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Published in:
Boundary-Layer Meteorology

DOI:
10.1007/BF00123816

Citation for published version (APA):
Jacobs, A. F. G., & van Boxel, J. H. (1988). Computational Parameter Estimation for a Maize Crop. *Boundary-Layer Meteorology*, *42*(3), 265-279. https://doi.org/10.1007/BF00123816

COMPUTATIONAL PARAMETER ESTIMATION FOR A MAIZE CROP

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(Received in final form 29 June, 1987)

Abstract. During a whole growing season, the evolution of the displacement height, d, and roughness length, z_0, of a maize crop has been estimated by a measurement programme. The results have been used to check different types of existing models to calculate these parameters from canopy characteristics only; a simple geometric model and two matching models have been investigated. A geometric model is based on geometric features of the surface only. After a simple modification, the geometric model gives good results for the displacement height as well as for the roughness length.

A matching model, based on gradient-diffusion theory, yields good results for the displacement height. The roughness parameter, however, is overestimated by 17%. By a simple modification, the model results could be improved considerably.

A matching model, based on a second-order closure procedure, yields excellent results for the displacement height and good results for the roughness length. But it appears that, when applying this model, the plant density index and plant area density distribution as a function of height must be well known.

1. Introduction

If a terrain is horizontally homogeneous, the flow above the surface can be described by the well-known log-profile (e.g., Monin and Yaglom, 1973):

$$u(z) = u_*/k\,(\ln((z - d)/z_0) - \psi((z - d)/L))\,. \qquad (1)$$

Here, u_* is the friction velocity which, physically, represents the shear stress, τ, ($\tau = \rho u_*^2$, where ρ is density) and k is von Kármán's constant which is taken as 0.41 in the present paper (Högström, 1985; Wieringa, 1980). The parameter z_0 characterizes the aerodynamic roughness of the underlying surface and d is the displacement height. The function ψ is a correction for the thermal stability effect, where L is the Obukhov length scale.

Usually, z_0 is interpreted as a length scale that characterizes the efficiency for removing momentum from the flow and d is interpreted as the effective level of the underlying surface. The introduction of z_0 and d in Equation (1) is well established; they are commonly used as descriptive parameters, whose physical significance has never been quite clear (Jacobs and Schols, 1986).

For example, several physical interpretations have been made for the displacement height. Thom (1971) suggested from a wind tunnel experiment that d could be identified with the mean height in the vegetation on which the bulk aerodynamic drag acts. Shaw and Pereira (1982) checked this hypothesis in a numerical experiment and found agreement with this idea.

To obtain a better physical understanding of the parameters z_0 and d, several models have been suggested. Marunich (1971), quoted by Tajchman (1981), defined d as the

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vertical displacement of the trajectory of an air parcel as it passes from a smooth reference surface (with $d = 0$) to the rough surface under consideration. This idea is tied to the requirement of a hypothetical smooth surface. This restriction was overcome by De Bruin and Moore (1985) by applying a modified mass conservation idea to the air flow (involving a transition layer). This idea was applied to a 18.5 m pine forest and proved to yield realistic results.

One of the earliest physical models used to calculate z_0 was that of Lettau (1969), in which a simple geometrical description was given of the mean roughness elements. Lettau checked his model results with Kutzbach's (1961) bushel basket experiments over frozen lake Mendota and found agreement within $\pm 25\%$.

Most models to estimate z_0 and d are based on a matching technique; the wind profile above the crop is matched at the interface with the flow regime within the crop. Examples are the model of Seginer (1974) and the model of Goudriaan (1977) who both applied a log-profile to describe the above-canopy flow and Inoue's model (1963) to describe the canopy flow regime. Beside geometrical parameters like canopy height and leaf area index, LAI (total area of one side of all plant leaves per unit ground area), aerodynamic parameters like drag coefficient of plant elements and an intrinsic mixing length were introduced. Generally speaking, the matching models are more complex but they also give a better understanding of the physical meaning of d and z_0.

Most of the existing models never have been checked systematically. The objective of the present paper is to compare some existing models with experimental evidence. That is why in 1985, during a whole growing season from bare soil condition to harvest condition, the evolution of z_0 and d have been followed for a maize crop (Zea mays L.; Vivia).

Wind speeds were measured at 15 levels with small cup anemometers. The cup-type anemometers were designed at the laboratory of Physics and Meteorology; the starting speed is 0.20 m s^{-1} and the first-order response distance (66%) is 0.90 m. The fluxes of momentum and heat were estimated by a sonic anomemometer/thermometer of Kayo–Denki. To obtain unique values for d and z_0, two independent techniques were combined: the log-fitting technique and the eddy correlation technique. The maize crop was planted in narrow rows; row spacings were 0.75 m and plant distances were 0.11 m (12 plants per unit ground surface). More experimental details as well as the applied calculation technique to estimate d and z_0 can be found elsewhere (Jacobs and Van Boxel, 1987).

