Environmental Research Center Papers

Number 3

1983

Environmental Research Center
The University of Tsukuba

AERODYNAMICAL PROPERTIES OF AN AIR LAYER AFFECTED BY VEGETATION*

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(received 17 December, 1982)

ABSTRACT

Over flexible vegetation, during windy conditions, a coupling of the airflow and the vegetation takes place. This builds up the waving form of the canopy surface in addition to producing streamlining and fluttering phenomena. Consequently, it may be estimated that the aerodynamic properties vary with the wind speed. This is one of the most striking phenomena of the airflow over a canopy.

In order to investigate the above problems, some measurements are carried out at the heat and water balances observation field in the Environmental Research Center of the University of Tsukuba, in 1978 to 1980. The main subjects of the measurements are the wind profile above and within a pasture canopy and the fluctuation of the vertical wind just over a canopy. Additionally, the author takes VTR films of the displacements of a plant showing simulteneous measurements of the wind velocity fluctuations. Further, for the purpose of verification of the theoretical relationships, a numerical solution of the wind profile is solved and compared with results of the field experiments.

At first, by the concept that the eddy diffusivity is uniquely decided by the leaf area density, the roughness length and the zero-plane displacement are defined as:

$$z_0 = h\left(\frac{k}{\beta\Gamma}\right)^{\frac{1}{m-1}} \exp\left(\frac{k\Gamma}{m-1}\right),\quad d = h\left[1-\left(\frac{k}{\beta\Gamma}\right)^{\frac{1}{m-1}} \exp\left(\frac{mk\Gamma}{m-1}\right)\right].$$

After the theoretical consideration, the following topics are evaluated. (1) From the static treatment of z_0 and d, their normalized parameters ζ_0 and δ can be approximated by: $\zeta_0 = 0.07$, $\delta = 0.04$. (2) The effective roughness parameter, $\eta = \zeta_0/(1-\delta)$, increases with an increase of the surface friction. For a pasture canopy, the above parameter is smaller than those of other canopies. This suggests that the pasture canopy contributes less effectively to aerodynamical roughness than does other canopies. But for an actual, the values approximated above are vary with the wind conditions. (3) For an actual canopy, the following equations are estimated:

$$\zeta_0 = (0.72\,\Gamma)^{3.08} \exp(-1.23\,\Gamma),\quad \delta = 1-(0.72\,\Gamma)^{3.08} \exp(-0.83\,\Gamma).$$

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These equations show that the normalized roughness length decreases and the normalized zero-plane displacement increases with the nondimensional rapidity respectively. (4) The peak value of the normalized spectrum is increasing with the wind speed and its frequency increases with an increase in the wind speed under the relation of $n_m = 0.71\ \bar{u}_h$. Further, the value of the dominant wavelength just over a canopy (λ_m = 1.41, for the present study) is in accordance with that of already researched. (5) The maximum reduced frequency is well represented by use of the variation of the wind speed. Namely, $f_m = \exp\ [0.50\ (3.02 - \Gamma)]$, This indicates that vegetations affect the airflow above a canopy and modity the above canopy turbulence. (6) Maximum frequency of the displacement of a leaf (n_m = 1.2 Hz) agrees well with that of the vertical wind fluctuation (n_m = 1.4 Hz). It is generally accepted that the former contributes to the latter just over a canopy. (7) From the integration of an ordinary differential equation, close agreement between the observed and the calculated wind profile is obtained. Consequently, a result which supports the validity of the theoretical relationships is verified.

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LIST OF SYMBOLS

Roman alphabet

A, A'	nondimensional constant.
a	leaf area density or nondimensional constant.
a'	nondimensional constant.
b'	nondimensional constant.
C_D	drag coefficient for vegetations.
C_d	drag coefficient for individual roughness.
d	zero-plane displacement.
F	luxuriant degree.
f	reduced frequency.
f_m	reduced frequency at which $nS_w(n)/\sigma_w{}^2$ is a maximum with variable value of zero-plane displacement.
f'_m	reduced frequency at which $nS_w(n)/\sigma_w{}^2$ is a maximum with constant value of zero-plane displacement.
g	acceleration of gravity.
h	plant height or mean obstacle height.
h'	deviation of plant height.
K_M	eddy diffusivity of momentum.
k	Kármán constant (k = 0.4).
L	Monin-Obukhov length.
l	mixing length.
ln	logarithm to the base e.
m	nondimensional constant.
n	frequency or nondimensional constant.
n_m	frequency at which $nS_w(n)/\sigma_w{}^2$ is a maximum.
Ri	Richardson number.
r	luxuriant length.
S	specific area.
S_d	leaf area index.
S_w	power spectral density function of vertical wind.
s	silhouette area.
$\bar{u}$	mean wind speed in the longitudinal component.
u', w'	wind fluctuations in the longitudinal and vertical components.
$\bar{u}_h$	mean wind speed at plant height.
u_*	friction velocity.
X, Y	co-ordinates in the longitudinal and vertical components.
z	height above ground surface.
z_0	roughness length.

Greek alphabet

α	nondimensional constant.
β, β', β''	nondimensional constant.
Γ	nondimensional rapidity.
δ	normalized zero-plane displacement.
ζ	normalized height or stability parameter.
ζ_0	normalized roughness length.
η	effective roughness parameter.
η'	nondimensional constant.
$\bar{\theta}$	mean absolute temperature.
θ'	temperature fluctuation.
λ	nondimensional constant.
λ'	nondimensional constant.
λ_m	wavelength at which $nS_w(n)/\sigma_w^2$ is a maximum.
ρ	air density.
σ_w	standard deviation of vertical wind speed.
τ	vertical momentum flux.
τ_s	sampling duration.
ϕ_M	stability function for momentum.

CHAPTER 1

INTRODUCTION

1-1 Review of the previous studies

It has been noted that the values of the roughness length z_0 and the zero-plane displacement d change systematically with the wind speed, when they are determined from wind profiles measured above a uniform stand of vegetation. Many observations on this phenomenon have done by Rider (1954) for oat fields, Tani et al. (1954, 1956) for rice fields, Yoshino (1957, 1958) for small topography, Penman and Long (1960) for wheat fields, Allen (1968) for Japanese larch, Thom (1971) for bean fields, Saugier and Ripley (1978) for short grass and so on. Additionally, Long et al. (1964), Udagawa (1966) and Maki (1969) have discussed the seasonal variation of z_0 and d. They pointed out that the variation of z_0 and d followed closely with the stage of growth of crop plants as well as wind speed.

On the other hand, according to Monteith (1975, 1976), in recent years various efforts have been made to describe the characteristics of atmospheric turbulence in the surface boundary layer and in the canopy layer, in order to understand the micrometeorological environment of plants. Concerning this point, Inoue (1952) introduced the concept of turbulon to establish the similarity laws of the experimental works. Uchijima and Wright (1964) observed the skewness and the kurtosis of the horizontal wind in a maize canopy and Show et al. (1974) examined the turbulent intensity within a corn field. They indicated that increasing wind speed influences the wind fluctuation differently at upper and lower levels within a canopy. In addition, Maitani (1977a, 1977b, 1977c) showed the existence of downward transport of turbulent kinetic energy just above a canopy. Tajchman (1981) discussed about actual problems of measuring the turbulent exchange in and above forests. Hicks and Wesely (1981) reported the slightly greater surface momentum flux detected over the rougher surface.

Theoretical investigations about z_0 and d may be replaced by the analysis of problems in evaluating the eddy diffusivity K_M within a canopy. With regards to this point, Inoue (1963), Saito (1964), Cionco (1965), Takeda (1966), Cowan (1968), Kondo (1971), Oikawa (1978) and Albini (1981) confirmed the idea that properties of K_M are affected by differences of vegetation. Furthermore, Kotoda (1979), Kotoda and Hayashi (1980), Hayashi (1980), Hayashi and Kotoda (1980) and Hayashi (1982) discussed the validity of z_0 and d using the concept that K_M is uniquely defined by the profiles of leaf area density.

1-2 Extent and purpose

In the analysis of wind structure in the lowest layers of the atmosphere, it is advantageous to regard some horizontal layers where individual relationships of physical amount are established. In the beginning, we will discuss the details of airflow above a roughness surface. The surface boundary layer is defined as the lower friction layer or constant shearing stress layer, in which the wind structure is strongly influenced by the nature of the surface and thermal conditions. In addition to this fact, it is possible to observe the formation of a new boundary layer generated under the surface boundary layer, if the ground is covered by vegetations. Inoue (1963), named it a canopy-eddy layer since it is influenced significantly by the canopy elements. The phenomenon generated in the layers mentioned above, i.e. surface boundary layer and canopy-eddy layer, will be treated in this investigation.

Natural ground surfaces are covered by arrays of original roughness elements protruding from the ground surface. The airflow over the surface builds up a peculiar vertical wind profile due to the drag, characterized by the individual roughness elements. From another point of view, tall roughness elements formed by flexible vegetation are deformed with increasing wind speed. When the wind reaches an inherent speed for the canopy, it may cause a change in the aerodynamic properties of the surface boundary layer. Simultaneously, under these conditions, roughness elements interfere with each other and then create a modification in turbulence above and within a canopy.

In general, a change in z_0 and d with wind occures for a fully rough surface. For a pasture canopy, in order to confirm this anticipation, the variation in z_0 and d with the friction velocity u_* is described. The results show that z_0 increases slightly with an increase in u_*, and d diminishes with an increase of u_*. This is due to the phenomenon of winds penetration more into the canopy as u_* increases and also to the fact that the height of the aerodynamic surface, d, becomes lower. From the experiences of the previous investigations, the present paper intends quantitatively to clarify the interrelationships between flexible roughness elements and an airflow above it under variation of wind speed.

CHAPTER 2

FIELD EXPERIMENT AND DATA REDUCTION

2-1 Vertical profile and turbulence observation

Measurements were carried out at the heat and water balances observation field in the Environmental Research Center of the University of Tsukuba, Ibaraki, Japan. The observation field is over 20,000 m^2 and circular in shape with a diameter of 160 m (Kotoda et al., 1978). Three observations were made in August of 1978, 1979 and 1980 as tabulated in Table 1. The main subjects of the observations were the wind profile above and in a canopy, the fluctuation of vertical wind just above a canopy, and the deformation of plants. Average heights of pasture grass (*Secale cereale*) were in the range of 0.46 m to 0.55 m.

Table 1 Summary of observations.

Observation period	Canopy height (m)	Main subject of observation	Main instrument
August 9 to 20, 1978	0.46	Wind profile above a canopy	Cup anemometer Thermister thermometer
August 8, 1979	0.55	Wind profile within a canopy	Hot-wire anemometer Resistant thermometer
August 5, 1980	0.50	Turbulence over a canopy Deformation of plants	Sonic anemometer-thermometer Video camera

Profiles of the wind speed and the air temperature above vegetation were measured during the observation period from August 9 to 20, 1978. The canopy height was about 0.46 m.

The lowest layers of the atmosphere may continually readjust to a new set of surface properties. Therefore we must be aware of the point that a boundary layer of air, influenced by the new surface, grows downwind from the changed surface. A measuring mast was located in a position to take advantage of the longest unobstructed fetch against the wind during the observation period. It was arranged to get 90 m to 110 m of fetch. The location of the mast and its surroundings are shown in Fig. 1.

In this study, vertical wind profiles were obtained with sensitive three-cup anemometers (photo detection type, starting velocity 0.2 m/s) mounted on arms pointing east and at mast heights of 0.5 m, 1.0 m, 2.0 m, 4.0 m and 8.0 m above the ground. The temperatures were measured by setting thermisters in ventilated cylinders and installing them on the mast at the same heights as the anemometers. Previously, thermometers were calibrated in a water bath controlled by a thermostat. The wind direction was sensed at the top of the mast at 8.0 m.

