, 328-336 pp.

McBean, G.A., and M. Miyake, 1972: Turbulent Transfer Mechanisms in the Atmospheric Surface Layer. Quart. J. R. Meteor. Soc., 98, 383-398.

McIntosh, D.H., and A.S. Thom, 1969: Essentials of Meteorology. Wykelham Sci. Series, Wykelham Publ. Ltd., London.

Monteith, J.L., 1973: Principles of Environmental Physics. Edward Arnold Ltd., London.

Munro, D.S., 1970: Adjustment of the Neutral Wind Profile over a Wheat Crop. M.Sc. Thesis, McGill University, Montreal.

Munro, D.S., and T.R. Oke, 1973: Estimating Wind Profile Parameters for Tall Dense Crops. Agr. Met., 11, 223-228.

Munro, D.S., and T.R. Oke, 1975: Aerodynamic Boundary-Layer Adjustment over a crop in Neutral Stability. Boundary-Layer Meteorology, 9, 53-61.

Oliver, H.R., 1971: Wind Profiles in and above a Forest Canopy. Quart. J. R. Meteor. Soc., 97, 548-553.

Priestly, C.H.B., 1959: Turbulent Transfer in the Lower Atmosphere. Univ. of Chicago Press, Chicago.

Rider, N.E., 1954: Evaporation from an Oat Field. Quart. J. R. Meteor. Soc., 80, 188-211.

Šestak, Z., J. Čatsky, and P.G. Jarvis, 1971: Plant Photosynthetic Production: Manual of Methods. Dr. W. Junk, N.Y., Publisher, The Hague.

Stanhill, G., 1969: A Simple Instrument for the Field Measurement of Turbulent Diffusion Flux. J. App. Met., 8, 509-513.

Sutton, O.G., 1953: Micrometeorology, McGraw Hill, New York.

Sziecz, G., G. Endrodi, and S. Tajchman, 1969: Aerodynamic and Surface Factors in Evaporation. Water Resources Res., 5, 380-394.

Tanner, C.B., 1963: Basic Instrumentation and Measurements for Plant Environment and Micrometeorology. Soils Bulletin, 6, Univ. of Wisconsin.

Tanner, C.B., 1963a: Energy relations in Plant Communities in Environmental Control of Plant Growth. L.T. Evans, ed., Academic Press, New York, 141-148.

Tanner, C.B., and W.L. Pelton, 1960: Potential Evapotranspiration Estimates by the Approximate Energy Balance Method of Penman. J. Geophy. Res., 65, 3391-3413.

Thom, A.S., 1971: Momentum Absorption by Vegetation. Quart. J. R. Meteor. Soc., 97, 414-428.

Wonnacott, T.H., and R.J. Wonnacott, 1972: Introductory Statistics, 2nd ed. John Wiley and Sons Inc.