In the following, two types of models are checked with the data set. In the first place, a simple geometric model is applied and checked, and secondly, two matching models are used. The mass conservation model of De Bruin and Moore (1985) could not be checked because measurements within the crop were not available.

2. Model Results

2.1 GEOMETRIC MODEL

Agricultural crops mostly consist of a large number of roughness elements with an irregular shape and which are distributed more or less uniformly over some area. To define z_0 and d from the geometrical description of such a complex terrain is hardly possible. That is why geometric models are based on a mixture of common sense, intuition and some experimental experience (Businger, 1977). As a first rough estimate of z_0, Lettau (1969) proposed the simple relation:

$$z_0 = 0.5hS/A\,, \tag{2}$$

where, h is the height of the crop, S the silhouette area of the average roughness element, and A the lot area taken up by the individual roughness element. Koloseus and Davidian (1966) found $z_0 \sim (S/A)^n$, where, for stiff obstacles, the exponent, n, varies from 0.90 (cubes) through 0.97 (spheres) to unity for several other forms of obstacle elements. So for stiff obstacles, a linear or near-linear relation between z_0/h and S/A was to be expected. The constant 0.5 in Equation (2) was suggested to represent the mean drag coefficient of the mean roughness element.

Businger (1977) extended this result by observing that S can generally be expressed as being proportional to h^2. For a tall and dense crop, the flow field will be displaced; consequently, a better effective height for the roughness elements felt by the displaced flow field will be $(h - d)$, where d is a measure for the displaced height of the flow by tall vegetation. Finally, the expression for z_0 proposed by Businger is:

$$z_0 = 0.5C_1(h - d)^3/A\,, \tag{3}$$

where C_1 is a geometrical constant which is supposed to be related to the geometry of the vertical cross-section, or in other words related to d/h.

If the flow is displaced, the dimensionless displacement, d/h, must be some function of the density, S/A, of the crop or of h^2/A since $S \sim h^2$; the larger the value of S/A, the higher the dimensionless displacement d/h. Subsequently assuming the simplest relationship (Businger, 1977):

$$d = 0.5hSA = C_2h^3/A\,, \tag{4}$$

where C_2 is a second geometrical constant which is supposed to be related to the horizontal cross-section.

It is recognized that Businger's relationship is based on roughness elements which are more or less uniformly distributed in the horizontal, and that this may to some extent include a random distribution. Our experiments, however, were executed above a row crop so that it is to be expected that the model results may deviate from the experimental evidence. For example, the measurement results may show a wind direction dependency. In order to exclude, as much as possible, effects from the row structure as well as from individual plant elements, only wind profile data above the so-called roughness layer z_*

(Tennekes, 1982) has been used in the analysis, where $z_* = d + 10z_0$. That is probably why the final experimental results did not show a significant wind direction dependency. This result agrees, more or less, with that of Marshall (1971) who showed in a wind tunnel experiment that the total shearing stress for regularly and randomly distributed roughness elements did not deviate much. Only for slim obstacles with a diameter/height ratio of the elements, D/H, of less than 1 was there a slight discrepancy.

Using the data set, Equation (4) can easily be checked by plotting the results on log-log graph paper, which has been done in Figure 1. Also in Figure 1, the regression line has been depicted for crop heights greater than 0.15 m ($\ln(h) > -1.9$). From these results it can be concluded that for a low maize crop, with heights less than 0.15 m, it is of no use to define a displacement height; the crop is very sparse and it is much more convenient to define a roughness length only.

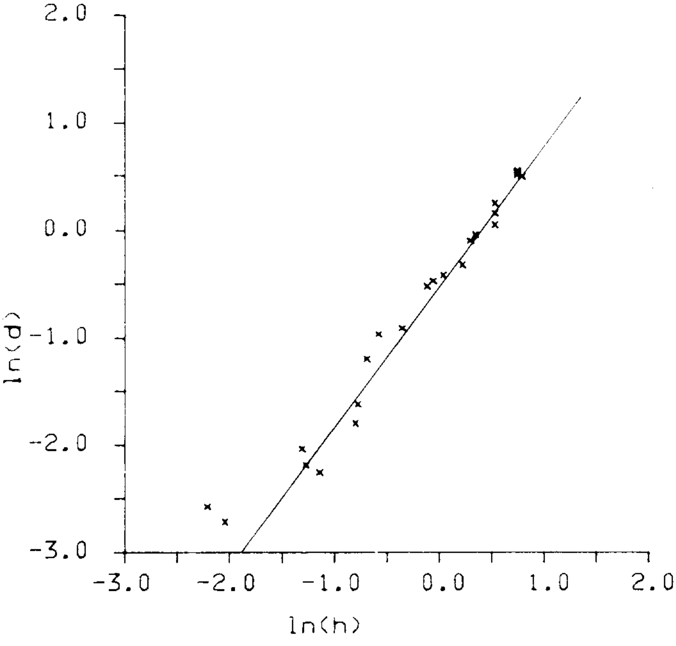

Fig. 1. The displacement height, d, as a function of the height, h, of a maize crop. —— regression line $d = 0.63h^{1.3}$ for $h > 0.15$ m.