Measurements were taken at 10 minutes intervals during the period. Accumulated analog data was changed into digital form by an A-D converter and transmitted from a junction-box to the observation room. This data was listed by a digital printer and registered in the disk file of a

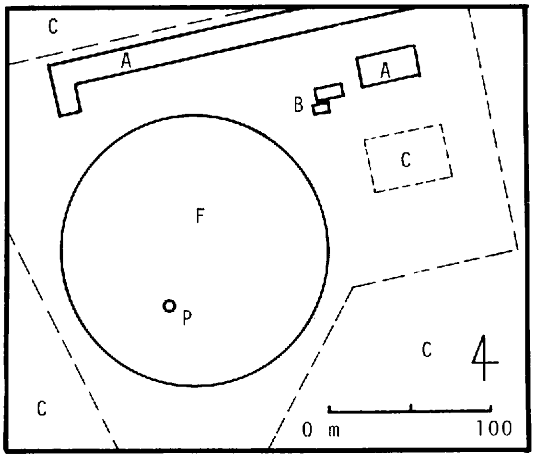

Fig. 1 Location of the measuring mast and its surroundings in 1978.

computer. Because of the intention to make data uniform in quality, data was selected by specific selection criteria. These criteria are: (1) the 10 minutes mean wind speed must be greater than 0.5m/s at 0.5 m above the ground, (2) the wind direction is between ENE (67.5°) and E (90.0°) at the mast, (3) near neutral thermal stratification, i.e. $|Ri| \leqslant 0.03$, where Ri represents the Richardson number defined as follows:

$$Ri = \frac{g\dfrac{d\bar{\theta}}{dz}}{\bar{\theta}\left(\dfrac{d\bar{u}}{dz}\right)^2} \qquad (1)$$

were $\bar{\theta}$ is the mean absolute temperature, z the height above the ground surface and $\bar{u}$ the mean horizontal wind speed. To evaluate the Richardson number, we used the values at z = 0.5 m to 4.0m. By the above criteria, in 1978, 62 records were selected for this analysis from the data taken continuously during the observation period (Appendix A).

On August 8, 1979, the vertical profiles of the wind speed within a canopy were measured with two sets of hot-wire anemometers at the same observation field as was used in 1978. One set was two-channel hot-wire anemoneter, used in conjunction with an X-probe. Its sensing elements were 5 μm diameter tungusten wires. This anemometer was fixed just above the canopy at a height of 0.55 m. The other set of anemometer was one-channel hot-wire, equipped with winding platinum wire, and also with a frame which protects the wire from leaves or stems of the canopy elements. This anemometer was mounted on a vertical traverser and sensed within the canopy. Fig. 2 shows the installations.

The anemometer signals were linearized and corrected for temperature fluctuations. The compensated signals were recorded on an analog tape recorder for future processing and analysis.

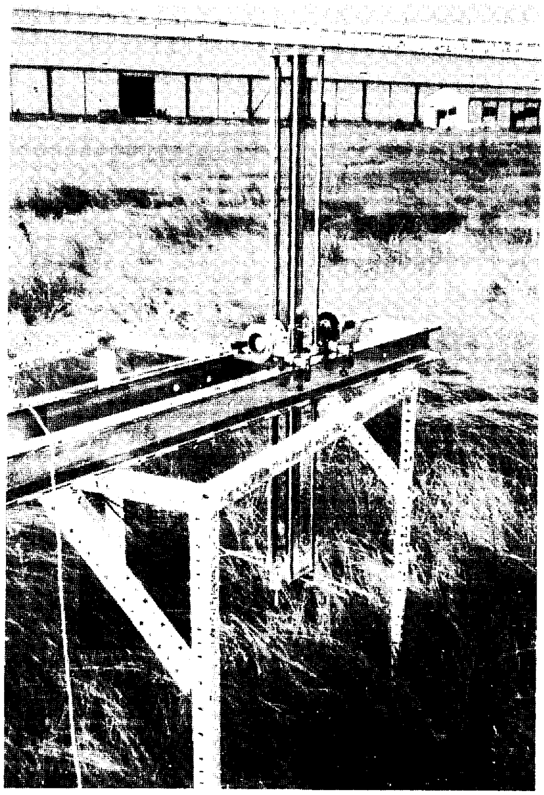

Fig. 2 Installation of the observation for the wind profile within a canopy in 1979.

It can be expected that the shape of a wind profile within a canopy essentially depends on the value of the mean wind speed at canopy height. Consequently, in advance, four ranges of the wind speed were set up as follows:

Range I	$2.0\ \mathrm{m/s} \leqslant \bar{u}_h < 2.5\ \mathrm{m/s}$
Range II	$1.5\ \mathrm{m/s} \leqslant \bar{u}_h < 2.0\ \mathrm{m/s}$
Range III	$1.0\ \mathrm{m/s} \leqslant \bar{u}_h < 1.5\ \mathrm{m/s}$
Range IV	$0.5\ \mathrm{m/s} \leqslant \bar{u}_h < 1.0\ \mathrm{m/s}$

Where $\bar{u}_h$ is the mean wind speed at $z = h$ and h the plant height. The averaging time for the vertical profile within a canopy was selected as 10 seconds.

The turbulence observations were carried out on August 5, 1980, at the same field as in 1978. Average heights of the pasture canopy was about 0.5 m, with stumps homogeneously planted in the field, having a leaf area index (LAI) of 0.63. The wind direction was E during the observation periods in 1980, so that the position of a measuring point allowed about 90 m of fetch over the field.

In the atmospheric boundary layer, several techniques to measure turbulent fluctuations and turbulent fluxes directly have been developed in the past 30 years (Businger et al., 1967; Businger et al., 1969; Hanafusa et al., 1982). The measurement of three components of fluctuating wind velocities and temperature fluctuations just over the canopy were carried out by use of a three-dimensional sonic anemometer-thermometer (SAT), with a sensing path of 0.2 m. From these wind velocity components, the horizontal wind speed and wind direction were obtained by a vector synthesizer unit. Further, using a digital computer, the instantaneous momentum flux and sensible heat flux were evaluated. This data was recorded at a sampling rate of 20 times per second on magnetic tape by a data acquisition system for heat and water balances observation system (Kotoda et al., 1978).

A set of SAT was mounted at 0.5 m above the ground surface. The installation is shown in Fig. 3. The records were analyzed for a typical duration of 50 seconds, and the statistical quantities such as the mean, the variance, the standard deviation, the skewness and flatness were calculated. Run names and analyzed periods are shown in Table 2.

Simultaneously, the displacements of a mark on a pasture leaf were taken at intervals of 1/60 seconds, using a video tape recorder (VTR) set at a height of 1.0 m above the ground. The

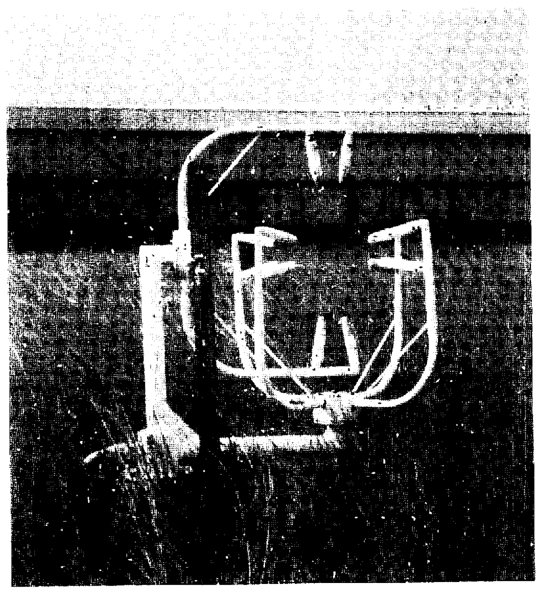

Fig. 3 Installation of the observation for the turbulence measurement over a canopy in 1980.

Table 2 Analyzed period on August 5, 1980.

Analyzed period	Run name	Case number
9h20m00s – 11h45m50s	Run A	174
12h00m00s – 15h30m50s	Run B	180
17h10m00s – 18h00m50s	Run C	61

VTR system on the field is shown in Fig. 4. The records were played back at 20 frames per second for analysis. The picture outputs from the VTR were analyzed by a two-dimensional position analyzer operated continuously throughout the observation period. Then the vertical and longitudinal displacements of plants were calculated. Subsequently, the wind velocity fluctuations and the displacements of a canopy surface were compared.

Fig. 4 VTR set on the pasture field for the observation of the deformation of plants in 1980.

2-2 Data selection for turbulence analysis

The dependence of wind fluctuation statistics on sampling duration and stability conditions must be taken into consideration. In practice a value approaching the true value may be achieved, if the sampling duration and averaging times are respectively long enough and short enough in comparison with the characteristic time-scale of a subject of study. The former is dependent on the stationarity of the fluctuation and the latter dependent on instrumental response. As the averaging time is fixed at 0.05 seconds here, we will try to discuss the sampling duration as follows.

For the purpose of evaluating typical statistical values designated by the waving phenomenon treated in a following section, one thing which we would like to emphasize at this stage is that the sampling duration must be as short as possible. This is because the waving phenomenon appears intermittently, within the range of the wind speed observed here. Consequently, we empirically set the sampling duration at 50 seconds.

The variations of u_* and σ_W with the sampling duration τ_s were constructed from records of the observation in 1980. Where σ_W is the standard deviation of the vertical wind speed. An analysis over 300 seconds from such records is shown in Fig. 5. The basic data were selected from near neutral conditions and the averages of u_* and σ_W calculated for sampling durations of 2, 5, 15, 30, 60, 100 and 150 seconds. In each case the standard deviation of the averages is represented by a

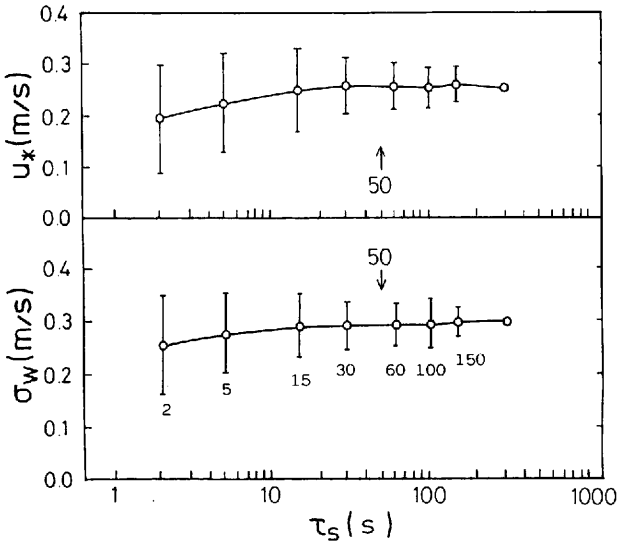

Fig. 5 Growth of u_* and σ_w with the sampling duration τ_s.

vertical straight line extending above or below the circle. The mean values for different sampling durations appear to follow an increase in relation to the sampling duration τ_s. At the point τ_s = 50 seconds, it is clear that the mean value may represent 98% of the averages over 300 seconds.

Subsequently, we must consider the effects on the thermal stratification on fluctuation statistics. The stability parameter ζ is defined by the flux elements as follows:

$$\zeta = \frac{z-d}{L} = \frac{-kg(z-d)(\overline{\theta' w'})}{\bar{\theta}(-\overline{u'w'})^{3/2}} \tag{2}$$

Where L is the Monin-Obukhov length, k the Kármán constant, g the acceleration of gravity, θ' the temperature fluctuation, u' and w' the wind fluctuations in the longitudinal and vertical component respectively. In nature, the average height of plant canopies varies with the instantaneous wind speed. Therefore, the value of d may be change. However, with regard to the stability parameter as in Eq. (2), we use the mean value of d evaluated by the profile technique used in 1978's observation.