The regression line in Figure 1 results in $\ln(d) = 1.3 \ln(h) + \ln(0.63)$ with a correlation coefficient $r = 0.99$ (number of points: 22). The exponent 1.3 deviates considerably from the value 3 proposed by Businger (1977). Hence, it can be concluded that for a maize crop the dependence of the dimensionless displacement, d/h, on the plant density, S/A, is according to the exponent 0.15 which is much weaker than the linear relationship originally suggested by Businger (1977). In addition, this result differs from that found

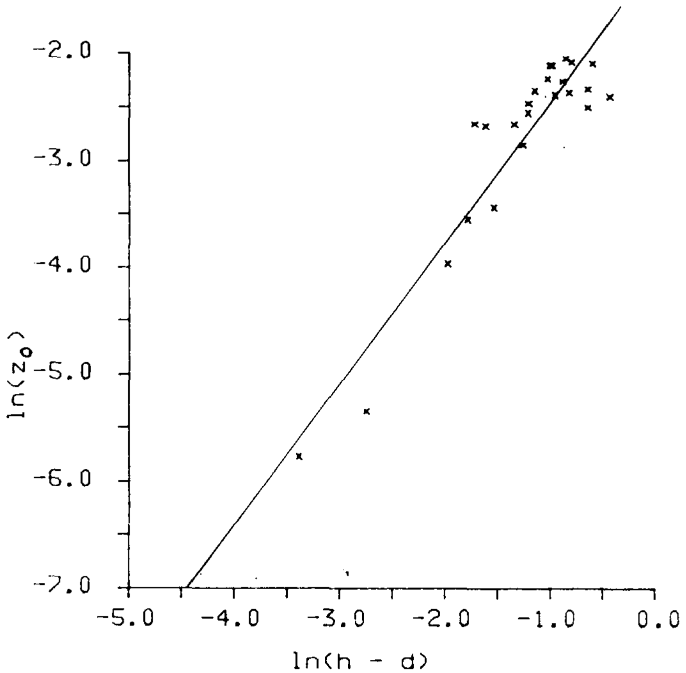

Fig. 2. The roughness parameter, z_0, as a function of the effective roughness length scale, $(h - d)$, of a maize crop. —— regression line $z_0 = 0.33(h - d)^{1.3}$.

for artificial bluff-rough obstacles as was found by Kutzbach (1961). Kutzbach gave the line of best fit for the bushel-basket experiments $d/h = 1.1(S/A)^{0.3}$.

The same procedure can be undertaken for the roughness length, z_0. In Figure 2 the results have been plotted in a log-log graph and, in addition, the regression line for all results is shown. Here, d represents results of our measurements. The regression line in Figure 2 results in $\ln(z_0) = 1.3 \ln(h - d) + \ln(0.33)$ with a correlation coefficient $r = 0.93$ (number of points: 24). In this result, the exponent 1.3 also deviates considerably from the value 3 proposed by Businger (1977). In addition, it is to be noted that the exponent in the relation between z_0 and $(h - d)$ is the same as was found in the relation between d and h. Finally, it is interesting to note that while exponents differ considerably, Businger (1977) also suggested the same value of the exponent (3 in his case) for the relationship between z_0 and $(h - d)$ and between d and h.

2.2 MATCHING MODEL BASED ON GRADIENT-DIFFUSION THEORY

Under thermally neutral conditions, the flow above a crop can be described by Equation (1) in which the stratification effect, ψ, is omitted. Inside the crop, the flow regime is dependent on a large number of parameters (Inoue, 1963) like the relative turbulence intensity, i_w, the intrinsic mixing length, l_m, inside the crop, the drag coefficient per leaf, C_d, and the leaf area density, L_d (one-sided leaf area per m^3 air of LAI/h). If the parameters mentioned are independent of height, the momentum equation inside the crop, in which the momentum flux is based on gradient-diffusion theory, can be solved analytically to yield (Inoue, 1963; Cionco, 1965):

$$u(z) = u(h)\exp(-a(1 - z/h))\,, \tag{5}$$

where, $u(h)$ is the mean windspeed at crop height and a is, physically speaking, an extinction coefficient for windspeed which is given by:

$$a = ((C_d L_d h)/(2 l_m i_w))\,. \tag{6}$$

Inoue's solution does not satisfy the boundary condition at the ground; however, it proved to be a fair approximation to the upper layer of a dense canopy (Seginer, 1974).