The variance σ_w/u_* as a ralation of ζ is shown in Fig. 6. In general, the standard deviation of the vertical component σ_w, can be viewed as systematically related to such factors as the mean wind speed, the nature of the surface, and the stability of the atmosphere. For ideal conditions of flow over a level uniform surface, in thermally neutral conditions, the similarity arguments suggests that in the surface layer σ_w should be determined uniquely by the friction velocity as follows:

$$\sigma_w = A' u_* \tag{3}$$

where A' is a constant. According to Pasquill (1974), at various sites, and using a variety of instru-

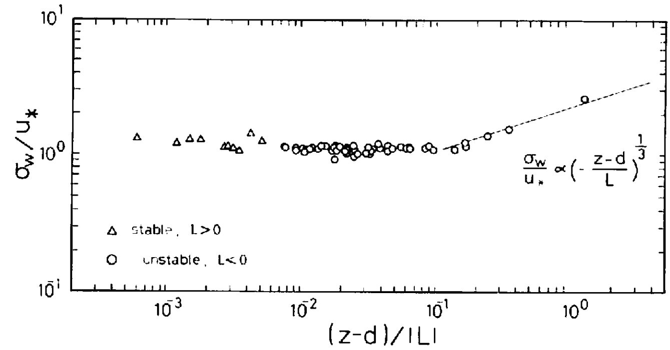

Fig. 6 Variation σ_w/u_* as a relation of $(z-d)/L$, where the solid line indicates the free convection regime of $\sigma_w/u_* \propto [-(z-d)/L]^{1/3}$.

ments, the average values of A' fall within the fairly narrow range of 1.2 to 1.4 and suggest an overall mean value near 1.3. On this point, we got the mean value of $A' = 1.2$ for the present study, which agrees with the above suggestion. Under the unstable conditions, the value of σ_w changes with the increase of an upward heat flux and establishes a regime of free convection where the velocity fluctuations are greater than at neutral condition by a factor of $(-\zeta)^{1/3}$. In Fig. 6, the regime mentioned above, in the range of $\zeta < -0.01$, is portrayed by a solid line. On the other hand, under the stable conditions, it seems the fluctuation of σ_w/u_* changes with similer relation observed in the unstable condition. However, in the present study, the relation is not clear because of the lack of data in the observed range of $\zeta < 0.005$. If we discuss the fluctuations of turbulence, allowing for a factor of safety, we can conclude that near neutral conditions correspond with a range of $-0.030 \leqslant \zeta \leqslant 0.003$ at $z = 0.5$ m with $d = 0.18$ m.

In the case of the statistical treatment of fluctuation of turbulence, it is necessary to assume a steadiness of the airflow. So more restriction must be made for further analysis, adding to the conditions which maximize the rationality about the smapling duration of 50 seconds. Namely we adopt the following criterion for the restriction, i.e. the absolute value of the skewness of the vertical fluctuation is less than or equal to 0.15. Finally from all observations, 107 cases were selected for turbulence analysis (Appendix B).

2-3 Reduction of roughness length and zero-plane displacement

Generally, we presume that the wind speeds are expressed by the logarithmic wind profile equation in an air flow over uniform surface under neutral condition. So that two parameters, i.e. z_0 and d, are found by plotting u against the logarithm of z. The value of d is required by a straight line plots, i.e. u against $\ln(z - d)$. The corresponding value of z_0 can then be found from the intercept of this line on the vertical axis. The log law can be applied within a reference boundary layer, if the fetch is not long enough.

For the observation in 1978, to examine a distortion in the logarithmic profile, an example (Case No. 7, Appendix A) is shown in Fig. 7. It seems that the top value is too large to agree with the logarithmic profile. Here, it is a necessary discussion whether the value observed at 8.0 m must be included for the evaluation of z_0 and d. Considering the zero-plane displacement, we can get the sum of the residuals for the regression line. By the data observed at four levels (exclusive of 8.0 m), the residual is smaller than by five levels (inclusive of 8.0 m). As seen from above example, we must exclude the cases which deviate from the logarithmic profile.

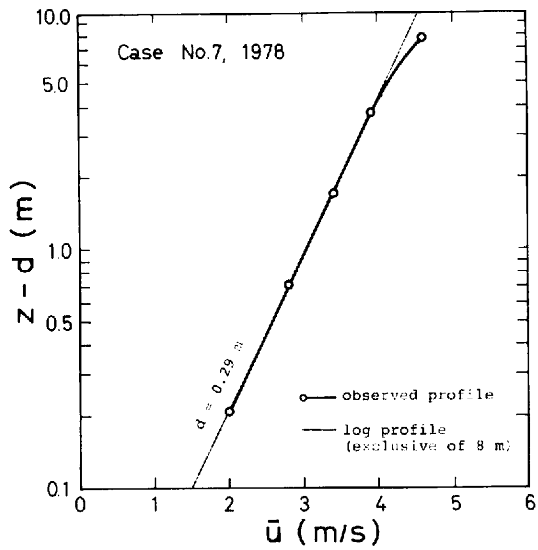

Fig. 7 Deviation of the wind speed from logarithmic wind profile.

Though we made an specific selection for the wind direction (Section 2-1), a tendency that the upper wind is relatively high was recognized in some cases. Accordingly, we must define the roughness length and zero-plane displacement by lower four values for further analysis.

CHAPTER 3

SOME STRIKING PHENOMENA OF THE AIR-CANOPY INTERACTION

3-1 Deviation of friction velocity over a canopy surface

Assuming z_0 and d are constant with rapidity, the linear equation, $u_* = A\bar{u}_h$, is rewritten from the log law. Where A is a constant. On this point, some linear relationships between $\bar{u}_h$ and u_* have been reported by Hicks (1976), Maki (1976), Maitani (1977a) and Saugier and Ripely (1978) over the ground, and by Emmanuel (1975) over the sea. Furthermore, Udagawa (1966) proposed the proportional expression $u_* \propto u_h{}^n$, where the value of n is closely related to the leaf area density.

From the observations in 1978, the relationship between $\bar{u}_h$ and u_* is shown in Fig. 8 by solid curve. The dotted line, in Fig. 8, describes the relation $u_*=0.18\ \bar{u}_h$, taking the value of $z_0 = 0.03$ m and $d = 0.18$ m. If we assume that the pasture canopy is in an aerodynamically steady state, the friction velocity is in direct proportion to the wind speed. But for an actual canopy, the friction velocity settles down and deviates from the linear relation. Accordingly, the relation between $\bar{u}_h$ and u_* are fitted by as follows, $u_* = 0.18\ \bar{u}_h{}^{0.84}$.

From the observations in 1980, we also represent the dependence of u_* with $\bar{u}_h$ as shown in Fig. 8. The observed data are fitted by a broken line as follows, $u_* = 0.17\ \bar{u}_h{}^{0.86}$.
From the fact mentioned above, a characteristic tendency that the friction velocity increases almost exponentially with the wind speed appears.

It may be asked, "What is the difference in quality between the linear and exponential relation?" Two main causes for the deviation of the value of u_* are considered in the following two paragraphs.

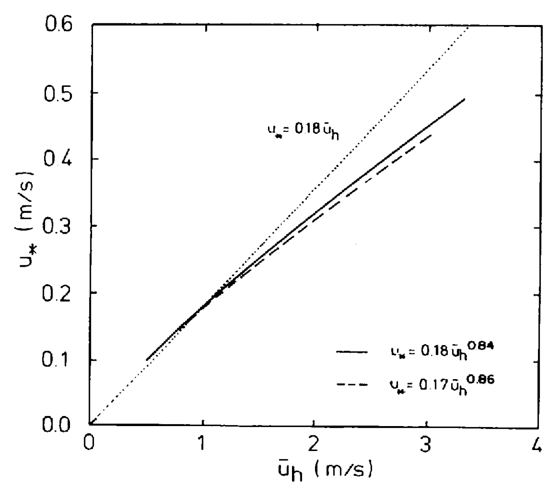

Fig. 8 Dependence of the friction velocity on the wind speed. Thick solid line: in 1978 by cup anemometer, broken line: in 1980 by SAT.

For the first cause, we suppose that a flexible vegetation is deformed by the wind at a certain speed and that vertical clearance between the mean height of the canopy and the measuring point is expanded. Consequently, the apparent $\bar{u}_h$ increases. For the observation in 1978, to evaluate the degree of the expansion, following calculations were made as a trial. That is we are concerned with the affected canopy height h' under conditions in which the wind speed $\bar{u}_h$ = 2.0 m/s becomes $\bar{u}_h$ = 2.5 m/s with a constant value of u_* = 0.38 m/s. In this case the ratio of the wind speed is 0.8. Using the value of z_0 and d corresponding to the condition of $\bar{u}_h$ = 2.5 m/s, we get an answer of h' = 0.36 m by compensation for the deviation of the upper level of the canopy. Then we can evaluate the clearance $(h - h')$ as equivalent to 0.1 m.

For the second cause, the canopy, constructed by the flexible vegetation, is exposed to wind and the individual leaves are deformed with an increase in wind speed. At the same time the deformation may be thought of as being mainly associated with streamlining effects. Moreover, when the wind reaches an inherent speed, it may turn into wave motion. Under these conditions, the canopy surface becomes smoother than at a certain state and then momentum transport decreases just over the surface. Consequently, at a certain wind speed, an aerodynamic regime may appear, and then the friction velocity becomes not so large value.

In general, there will be some cases where there is no distinction between them. On this point, a consecutive study by Thom (1968) has clarified that the attack anlge of a leaf is a main function of the drag coefficient. Quantitatively, when the leaf surface was facing the airstream, the drag was five times as much as the case when it was in the direction of the airstream. Here, it may be reasonable to estimate that the reduction of the friction velocity above a canopy is induced by streamlining and fluttering effects in the windy conditions.

3-2 Deformation of plants

In order to investigate the vertical displacement of a plant, the author took VTR films of the fluctuating leaves with every 0.05 seconds. An example of the time variation of the instantaneous displacement of pasture grass is shown in Fig. 9. The wind direction was almost perpendicular to the facing direction of the VTR camera. As indicated in Fig. 9, the fluctuations within periods of 1.0 ~ 1.2 seconds prevail in the vertical (Y) and longitudinal (X) components of the displace-

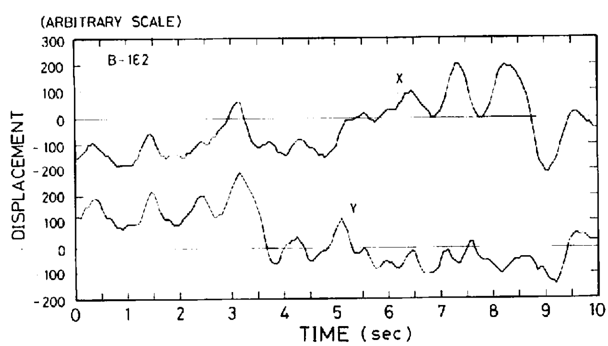

Fig. 9 Time variation of the instantaneous displacement of a leaf, where X is in longitudinal and Y is in vertical.

ments. Further, small variations are superimposed on the prevailing fluctuations so that the displacements are not always parallel to each other.

At 0.05 seconds intervals, the scattering points of a mark painted on a leaf are plotted in Fig. 10. This corresponds with case B-162 of $\bar{u}_h$ = 2.41 m/s. The co-ordinates are in arbitrary scales of displacements. Dotted values indicate the number of overlapped points. It can be estimated from Fig. 10 that the envelope of the points is fan-shaped and its occupied area expands in accordance with the degree of deformation of vegetation. The root of a plant is placed at down right side on the co-ordinates.

Fig. 11 shows the mean position of a series of observations (B-162 ~ B-165) and its standard deviation along the co-ordinates. The straight line indicates the standard deviation over the data set in centimeters. The displacements of 50 seconds mean are more scattered than the standard deviation (about 4 cm) in each sampling time. The correlation between the vertical displacement and $\bar{u}_h$ is not recognized in the present observation.

In order to obtain a relationships between the vertical wind fluctuation and the displacement of a leaf, the normalized power spectra of the displacements is shown in Fig. 12. In this figure, the displacement of the X-component and Y-component are represented by a broken and solid line respectively. The value of the frequency response of the Y-component shows a remarkably high peak at n = 1.2 Hz. On the other hand, the shape of the X-component shifts toward a low frequency with a relatively low peak at n = 0.9 Hz. To discuss the aerodynamic features of the air layer just above a canopy, we must take notice of the displacement of the Y-component rather than the X-component. As discussed above, it is clear that a leaf constructed of the canopy moves with a period of about 0.8 seconds in a relatively high wind.