If the shape of the leaves and the leaf area density of a crop are known, the mean space distance between the plant material can be estimated; according to Goudriaan (1977), this length scale can be considered as the mean intrinsic mixing length, l_m, within the crop. For a crop with long and narrow leaves, for example grass and maize, this length scale is given by (Goudriaan, 1977):

$$l_m = ((4w)/(\pi L_d))\,, \tag{7}$$

where w is the mean width of the leaves.

If the flow field, the exchange coefficient and windspeed gradient above the canopy are matched at the interface with the inside regime, the displacement height and roughness length can be expressed explicitly in crop parameters and canopy flow characteristics only (Goudriaan, 1977) as follows:

$$d = h - (l_m i_w h/a)^{0.5}/k \quad \text{and} \quad z_0 = (h - d)\exp(-h/(a(h - d)))\,. \tag{8}$$

The model results for the displacement height have been plotted against the measurement results in Figure 3 as well as the line $x = y$. In the calculations, the drag coefficient $C_d = 0.20$ is the value given by Wilson and Shaw (1977) and the relative turbulence intensity $i_w = 0.30$ is the value given by Shaw *et al.* (1974a) in the upper layer of a maize crop. From this graph, it can be seen that the displacement model yields correct d values. Only for small values ($d < 0.4$ m) does the model deviate considerably from the measurement results.

In our analysis, a value of the relative turbulent intensity of $i_w = 0.30$ was used. As Shaw *et al.* (1974b) state, the experiments were made in September when the structure of the crop was quite different from that of a healthy crop; hence the crop may not be representative of that during the major portion of its growth cycle. Consequently, uncertainty exists in applying the value $i_w = 0.30$ in the model calculations. On the other hand, the same relative turbulent intensity was found by Inoue (1981) for an immature maize crop with a height of 1.4 m. That is why it was decided to use the value of $i_w = 0.30$ in Goudriaan's model.

Displacement heights of $d < 0.4$ m agree with a drag coefficient per unit ground surface, *cah*, of *cah* < 0.25, where *cah* $= C_d$ LAI. The value *cah* $= 0.25$ lies close to the criterion for sparse vegetation of *cah* $= 0.32$ found by Shaw and Pereira (1982) in a

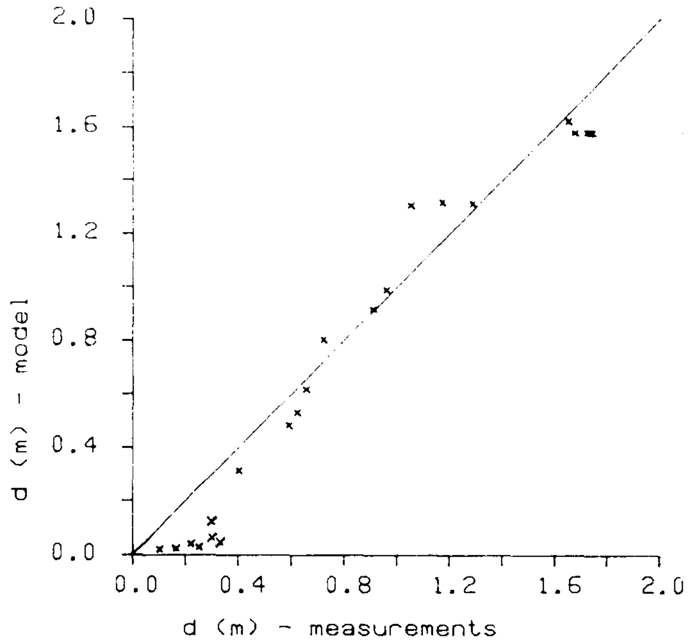

Fig. 3. The model results according to Goudriaan's model for the displacement height during a whole growing season, compared with the measurement results.

computer experiment and lies between the criterion for sparse vegetation given by Kondo and Akashi (1976) of *cah* = 0.5 for their *B-c* canopy and the criterian of *cah* = 0.125 of Seginer (1974). According to Goudriaan's model and the measurement results, we can conclude that sparse maize vegetation can be defined as having *cah* < 0.25. This implies that by applying this model for a crop with a *cah* < 0.25, it is more convenient to define a roughness parameter only.

It should be noted that the last result differs from that found with the geometric model. The geometric model yielded a criterion for sparse vegetation at vegetation height $h = 0.15$ m which agrees with a *cah* = 0.125, the criterion given by Seginer (1974).

For the results in Figure 3, where *cah* > 0.25, the following regression line without zero bias is found: d(model) = 0.97d(measurement) with a correlation coefficient of $r = 0.97$ (number of points: 15). The model slightly underestimates the measurement results by 3%; hence, we can conclude that for a dense maize crop (*cah* > 0.25), Goudriaan's model describes the displacement height well.

In Figure 4, model predictions of the roughness length have been plotted versus the measurement results as well as the line $x = y$. Here, $d = 0$ has been taken for all values where *cah* < 0.25 and the calculated d values according to Equation (8) have been taken in the cases of a dense crop (*cah* > 0.25).

The regression line without zero bias yields z_0(model) = 1.17z_0(measurement) with a correlation coefficient of $r = 0.97$ (number of points: 24). From this result, it can be

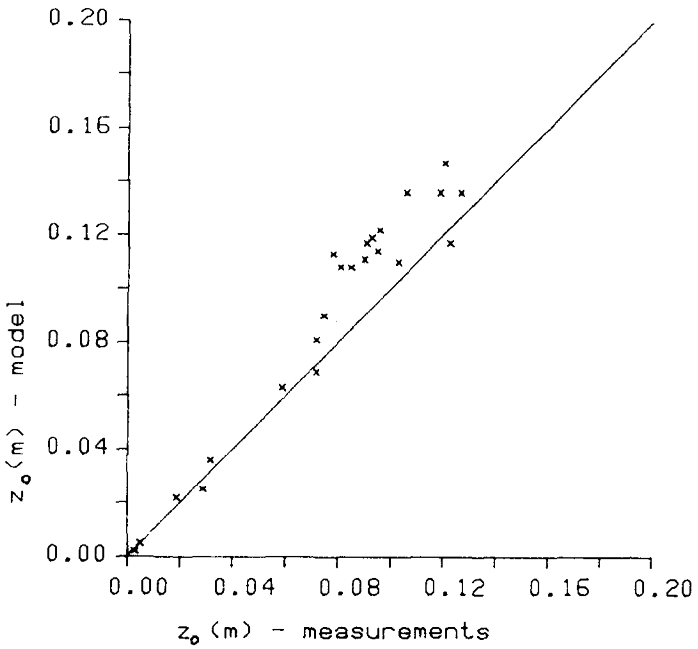

Fig. 4. The model results according to Goudriaan's model for the roughness parameter, z_0, during a whole growing season, compared with the measurement results.

seen that Goudriaan's matching model overestimates z_0 on average by 17%. In addition, from Figure 4 it can be seen that agreement is excellent for roughness lengths with $z_0 < 0.08$ m, which agrees with *cah* < 0.25, i.e., for sparse vegetation for which *d* is taken as zero in the model calculations. Hence, it is likely that the discrepancy between model and measurement results is caused by underestimation of the calculated displacement heights.

From Equation (8), it can be shown that the calculated z_0 values are very sensitive to small changes of the calculated *d* values. In the foregoing, it was shown that the displacement model underestimates the measurements by 3%. An underestimation in the displacement height implies an overestimation of the z_0 values because both parameters are highly negatively interrelated (Jacobs and Van Boxel, 1987; Legg and Long, 1975).

If, however, the z_0 model is used with modified displacement heights which are increased by 3%, an unbiased regression line is found: $z_0(\text{model}) = 0.998 z_0(\text{measurement})$ with a correlation coefficient of $r = 0.94$. In other words, it can be concluded that in fact the z_0 model produces correct values for the roughness parameter of a maize crop. The modified z_0 results are plotted in Figure 5.

2.3 MATCHING MODEL BASED ON SECOND-ORDER CLOSURE PROCEDURE

To describe the flow inside a crop, Inoue (1963) applied gradient-diffusion theory. However, a crop environment is complex; consequently, the crop flow field is complex

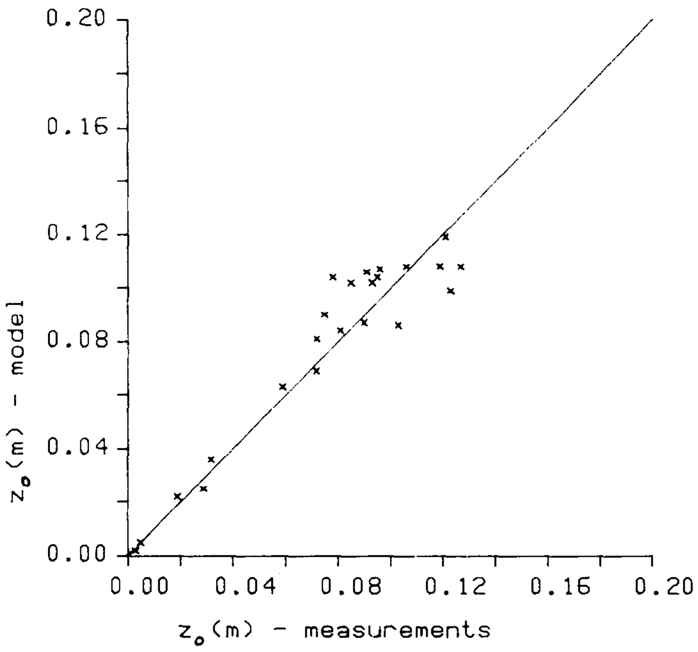

Fig. 5. The modified results according to Goudriaan's model for the roughness parameter, z_0, compared with the measurement results.