The problem of the dominant frequency for a waving plant has been studied by Maitani (1979) and Sato et al. (1980), getting the values of n = 0.80 Hz and n = 1.25 Hz for the obser-

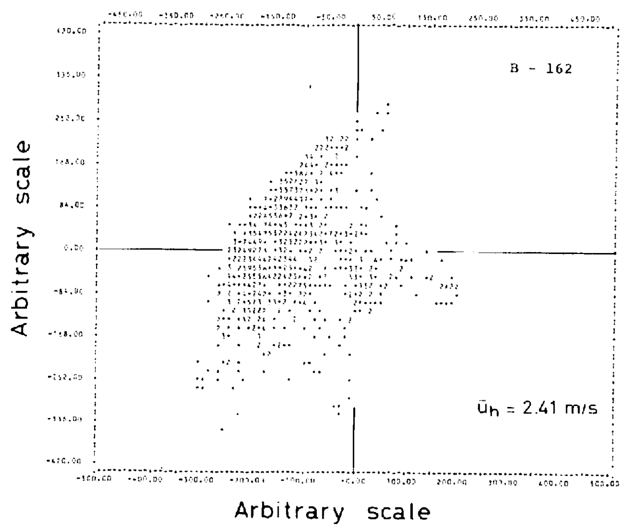

Fig. 10 Scatter of the displacements of a leaf at 0.05 seconds intervals, where the numbers mean the overlapped data.

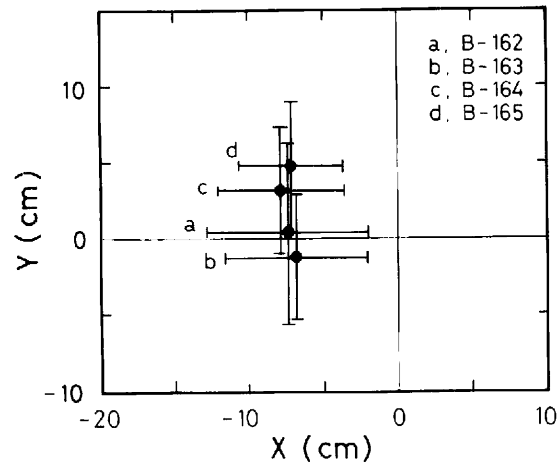

Fig. 11 Mean positions of the displacements of a leaf and their standard deviations in the co-ordinates. The mean wind speed are as follows: 2.41 m/s (B-162), 1.91 m/s (B-163), 2.21 m/s (B-164), 1.96 m/s (B-165).

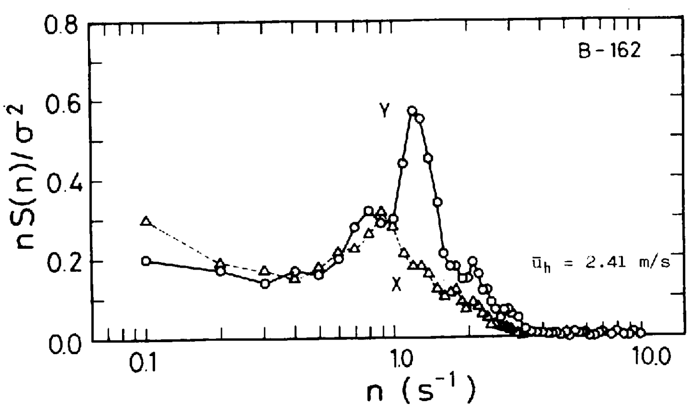

Fig. 12 Normalized spectum of the displacement of a leaf. Here solid (○) and broken (△) lines are in Y and X-component respectively.

vations over a wheat field and a paddy field respectively. Maitani (1981) showed that the spectrum of the strain rate of plant has a remarkably high peak at about $n = 1$ Hz, corresponding to the natural frequency of rice plants. Tani (1963) dealt with the models for several plants and estimated that their natural frequency are about 1 second. Considering the fact that pasture grass is more flexible than other vegetation, the present value of $n = 1.2$ Hz is consistent with the values which have been evaluated.

CHAPTER 4

THEORETICAL CONSIDERATIONS

4-1 Physical parameters within a canopy

The theoretical study of surface boundary layers above a horizontally homogeneous surface, in an idealized steady state, has been described by the Monin-Obukhov similarity theory. According to this theory, with thermal stratification, the following equation can be generalized:

$$\frac{d\bar{u}}{dz} = \frac{u_*}{kz}\,\phi_M\left(\frac{z}{L}\right) \tag{4}$$

where $\phi_M(z\ /\ L)$ is the universal function. If steady and horizontally uniform conditions are assumed, the quantity u_* is independent of height. Under neutral conditions, introducing the values of z_0 and d, the vertical wind profile above a canopy is represented by the integrated form of Eq. (4):

$$\bar{u} = \frac{u_*}{k}\ln\left(\frac{z-d}{z_0}\right) \tag{5}$$

In the canopy-eddy layer, the following basic equations are arranged by:

$$\tau = \rho\,K_M\frac{d\bar{u}}{dz} \tag{6}$$

$$\frac{d}{dz}\left(\frac{\tau}{\rho}\right) = \alpha\,a\,C_d\bar{u}^2 \tag{7}$$

$$K_M = \beta\,\zeta_0{}^m\bar{u}h\,(1-ra) \tag{8}$$

where K_M is the eddy diffusivity of momentum and τ the vertical transfer of momentum defined by $\tau = \rho u_*{}^2$. ζ_0 is the normalized roughness length, i.e. $\zeta_0 = z_0/h$, h the mean height of vegetation, and a the leaf area density (LAD) of vegetation elements including leaves and stems. It can be assumed that, for a vertically heterogenious canopy, mean LAD varies continuously with height. C_d is the drag coefficient for individual roughness elements, ρ the air density and α, β and m are nondimensional constants, r is the luxuriant length, which is newly defined. The product ra denotes the degree of the extinction effect against momentum transfer, assumed to take a value between 0 (open case without vegetation) and 1 (closed case caused by completely dense growth of vegetation).

The eddy diffusivity of momentum K_M is defined by the ratio of the momentum flux τ to its concentration gradient ρ $(d\bar{u}/dz)$ as expressed by Eq. (6). This is also established within a canopy as well as above a canopy. Further, the momentum flux τ, i.e. the drag force per unit horizontal area, for an existing plant canopy can be written in the form:

$$\tau = \rho S_d C_d\bar{u}^2 \tag{9}$$

Eq. (7) is equivalent to Eq. (9), if the value of leaf area index (LAI) S_d is given by:

$$S_d = \int_{z_1}^{z_2} a dz \tag{10}$$

When we put 0 into the right side of Eq. (7), it defines constant flux and is suitable only for use above a canopy.

Next, we consider the eddy diffusivity of momentum itself. According to the Prandtl hypothesis, the eddy diffusivity of momentum is defined as follows (Sutton, 1953):

$$K_M = l \sqrt{\overline{w'^2}} \tag{11}$$

where w' is the vertical component of turbulence and l is the mixing length. Above a canopy, i.e. in the constant flux layer, governed by the relations $\sqrt{\overline{w'^2}} \propto u_*$ and $l = k(z - d)$, K_M can be rewritten as:

$$K_M = ku_* (z - d) \tag{12}$$

On the other hand, within a canopy, we concerned with $\sqrt{\overline{w'^2}} \propto \bar{u}$ and $l \propto h \zeta_0^m (1 - ra)$. Accordingly we can write Eq. (8).

The features of the K_M obtained from the above relation is illustrated in Fig. 13. For a pasture canopy the product ra, i.e. the degree of the extinction effect measured against momentum transfer, becomes larger in the lower part of the canopy-eddy layer. The arrangement of eddy size is affected considerably by the distribution of the product ra. We can see in Fig. 13 that the eddy structure can be conceived of as a set of circular eddies with diameters given by the mixing length, rotating at a tangential speed, with the size of the eddies increasing with height. Here, inhomogeneity of an eddy is not considered in the figure. An actual distribution of a for a pasture grass is shown in the following section.

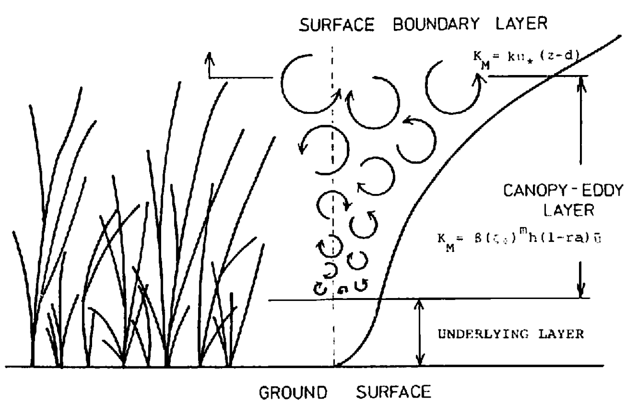

Fig. 13 Definition of the eddy diffusivity of momentum and its extension.

At the level of plant height, we may rewrite Eq. (5) as follows:

$$\frac{\bar{u}_h}{u_*} = \frac{1}{k} \ln \left(\frac{h-d}{z_0}\right) \tag{13}$$

assuming K_M is continually changing and $a = 0$ at $z = h$, we can write Eq. (8) as being equal to Eq. (12). So that, we have:

$$\frac{\bar{u}_h}{u_*} = \frac{k(h-d)}{\beta \left(\frac{z_0}{h}\right)^m h} \tag{14}$$

If we eliminate $\bar{u}_h/u_*$ from Eq. (13) and Eq. (14), we can write the relationship between z_0 and $(h-d)$ as follows:

$$\ln \left(\frac{h-d}{z_0}\right) = \frac{k^2 (h-d)}{\beta \left(\frac{z_0}{h}\right)^m h} \tag{15}$$

where $(h - d) > z_0$. It has shown by Kotoda and Hayashi (1980) that the magnitudes of the parameters m and β may vary with the species of canopy or its degree of growth.

On the other hand, from Eq. (13) and Eq. (14) we can evaluate the values of z_0 and d as a function of $\Gamma\ (= \bar{u}_h/u_*)$:

$$z_0 = h \left(\frac{k}{\beta \Gamma}\right)^{\frac{1}{m-1}} \exp\left(\frac{k\Gamma}{m-1}\right) \tag{16}$$

$$d = h \left[1 - \left(\frac{k}{\beta \Gamma}\right)^{\frac{1}{m-1}} \exp\left(\frac{mk\Gamma}{m-1}\right) \right] \tag{17}$$

where $m \neq 1$. These equations show that the values of z_0 and d can be calculated if Γ is known.

Generally, the drag coefficient of the field C_D can be written in the form:

$$C_D = \frac{\tau}{\rho \bar{u}^2} = \left(\frac{u_*}{\bar{u}_h}\right)^2 \tag{18}$$

The value of C_D is determined by the shearing stress which is equivalent to the drag force act on an air layer just over a canopy. In addition, the value of C_d seems to be attributed to differences in the orientation of leaves which block the airflow, or to the nature of their skin or to the interrelationships of individual leaves of a canopy. As an example, C_d is almost an order of magnitude larger than C_D (Inoue and Uchijima, 1979).

From the simultaneous equations of Eqs. (6), (7) and Eq. (8), we can obtain the wind profile for the canopy-eddy layer, by eliminating τ and K_M from both sides of the equations. Using the above procedures, the wind profile is expressed as follows.

$$\frac{d^2 \bar{u}}{d\zeta^2} - \frac{r}{(1-ra)} \frac{d\bar{u}}{d\zeta} \frac{da}{d\zeta} + \frac{1}{\bar{u}} \left(\frac{du}{d\zeta}\right)^2 - \frac{\eta' a \bar{u}}{(1-ra)} = 0 \tag{19}$$

where $\eta' = aC_d h/(\beta \zeta_0{}^m)$, and ζ is the height from the ground surface to the measuring point, relative to the canopy height. This ordinary differential equation can be solved by forward integration beginning at the surface, if the form of a is defined as a function of ζ.

4-2 Structure of a canopy and determination of its parameter

When we deal with the phenomena above and within a canopy, aerodynamical characteristics of vegetation may be regarded as of major importance. The upper part of Fig. 14 describes the variation of height of a pasture grass during the summer of 1978. A solid straight line denotes the observation period. Just before the experiment, the pasture was cut down and weeded, and the mean height was determined at h = 0.45 m during the observation period. The variation of canopy height follows a pattern similar in total aspect to the results obtained by Paltridge (1970).