as well. Additional terms, like for example a pressure term, emerge in the momentum equation for the flow within the crop canopy (see, e.g., Raupach and Thom, 1981). These terms are not taken into account in Inoue's solution. A better flow solution within the crop canopy is obtained by applying a second-order closure procedure as for example has been carried out by Wilson and Shaw (1977). Shaw and Pereira (1982) applied this second-order closure model and by using Equation (1) for the flow above the crop, they were able to calculate d and z_0 parameters as functions of the plant area index, PAI (total area of the one side of all material per unit ground area) and the plant area density distribution (the distribution of PAI with height).

A maize crop appears to have a plant area density distribution which approaches a triangular form with height quite closely (Shaw *et al.*, 1974a). Examples of these distributions are given in a non-dimensionized form in Figure 6. Shaw and Pereira computed z_0 and d over a range of triangular plant area density distributions and over a range of plant area indices. Their computed results for d and z_0, as presented in their Figures 4 and 5, have been compared with our data set.

The results of the displacement height and the line $x = y$ have been plotted in Figure 7. Here, the data of Pereira and Shaw (1982) have been used where the plant area density distribution has a maximum at the level $z_{\max} = 0.5h$.

For these results, the following unbiased correlation line has been found: d(model) = 0.93d(measurement) with a correlation coefficient of $r = 0.99$ (number of

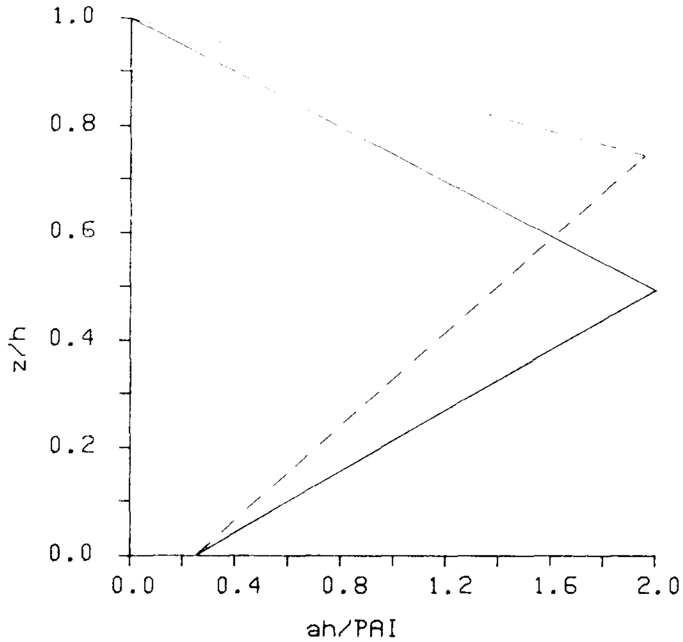

Fig. 6. Non-dimensional graph of examples of schematic triangular plant area density distributions as a function of height according to Shaw and Pereira (1982). —— $z_{max} = 0.5h$; – – – $z_{max} = 0.75h$. The area under each curve is equal to 1.

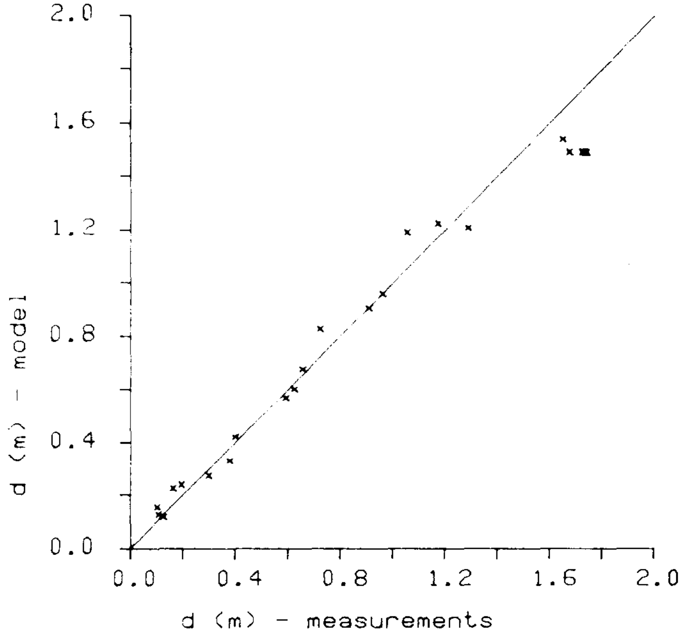

Fig. 7. The model results according to a second-order closure procedure for the displacement height compared with the measurement results. The plant area density distribution has been taken constant during the whole growing season and has a triangular form with height with a maximum at $z_{max} = 0.5h$.

points: 22). From these results, it can be concluded that the correlation between both data sets is excellent but that the model underestimates the measurements by 7%.