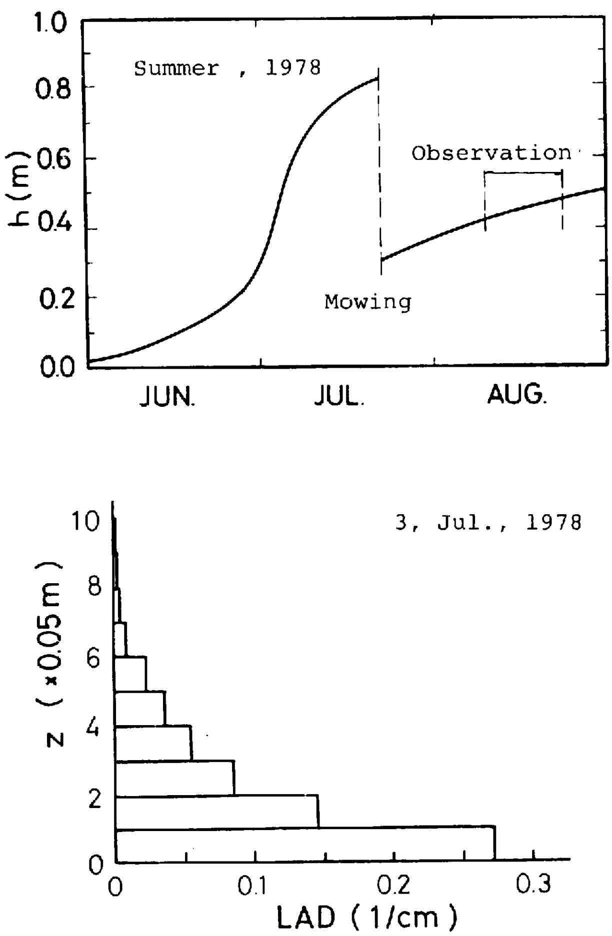

Fig. 14 Upper part: variation of height of a pasture grass, in 1978. Lower part: typical profile of the leaf area density (LAD), observed on July 3, 1978.

Density of the vegetation is usually characterized by the leaf area density (LAD), i.e. the total area of leaves and stalks (counting one side only) per unit volume within a canopy. Practically, the profile of the LAD was measured per unit surface area of 0.4 m^2, in vertical partitions of 5 cm along the stretched leaf, by an automatic area meter. A profile of LAD sampled on July 3, 1978 is shown in the lower part of Fig. 14, which indicates the typical shape of LAD for pasture grass. Specifically, it shows that leaves tend to be located lower in the canopy.

As mentioned in Section 4-1, LAD i.e. a, is one of the most important parameters used to determine the degree of the extinction effect against momentum transfer within a canopy. In order to estimate the value reasonablly, it is necessary to make a few corrections, because the standing shape of individual pasture grass bends under natural conditions even during a calm. Next, we assumed the ideal bent form of a tangential function and compensated for the distortion due to the deviations between the bent and the stretched form. Consequently, a vertical profile of LAD can be expressed effectively by the following polynominal approximation:

$$a = 0.34 - 1.23\zeta + 1.51\zeta^2 - 0.63\zeta^3 \qquad (20)$$

So that we can calculate the leaf area index (LAI) of 3.1, by integrating Eq. (20).

From Eq. (15), we can evaluate the value of λ by using the following nondimensional form:

$$\lambda = \beta\zeta_0{}^m = \frac{k^2(1-\delta)}{\ln\left(\frac{1-\delta}{\zeta_0}\right)} \qquad (21)$$

If we get the values of ζ_0 and δ from the observed data, we can estimate the magnitudes of the parameters m and β with the aid of Eq. (21). This is done by putting the values of ζ_0 and δ into the right side of Eq. (21), from which we can evaluate λ as shown in Fig. 15. By the Symplex method, we obtained:

$$m = 0.68, \ \beta = 0.29 \qquad (22)$$

Solid line A in Fig. 15 represents Eq. (21) making use of the observation results.

By the way, the momentum diffusivity K_M is of importance in determining the wind profile within a canopy. Takeda (1966) introduced the following relation as an alternative to Eq. (8).

$$K_M = \beta'\bar{u}h(1-F) \qquad (23)$$

Where β' is a constant and F the luxuriant degree defined by Takeda. On the other hand, Maki (1975) defined the eddy diffusivity of momentum within a canopy as follows:

$$K_M = \beta''\zeta_0\bar{u}h(1-F) \qquad (24)$$

where β'' is a constant. Eq. (23) describes the concept that the value of λ is equivalent to β', i.e. constant with the condition of $m = 0$ in Eq. (21). Using this equation we get the mean value, $\beta' = 0.05$, shown by broken line C in Fig. 15. Additionally under the condition of $m = 1$ in Eq. (21), Eq. (24) denotes $\lambda \propto \zeta_0$ which is shown by dotted line B with $\beta'' = 0.61$.

From the above mentioned facts, it is clearly indicated that the definition of Eq. (8) is reasonable, because the data is in closest agreement with the value calculated by Eq. (21) with Eq. (22).

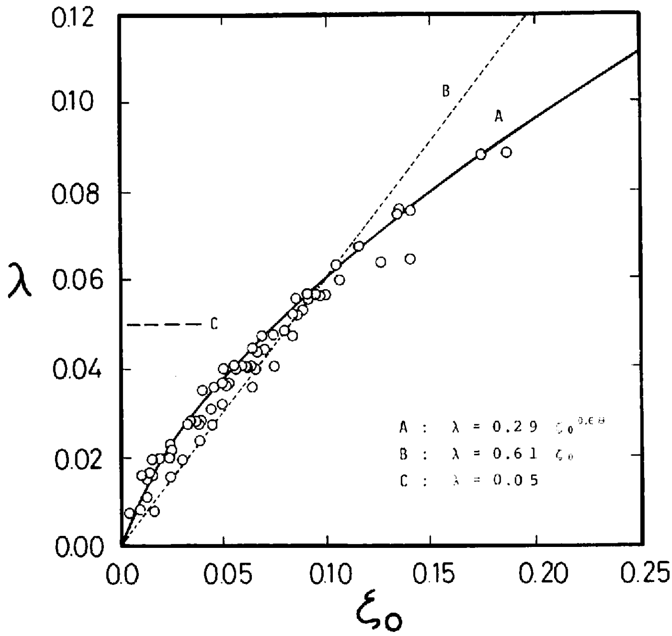

Fig. 15 Relation between normalized roughness length ζ_0 and nondimensional constant λ, where line A, B and C are evaluated from Eqs. (21), (24) and (23) respectively.

4-3 Characteristics of wind profile within a canopy and comparison with numerical solution

In order to investigate the phenomena above and within a canopy, we have assumed three equations as mentioned in Section 4-1. For the purpose of verification of the theoretical relationships in physical amounts, a numerical solution of the wind profile is solved within a canopy and compared with the results of field observation.

First, we will deal with the observed results of 10 minutes mean vertical wind profiles measured by a hot-wire anemometer within a canopy in 1979. Fig. 16. shows mean profiles in the range of I ~ IV which were determined previously in Section 2-1. In the upper half layer of a canopy, it has been shown that the shape of the profile becomes linear with increasing wind speed at the top of canopy.

Next, from three simultaneous equations, i.e. Eq. (6), Eq. (7) and Eq. (8), we obtained the ordinary differential equation of Eq. (19). Then we can solve for the relationship between ζ and $\bar{u}$, if the form of $da/d\zeta$ is determined for a continuous function. Eq. (19) can be solved by forward integration beginning at the ground surface using the Runge-Kutta-Gill method. Before a practical

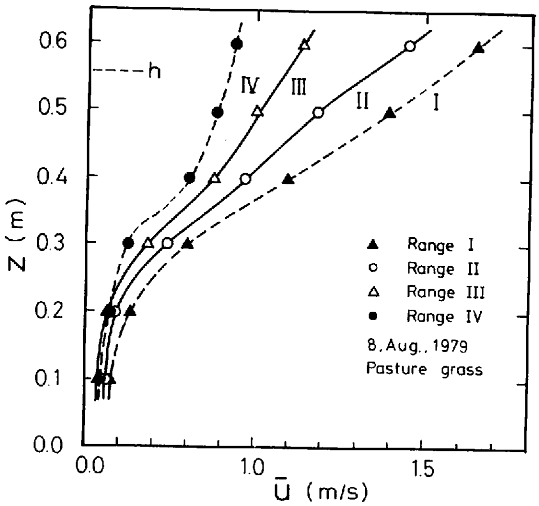

Fig. 16 Vertical wind profiles within a pasture canopy, on August 8, 1979. The symbol h means the height of canopy.
Range I: 2.0 m/s $\leqslant \bar{u}_h <$ 2.5 m/s,
Range II: 1.5 m/s $\leqslant \bar{u}_h <$ 2.0 m/s,
Range III: 1.0 m/s $\leqslant \bar{u}_h <$ 1.5 m/s,
Range IV: 0.5 m/s $\leqslant \bar{u}_h <$ 1.0 m/s.

calculation, it is necessary to check the results obtained by the analytic method. Therefore, some comparisons were made with the Bessel function rewritten from Eq. (19) using the special conditions (Hayashi, 1980). As a result of this consideration, we find that the numerical method is successful in investigating an airflow within a canopy-eddy layer under the more complicated conditions.

For an actual canopy, the following estimations are discussed. Differentiating a with respect to ζ, Eq. (20) becomes as follows:

$$\frac{da}{d\zeta} = -1.23 + 3.03\zeta - 1.89\zeta^2 \tag{25}$$

and then substituting Eq. (25) into Eq. (19), using the procedure of numerical integration demonstrated by Hayashi (1982), a solid line in Fig. 17 is simulated. The underlying condition for the wind profile is set as $\eta' = 40.0$. A broken line expresses the vertical wind profile observed in Range I, i.e. 2.0 m/s $\leqslant \bar{u}_h <$ 2.5 m/s. From the results of integration, there is relatively small underestimation concerning the upper part within a canopy. But a close agreement between the observed and the calculated profiles is obtained.

As mentioned in Section 4-1, parameter η' is in direct proportion to the drag coefficient C_d. Consequently, the vertical wind profile depends not only on the LAD profile but also on the drag coefficient for individual plant surfaces. In order to estimate the dependence, dotted line A and B in Fig. 17 were simulated with the condition of large η' and small η' respectively. The line A

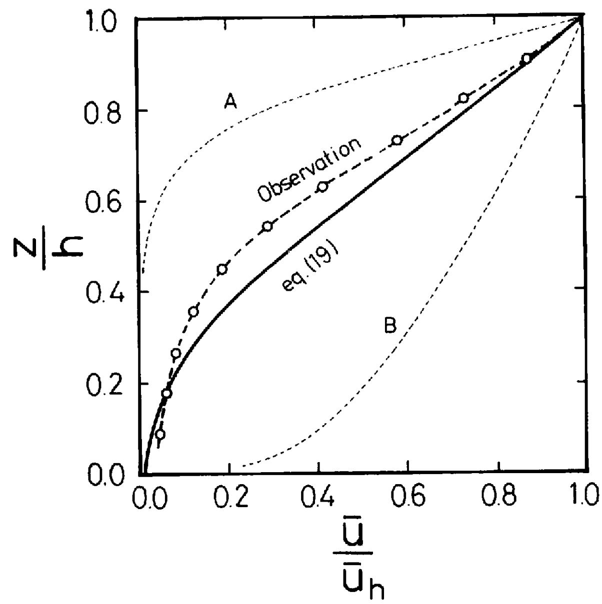

Fig. 17 Comparison of calculated and observed wind profiles within a canopy. Solid line: Eq. (19) with $\eta' = 40.0$, broken line: observation, dotted line A: Eq. (19) in the case of large drag coefficient, dotted line B: Eq. (19) in the case of small drag coefficient.

shows that the airflow above a canopy does not penetrate into the deeper layer. This is due to the reduction of momentum transfer with the large value of C_d. On the contrary, when the value of C_d is small for all the existing vegetation, the airflow blows into the canopy and establishes a near logarithmic profile as expressed by the line B.