The model calculations of the roughness parameter according to Shaw and Pereira (1982) (with maximum plant area density at $z_{max} = 0.5h$) have been compared with the measurement results and are plotted in Figure 8. The following unbiased correlation line has been found: $z_0(\text{model}) = 1.34z_0(\text{measurement})$ with $r = 0.90$ (number of points: 22). From Figure 8 it is clearly shown that the model predicts the roughness parameter well for small roughness lengths ($z_0 < 0.09$ m) but for large roughness values, the model overestimates the measurement results considerably.

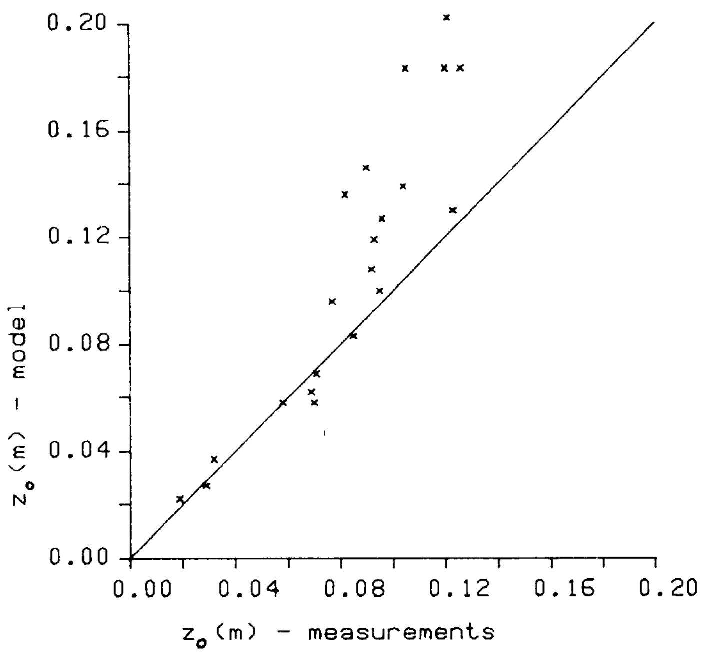

Fig. 8. The model results according to a second-order closure procedure for the roughness parameter compared with the measurement results. The plant area density distribution is the same as in Figure 7.

During the experiment, the initial distributions of the plant area density as a function of height were close to a triangular form where the maximum density occurred at the height $z_{max} = 0.5h$. This result for a maize crop agrees with that found elsewhere in the literature (see, e.g., Monteith, 1976); Shaw *et al.*, 1974a). However, towards the end of the vegetative period of the maize plants (after about 50 days), the cobs started to develop and, meanwhile, the lower level of plant leaves started to senesce. As a consequence, the level with the maximum plant area density shifted to a relatively higher level. During the experiments, the maximum level shifted gradually from $0.5h$ to $0.75h$. Hence, it is better to undertake comparisons with a time-variable plant area density distribution.

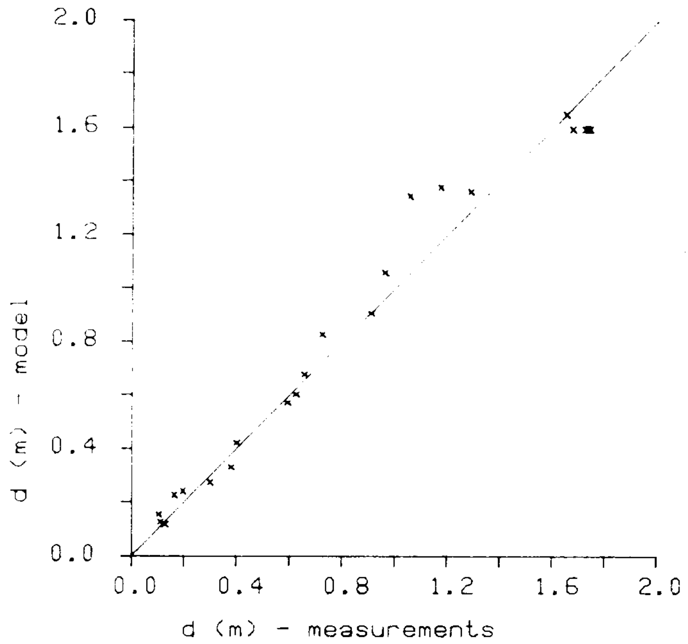

Fig. 9. The displacement model results according to a second-order closure procedure with a time-variable plant area density distribution.

The model results for the displacement height, using a time variable plant area density distribution, have been plotted in Figure 9. The unbiased regression line is found to be: d(model) = 0.996d(measurement) with a correlation coefficient of $r = 0.98$. From this result, it can be concluded that with a time variable distribution (or better expressed, with a realistic plant area distribution), the model yields correct displacement heights.