From the facts mentioned above, a result which supports the validity of the theoretical relationships is obtained within a canopy. It will be necessary for further numerical researches to precisely describe a direct measurement of the momentum diffusivity and the drag coefficient within a canopy.

CHAPTER 5

OBSERVATION RESULTS AND DISCUSSIONS

5-1 Static characteristics of roughness length and zero-plane displacement

The mean values of the principal properties which indicate the static-state of the airflow, as observed in 1978, are tabulated in Table 3. The value of $\bar{u}_h$ is at $z = h = 0.46$ m. The value of K_M and C_D are also calculated at $z = h$.

Table 3 Mean values of the principals of the aerodynamic properties observed in 1978.

Element	Value
Wind speed	$\bar{u}_h$ = 1.77 m/s
Friction velocity	u_* = 0.30 m/s
Richardson number	Ri = -8.4×10^{-3}
Roughness length	z_0 = 0.03 m
Zero-plane displacement	d = 0.18 m
Momentum diffusivity	K_M = 3.4×10^{-2} m^2/s
Drag coefficient	C_D = 3.1×10^{-2}

Some characteristics of the roughness length and the zero-plane displacement will be dicussed first. The values of z_0 and d are presented as nondimensional fractions of the vegetation height in the form:

$$\zeta_0 = \frac{z_0}{h}, \quad \delta = \frac{d}{h} \tag{26}$$

The analysis of wind data obtained from neutral conditions shown that mean values of z_0 and d increase with increasing plant height. For a pasture canopy, using values from Table 3, upper dependencies can be approximated by:

$$\zeta_0 = 0.07, \quad \delta = 0.40 \tag{27}$$

On the other hand, several researchers have drawn attention to the relationship between h and z_0 or d. An empirical equation with regard to the former relationship, i.e. between h and z_0, have been reported as $z_0 = a'h^{b'}$, where z_0 and h are in centimeters. According to Sellers (1965), the values of constants a' and b' were obtained as the following sets of [$a' = 0.06$, $b' = 1.19$] and [$a' = 0.13$, $b' = 1.00$]. In addition, Uchijima (1976) quoted the values of $a' = 0.06$ and $b' = 1.08$ for rice and maize fields. The empirical relations mentioned above are lacking in physical meaning because they are not dimensionally homogeneous. However, substituting $h = 0.46$ m for the present observation into the above empirical equations, we can get the values of z_0 = 0.06 m, 0.06 m and 0.04 m, with the constants evaluated by Sellers and Uchijima. These values are larger than the value of z_0 = 0.03 m shown in Table 3.

Typical values of ζ_0 for various surface types were summarized by Sutton (1953), Plate (1971) and Oke (1978). Their results may be arranged on the scale of ζ_0 as shown in Table 4. This table shows that the pasture canopy is a more smooth surface, because the value of ζ_0 is remarkably smaller than for other surfaces. However, the roughness may be changed not only by the surface type, but also by the roughness density. Then Lettau (1969) proposed the relation $z_0 = 0.5hs/S$, depicting the roughness density. Where s is the silhouette area of the average obstacle measured in the vertical-crosswind-lateral plan and S the specific area measured in the horizontal plane. However for a natural canopy, close agreement between the observation and the calculated value of Lettau's equation is not obtained. This means that it is necessary, when looking natural vegetations, to consider the variety of aerodynamical characteristics in relation to wind speed.

Table 4 Typical surface and its normalized roughness length.

ζ_0	Surface type	h (m)
0.21	Flat country	0.10
0.20	Thick grass field	0.10
0.17	Grassy surface	0.10
0.16	Snow covered plane	0.03
0.16	Low grass field	0.20
0.14	Beet field	0.45
0.13	High grass field	0.30
0.12	Thick grass field	0.50
0.10	Lawn grass field	0.01
0.10	Thin grass field	0.50
0.07	Thin grass field	0.10
0.07	Pasture grass field (The present study)	0.46
0.04	Wheat field	1.30

Subsequently, we examined the relationship between h and d. Stanhill (1969) and Uchijima (1976) demonstrated this relationship with the empirical equations $d = 1.42\, h^{0.98}$ and $d = 1.04\, h^{0.88}$ respectively, where in both cases d and h are in centimeters. Substituting h = 0.46 m into the above equations, we get the values of d = 0.30 m in each case. This value is considerably larger than the value d = 0.18 m in Table 3.

Further, Kawatani and Meroney (1970) studied the relationship between the roughness length and its density, using a wind tunnel experiment, with the result that the maximum value of u_* appears at a medium density of roughness elements. In addition, Oliver (1971) investigated the variation of the roughness length with stability conditions and pointed out a significant trend in z_0 and Ri. To be sure, it is interesting that z_0 and d are not determined only by vegetation height.

5-2 Definition of effective roughness parameter

A typical relationship between z_0 and d is consistent with Thom's suggestion such that a first approximation to z_0 is given by $\lambda'(h - d)$, where λ' is constant and $(h - d)$ is considered to imply the exposed length of vegetations. Though z_0 and d were introduced independently of each other, the systematic changes that z_0 is proportional to the value of $(h - d)$ were suggested by Thom (1971). We can rewrite the relation as normalized values as follows:

$$\zeta_0 = \lambda' (1 - \delta) \tag{28}$$

where the value of $(1 - \delta)$ may be regarded as an extinction scale of the downward momentum.

From the physical meaning of the scale $(1 - \delta)$, it seems to be quite rational to consider that the proportional constant λ' can be represented as the effective roughness parameter η. Here the following concept is newly presented, i.e.:

$$\boxed{\text{effective roughness parameter } (\eta)} = \frac{\boxed{\text{normalized roughness length } (\zeta_0)}}{\boxed{\text{normalized exposed scale } (1 - \delta)}}$$

The value of $(1 - \delta)$ must be smaller for a densely planted canopy than for a sparsely planted canopy with the same plant height. For a pasture canopy, we can get the value $\eta = 0.11$ which is smaller than those found by many other canopies. Examples for other canopies are 0.44 over wheat fields, 0.26 over needle-leaved trees, 0.24 over bean fields and 0.12 over corn fields as tabulated in Hayashi and Kotoda (1980). Furthermore, a value of $\eta = 0.31$ was found by Legg and Long (1975) for wheat field. It is noteworthly that the pasture canopy contributes less effectively to aerodynamical roughness than the other canopies, even though upper wind blows more into the canopy.

In order to make clear the behavior of ζ_0 in contrast with $(1 - \delta)$, the observed results are plotted in Fig. 18. Eq. (28) which is led the conception of mean conditions and characterized by the value of $\eta = 0.11$ is shown in the figure by a broken line. Where the value of $(1 - \delta)$ increases with an increase of ζ_0. Notwithstanding the fact that the observed results are more scattered with as increase of $(1 - \delta)$, their values obey Eq. (28) to the first approximation. As compare to the particulars, Eq. (28) estimates greater values than the observed results in the case of $(1 - \delta) < 0.7$, to the contrary the equation estimates smaller in the case of $(1 - \delta) > 0.7$.

Well, the relation between z_0 and d was expressed as Eq. (15), and using the value of m = 0.68 and $\beta = 0.29$, it can be rewritten as follows:

$$\ln\left(\frac{1 - \delta}{\zeta_0}\right) = \frac{0.56\,(1 - \delta)}{\zeta_0^{\,0.68}} \tag{29}$$

The solid line in Fig. 18 expresses Eq. (29), which is in almost complete agreement with the observation results and indicates that the ratio η, defined before as the effective roughness parameter,

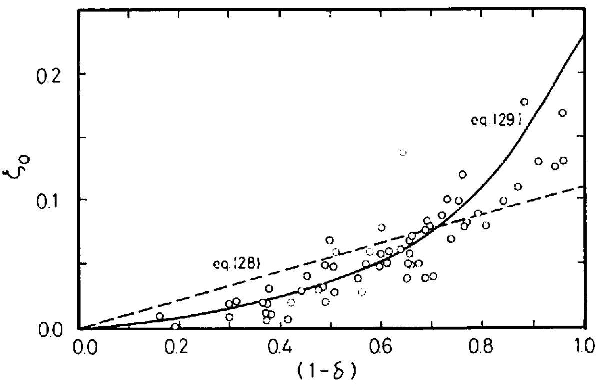

Fig. 18 Relation between the normalized exposed scale $(1 - \delta)$ and the normalized roughness length ζ_0, where solid line and broken line are represented by Eq. (29) and Eq. (28) respectively.

increases with an increase of $(1 - \delta)$.

The discussion above explains that the effective roughness paremeter η is changeable and mainly affected by aerodynamical properties of the canopy. Although the effective roughness parameter is one of the most important elements for a canopy, no systematic observation has been undertaken. According to Monteith (1973), the ratio of $(h - d)$ to z_0 was not constant for rice field. In the following, it is anticipated that η varies with wind speed. In order to confirm this expectation, we can evaluate the variation of η with nondimenisonal rapidity Γ ($= \bar{u}_h/u_*$). Substituting Eq. (16) and Eq. (17) into Eq. (28) and arranging the expression, we have:

$$\eta = e^{-k\Gamma} \tag{30}$$

This equation means that the value of η can be estimated independently of the parameters m and β. Only Γ must be known. This dependence is shown in Fig. 19, where an increase of Γ is identical with the exponential decrease of η.

From the definition of the drag coefficient C_D; i.e. Eq. (18), we get the relation of $\Gamma = C_D^{-1/2}$. Substituting the above relation into Eq. (30), we can write it as:

$$\eta = \exp\left(-\frac{k}{\sqrt{C_D}}\right) \tag{31}$$

which means that the effective roughness parameter is increasing as the drag coefficient increases.

5-3 Variation of roughness length and zero-plane displacement with rapidity

Qualitatively, the friction velocity u_* can be considered proportional to the size of the friction-driven-eddies in the flow near the ground. Therefore, if we take notice of the behavior of the airflow, u_* will be larger over a rough surface than over a smooth surface. Then the magnitude of turbulent transfer over a paticular surface must ralate directly to its aerodynamical roughness.

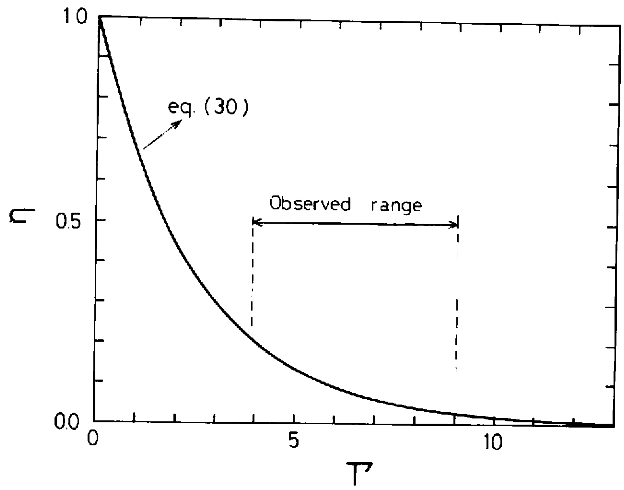

Fig. 19 Variation of the effective roughness parameter with the nondimensional rapidity.

From the point of view described above, the variations of z_0 and d with rapidity were investigated by many researchers.

According to Yoshino (1975), it is clear that z_0 and d vary with wind speed. The problem of the behavior of z_0 and d with wind speed as well as with friction velocity has been discussed by many field observations. Table 5 summarizes those relationships, which each arrow describing the following. Namely, →, independent of rapidity; ↗, increasing with rapidity; ↘, decreasing with rapidity. The outline of the main results will be described as follows. Rider (1954) observed an airflow above an oat field which changes continuously from 0.1 m to 0.8 m in canopy height. He investigated the phenomenon of magnitude of d increasing with an increase of h and $\bar{u}$. Tani et al. (1954) showed that d increases and z_0 decreases with $\bar{u}$ in the range of 1.5 m/s $< \bar{u} <$ 5.0 m/s at z = 2 m, over a rice field. On the other hand, the former decreases and the latter increases in the range of $\bar{u} >$ 5.0 m/s. Tani et al. (1956) got contradictory results in that z_0 increases and d decreases with $\bar{u}$ for a mature rice caonopy. They hypothesized that the cause of this discrepancy may be due to the different conditions of a canopy in the growth stage. Penman and Long (1960) reported a condition of decreasing d and increasing z_0 with increasing $\bar{u}$ over a wheat field of h = 0.6 m. Allen (1968) observed within and above a plantation of Japanese larch of h = 10.4 m and discovered that d decreases while z_0 increases with an increase in u_*. These results are in close agreement with those reported by Lemon et al. (1969) and Maki (1976) for corn fields. Further, over short grass of h = 2.5 cm, it was reported by Saugier and Riplay (1978) that z_0 decreases with $\bar{u}$. In Table 5, peculiar behaviors that the value of z_0 and d changes almost in opposite direction are recognized.