The model results for the roughness parameter, using a time variable plant area density distribution, have been plotted in Figure 10. The unbiased regression line is found to be: z_0(model) = 1.07z_0(measurement) with a correlation coefficient $r = 0.92$. From this result, it can be concluded that the model overestimates the measurements by 7% which, for the estimation of the roughness parameter, is encouraging. Moreover, it can be concluded that it is very important to have accurate information about the evolution of the real plant density distribution within the crop, because the model is rather sensitive to this parameter.

3. Conclusions

A geometric model is based on geometric features of the surface only. It yields, after modification, good results for the displacement height as well as for the roughness parameter. For a maize crop, the relation between the dimensionless displacement, d/h,

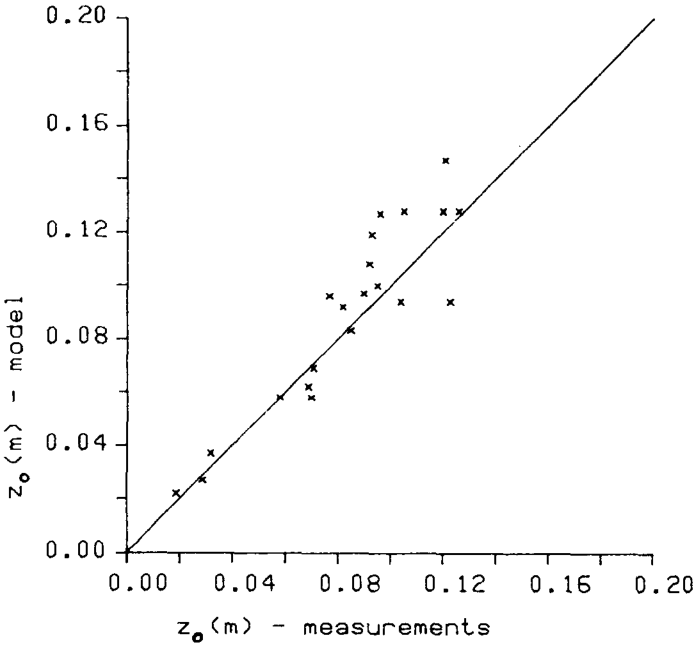

Fig. 10. The roughness length model results according to a second-order closure procedure with a time-variable plant area density distribution.

and the plant density, S/A, proved to be $d/h \sim (S/A)^{0.15}$, which is much weaker than the linear relationship originally suggested by Businger (1977).

For the geometric model, displacement height predictions deviate from the measurement results for sparse vegetation where $cah < 0.125$; cah is the drag coefficient per unit ground surface. Hence, by applying this model, it is recommended to define only a roughness parameter (z_0) and not an associated d value if $cah < 0.125$. The value $cah = 0.125$ agrees with Seginer's criterion for sparse vegetation.

Goudriaan's matching model is based on simple gradient-diffusion theory. In this model, some bulk plant characteristics (leaf area index and leaf area density) and some canopy flow characteristics (canopy turbulence intensity and drag coefficient) have been taken into account. Goudriaan's model yields displacement heights which are underestimated by 3%. The roughness parameter, however, is overestimated by 17%. In addition, it appears that the model for the roughness parameter is very sensitive to small changes in displacement height. For a maize crop, the model yields correct roughness parameters if the calculated displacement heights are increased by 3%.

Goudriaan's model predictions for displacement height deviate from the measurement results for sparse vegetation if $cah < 0.25$. Hence, when applying the model it is recommended that only a roughness parameter (z_0) be defined and not an associated d value if $cah < 0.25$. The value, $cah = 0.25$, lies close to the criterion for sparse vegetation, $cah = 0.32$, found by Shaw and Pereira (1982) in a computer experiment.

The matching model of Shaw and Pereira is based on a second-order closure procedure. In this model, canopy characteristics (plant area index and plant area density distribution) and canopy flow characteristics (canopy turbulence intensity and drag coefficient) have been taken into account.

The second-order closure model underestimates the displacement by 7%, if a constant plant area distribution ($z_{\max} = 0.5h$) for the whole season is used. However, if a time-variable plant area distribution is used, the model describes the measurement results excellently: (d(model) = 0.996d(measurement)). The roughness parameter is overestimated by 7% if, during the growing season, a time-dependent plant area density distribution is used.

The second-order model results are sensitive to the plant area density distribution. Hence, it must be emphasized this plant characteristic should be estimated with great care during an experiment.

Acknowledgements

During the investigations, one of us, J. H. v. B., was supported by the Working Group on Meteorology and Physical Oceanography (MFO) with financial aid from the Netherlands Organization for Advancement of Pure Research (Z.W.O.).

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