In order to clearly see the variations of z_0 and d with rapidity, we can discuss as follows. The dependences of z_0 and d with Γ are represented by Eq. (16) and Eq. (17) respectively. The values of the parameters m and β which characterize the aerodynamical figures were decided by Eq. (22) for a pasture canopy. Doing this we can estimate the following equations for an actual canopy:

Table 5 Wind dependence of the roughness length and the zero-plane displacement.

Canopy	h (m)	Relationships		Reference
		z_0 and $\bar{u}$ or u_* (m/s)	d and $\bar{u}$ or u_* (m/s)	
Short grass	0.025	↘, $2.0<\bar{u}_{0.24}<5.0$		Saugier and Ripely (1978)
Long grass	0.6	↘, $1.5<\bar{u}_2<6.2$		Deacon (1949)
Oat	0.1 - 0.8		↗, $1.0<\bar{u}_2<4.0$	Rider (1954)
Wheat	0.6		↘, $0.26<u_*<0.55$	Penman and Long (1960)
	0.8		↘, $0.17<u_*<0.35$	Isobe (1964)
	0.9		↘, $0.12<u_*<0.63$	Isobe (1964)
	1.3	↘, $0.3<\bar{u}_{1.3}<1.6$	→, $0.3<\bar{u}_{1.3}<1.6$	Legg and Long (1975)
Rice	0.9		↘, $0.1<u_*<0.36$	Isobe (1964)
	1.0 - 1.05	↗, $1.0<\bar{u}_2<5.0$	↘, $1.0<\bar{u}_2<5.0$	Tani *et al.* (1956)
	1.1	↘, $1.5<u_2<5.0$	↗, $1.5<\bar{u}_2<4.5$	Tani *et al.* (1954)
		↗, $5.0<\bar{u}_2<10.0$	↘, $4.5<\bar{u}_2<10.0$	Tani *et al.* (1954)
Corn	2.4 - 2.7	↗, $0.2<u_*<1.2$	↘, $0.2<u_*<1.2$	Maki (1976)
	2.85	↗, $0.48<u_*<0.62$	↘, $0.48<u_*<0.62$	Lemon (1969)
Sorgo	1.25 - 2.7	↗, $0.1<u_*<0.6$	↘, $0.1<u_*<0.6$	Maki (1976)
Teosinte	0.6 - 1.5	↗, $u_*<0.95$	↘, $u_*<0.95$	Maki (1976)
Bean	1.18	→, $0.19<u_*<0.35$	↘, $0.19<u_*<0.35$	Thom (1971)
Larch	10.4	↗, $0.5<u_*<1.2$	↘, $0.5<u_*<1.2$	Allen (1968)
Many species		↗, $\bar{u}_{1.5}<2.0$	↘, $\bar{u}_{1.5}<2.0$	Tani (1960)
		↘, $2.0<\bar{u}_{1.5}<4.5$	↗, $2.0<\bar{u}_{1.5}<4.0$	Tani (1960)
		↗, $4.5<\bar{u}_{1.5}<10.0$	↘, $4.0<\bar{u}_{1.5}<10.0$	Tani (1960)
Pasture	0.46	↗, $0.1<u_*<0.5$	↘, $0.1<u_*<0.5$	The present study

$$\zeta_0 = (0.72\,\Gamma)^{3.08}\ e^{-1.23\Gamma} \tag{32}$$

$$\delta = 1-(0.72\,\Gamma)^{3.08}\ e^{-0.83\Gamma} \tag{33}$$

Fig. 20 shows the above relationships, in which data are well supported by estimation curves. Accrding to Eq. (32) and Eq. (33), the maximum and minimum appear at different values of Γ. Furthermore, composing two curves, some aerodynamical properties appear within the range of $3.8<\Gamma<9.1$. Namely, as shown in Fig. 21, it is evident that the reduction of the canopy surface friction corresponds to the contraction of the thickness $(1-\delta-\zeta_0)$ in which wind penetrates, and induces the decreasing trend of z_0 and increasing trend of d. The line $(\delta+\zeta_0)$ gives the level at which the extrapolated wind speed is zero.

From the facts discussed above, it is naturally introduced that the variations of z_0 and d with rapidity induce the reduction of the friction velocity.

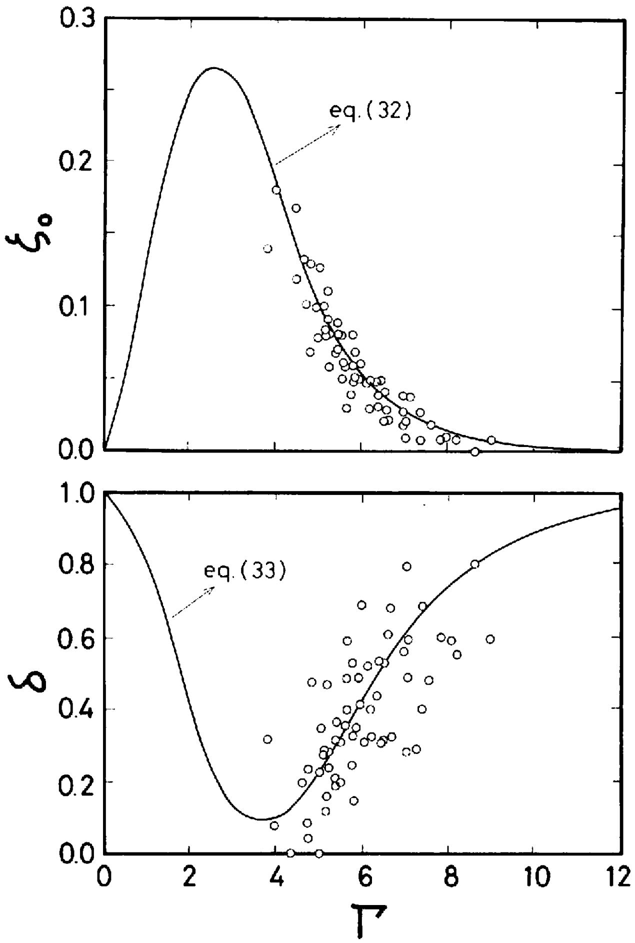

Fig. 20 Variation of the normalized roughness length and the normalized zero-plane displacement with the nondimensional rapidity.

5-4 Dependence of frequency and wavelength on wind speed

In the previous sections, the idea of the aerodynamic properties varying with the rapidity of the airflow was discussed. Especially for long and flexible vegetation, it seems that the momentum flux settles down under windy conditions. For further understanding of the interrelationship between the air layer and the canopy layer, the following discussions are of importance.

According to Busch (1973), in near-neutral conditions, normalized power spectra of the vertical wind components are described well by:

$$\frac{nS_w(n)}{\sigma_w{}^2} = \frac{A\left(\frac{f}{f_m}\right)}{\left[1 + 1.5\left(\frac{f}{f_m}\right)^a\right]^{\frac{5}{3a}}} \tag{34}$$

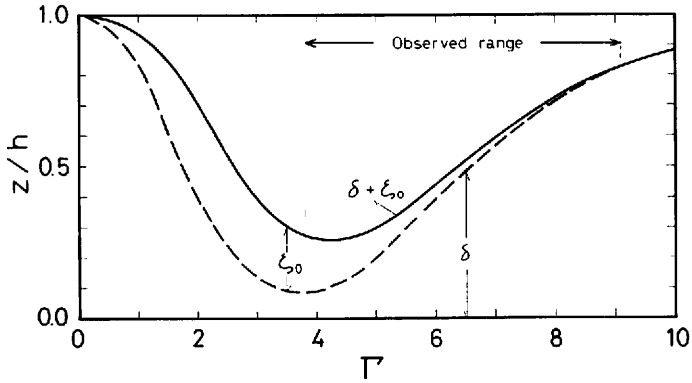

Fig. 21 Dependences of the aerodynamical parameter ζ_0 and δ on nondimensional rapidity Γ. The value $(\delta + \zeta_0)$ indicates the level where the extrapolated wind speed is zero.

where S_w is the power spectral density function and:

$$f = \frac{nz}{\bar{u}} \tag{35}$$

Here n is the frequency, f the reduced frequency, and f_m the reduced frequency at which $nS_w(n)$ reaches the maximum. If the vertical spectrum scales only with height, f_m and a should be universal constants. The constant A is determined by a, since the integral of $nS_w(n)/\sigma_w^2$ must be unity.

From the observations in 1980, two normalized spectra of the vertical component of the wind fluctuation just above a canpoy are shown in Fig. 22. The spectrum reaches a maximum peak of n = 0.8 Hz when $\bar{u}_h$ = 1.15 m/s is shown, and it shifts to a high frequency of n = 1.4 Hz

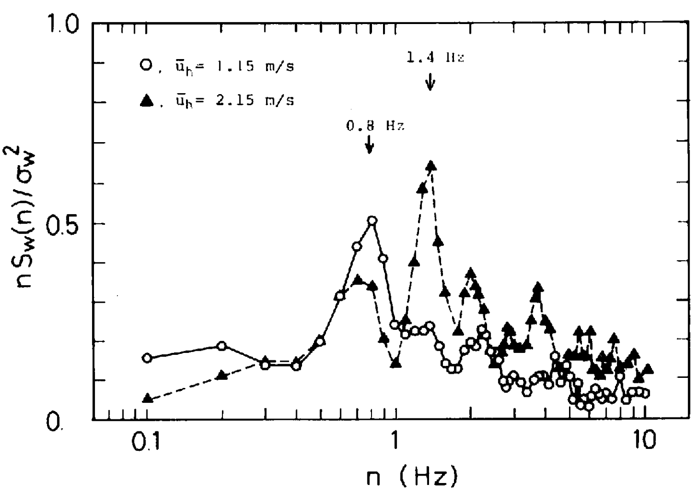

Fig. 22 Normalized spectra of the vertical wind fluctuations.

when $\bar{u}_h$ = 2.15 m/s. In order to investigate the problem of whether the shifting is reasonable or not, spectrum analyses were made for all 107 cases. In the present study the values of n_m were evaluated from eye estimates of the position of the maximum value of $nS_w(n)/\sigma_w^2$. Consequently, by a number of spectral forms, as shown in Fig. 23, it is recommended for shifting that all of the spectra provide a good fit under the following empirical relation:

$$n_m = 0.71\,\bar{u}_h \tag{36}$$

Here, the number 0.71 is in meter. Although there is some scatter, a fitted line can be drawn in the figure in which the value of n_m increases with an increase in wind speed.

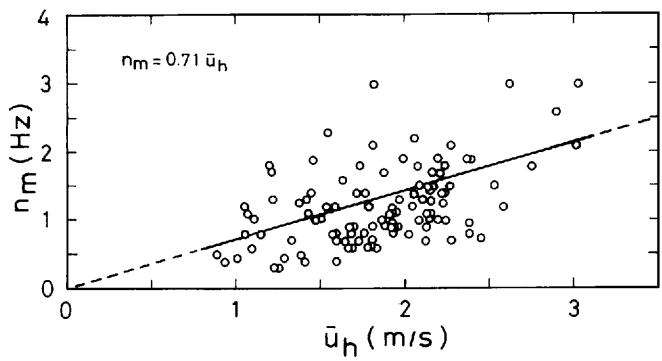

Fig. 23 Dependence of the dominant frequency on the wind speed just over a canopy.

Here, we will discuss about a relationship between n_m and the deformation of plants. In Section 3-2, normalyzed spectrum of the deformation degree was represented. The mean wind speed throughout the analyzed cases is 2.1 m/s. Substituting this into Eq. (36), we get the value of n_m = 1.4 Hz, which agrees well with n_m = 1.2 Hz for Y-component displacement as shown by Fig. 15. It is generally accepted that the deformation of plants contributes to the flucturation of the vertical wind just over a canopy. At least in the condition of $\bar{u}_h \simeq 2.0$ m/s, this is feasible and very much interesting.

In Fig. 22 the increasing value of $n_m S_w(n_m)/\sigma_w^2$ is also depicted. The variation of the value of $n_m S_w(n_m)/\sigma_w^2$ with $\bar{u}_h$ is shown in Table 6. The peak value of the normalized spectrum is slightly increasing with the wind speed.

The dominant wavelength, i.e. the horizontal peak scale λ_m is defined by:

$$\lambda_m = \frac{\bar{u}}{n_m} \tag{37}$$

Substituting the value obtained from Eq. (36) into Eq. (37) we get the value of λ_m for a given $\bar{u}_h$ as follows:

$$\lambda_m = 1.41 \tag{38}$$

Table 6 Variation of the parameters evaluated from the spectrum analysis. Here d* is a constant value of 0.18 m.

$\overline{u}_h$ (m/s)	$\frac{n_m S_w (n_m)}{\sigma_w^2}$	n_m (1/s)	λ_m (m)	$\frac{\lambda_m}{z - d^*}$
1.0	0.45	0.71		
1.5	0.46	1.07		
2.0	0.49	1.42	1.41	4.41
2.5	0.54	1.78		
3.0	0.64	2.13		

This relation means that the dominant wavelength is independent of the wind speed. According to Pasquill (1974), the values of λ_m/z are nearly constant in the surface boundary layer and lie in a range of 2 ~ 4 under neutral conditions. In the present case, the value of $\lambda_m/(z - d)$ is in close agreement with Pasquill's value under the restriction of the concept that the zero-plane displacements do not change with a variety in the wind conditions. However, this restriction is not realistic for an actual canopy, because we have already pointed out the variation of the zero-plane displacement with the nondimensional rapidity as shown in Fig. 20. This dependency will be discussed in next section.

Inoue and Uchijima (1979) obtained a linear relationship between $\overline{u}$ and λ_m, i.e. $\lambda_m = 2.26\ \overline{u}$, within a range of 0.2 m/s $< \overline{u} <$ 3.2 m/s. Eq. (38) for the present study is not in accordance with the above linear relation.

5-5 Characteristics of reduced frequency

The maximum peak in a spectrum is important because the frequency of this peak is generally a good indication of the characteristics scale of the fluctuations.

In discussing a canopy, we must make use of the zero-plane displacement in Eq. (35) and then define the reduced frequency as follows:

$$f = \frac{n(z - d)}{\overline{u}} \tag{39}$$

In the same way, the maximum reduced frequency f_m is represented by the use of n_m. At the level of the plant height, i.e. at $z = h$, we can rewrite Eq. (39) as:

$$f_m = \frac{n_m h (1 - \delta)}{\overline{u}_h} \tag{40}$$

Here, as mentioned in Section 5-3, the normalized zero-plane displacement δ must be change depending on wind conditions. Then the value of $(1 - \delta)$ can be calculated from Eq. (33) as follows:

$$1 - \delta = (0.72\,\Gamma)^{3.08}\ e^{-0.83\Gamma} \tag{41}$$

If Γ is made known by measurement with a sonic anemometer-thermometer just above a canopy, we can evaluate the maximum reduced frequency. The dependencies of the maximum reduced frequency on the wind speed are shown in Fig. 24, in which the upper part shows the variation of f_m' with a constant value of $\delta = 0.40$. This value was determined by the observations in 1978. The lower figure indicates the variation of f_m evaluated with the variation of δ. The lines were fitted by eye. Comparing the upper and the lower figures, there seems to be a relatively strong dependency on the wind speed in the lower figure. At the same time, mean values appear at 0.21 and 0.18 respectively.

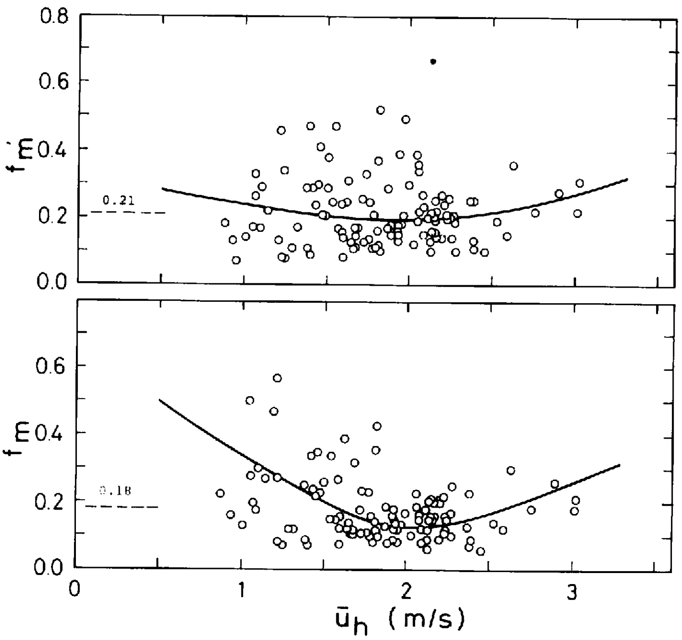

Fig. 24 Dependence of the maximum reduced frequency on the wind speed. Upper part: f_m' is an apparent maximum reduced frequency evaluated from the constant value of $\delta = 0.40$. Lower part: f_m is an actual one evaluated from the variable value of Eq. (41).

As far as the average is concerned, we can compare it with other researcher's. Panofsky and McCormick (1960) have shown that the vertical spectra from widely different locations and heights show approximately similar shape with their peaks of $f_m = 0.25$. In the neutral case, the fact that the peak lies within $0.15 < f_m < 0.35$ was suggested by Kaimal and Haugen (1967). According to Busch and Panofsky (1968), under neutral and unstable conditions, the value of f_m appears at $f = 0.32$. And Kaimal et al. (1972) introduced the idea of f_m reaching a universal constant of $f_m = 0.6$ under neutral conditions. These values are relatively larger than that of the present study of $f_m = 0.18$.

One more thing made clear by the lower figure of Fig. 24 is that the maximum reduced frequency f_m has a minimum value of $f_m = 0.12$ at $\bar{u}_h = 2.0$ m/s. This is the most striking property of the interrelationship between the airflow and vegetations. In order to make clear the behavior of f_m with the normalized rapidity, we mede rearrangements and constructed Fig. 25. The solid line in Fig. 25 indicates the following exponential function:

$$f_m = e^{0.50\,(3.02-\Gamma)} \tag{42}$$

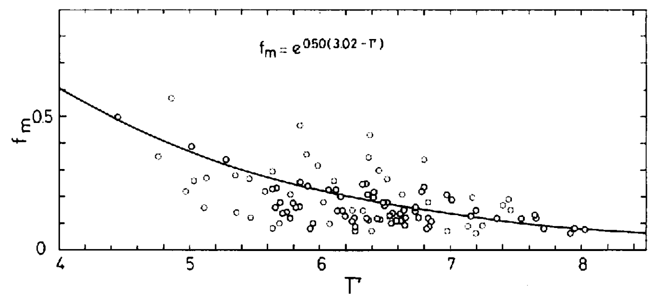

Fig. 25 Dependence of the maximum reduced frequency on the nondimensional rapidity.

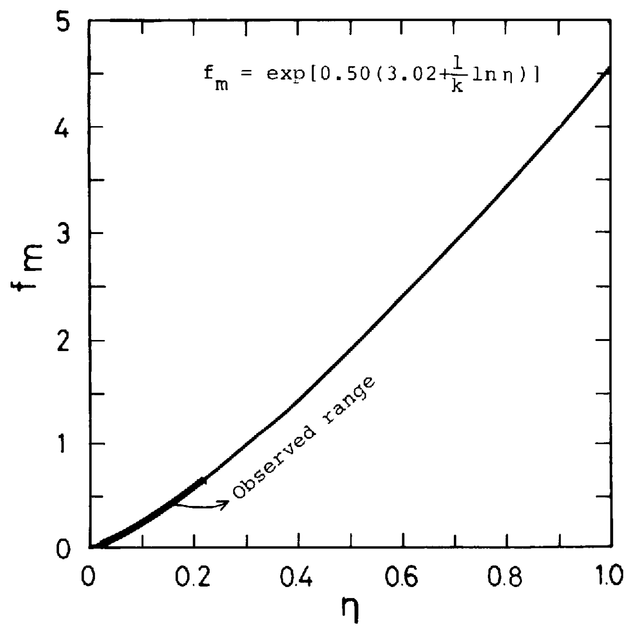

Fig. 26 Relation between the effective roughness parameter and the maximum reduced frequency.

This equation means that the value of f_m can be calculated if Γ is given, and indicates that f_m is decreasing with Γ within the range of $4.4 < \Gamma < 8.1$. Furthermore, as mentioned in Section 5-2, the effective roughness parameter η was independent of the parameters m and β. Accordingly, eliminating Γ from Eq. (42) and Eq. (30), we can represent the relationship between f_m and η as follows:

$$f_m = \exp\ [0.50\,(3.02 + \frac{1}{k}\ln\eta)] \tag{43}$$

The above relationship is shown in Fig. 26 which means the increase of the effective roughness parameter η essentially corresponds with the increase of the maximum reduced frequency f_m. It is important to note that there is a systematic relationship between f_m (correspond to frequency) and η (correspond to roughness) even though they are introduced independently of each other.

From the definition of the drag coefficient of the field, we got the relation $\Gamma = C_D^{-1/2}$ from Eq. (18). Consequently, we may discuss the relationship between the maximum reduced frequency and the drag coefficient. That is to say, the decrease of f_m is in accordance with the decrease of C_D. And the appearance of the minimum value of drag of the canopy may have resulted from induced deformation of vegetation at a critical wind speed. In the present study, the critical value is deduced $\bar{u}_h$ = 2.0 m/s from the lower part of Fig. 24 and Fig. 25.

CHAPTER 6

CONCLUSION

Micrometeorological experiments were carried out over a pasture canopy and some aerocynamic properties were analyzed in the surface boundary layer and in the canopy-eddy lyer. The results are summarized in the following paragraphs.

The friction velocity u_* settled down in the high range of the wind speed $\bar{u}_h$, and deviated from the linear relation. This was fitted by the relation $u_* = 0.18\ \bar{u}_h^{0.84}$ in 1978 or $u_* = 0.17\ \bar{u}_h^{0.86}$ in 1980. From the above mentioned facts, it was surmised that the surface becomes smoother than at a certain state and then the momentum trnsport decreases at a level just over the surface of the canopy. This was closely related to the variation of the roughness length and zero-plane displacement.

From the displacement of a leaf, it was concluded that the dominant frequency of 1.2 Hz was nearly equal to the frequency of the wind fluctuation. It was also concluded that the displacement of the canopy element was directly contributed to the fluctuation of the vertical wind just above a canopy.

The normalized roughness length of a pasture canopy was 0.07. Further, the newly defined effective roughness parameter η was 0.11. Their values were smaller than those found by many other canopies. It was noteworthly that the pasture canopy contributed less effectively to aerodynamical roughness than did other canopies. This occurred even though the upper wind blows more directly into the canopy.

An available relation of $\eta = \exp(-k\Gamma)$ was obtained as a result of the variation of the effective roughness parameter η with the nondimensional rapidity Γ. This suggests that η increased with an increase of the surface friction. Additionally, the reduction of the surface friction corresponded to the contraction of the thickness in which wind penetrated. This induced the decreasing and increasing tendencies of the roughness length and the zero-plane displacement respectively.

The variations of the roughness length and the zero-plane displacement were represented by the following equations. Namely, they are $\zeta_0 = (0.72\ \Gamma)^{3.08} \exp(-1.23\ \Gamma)$ for the normalized roughness length, and $\delta = 1 - (0.72\ \Gamma)^{3.08} \exp(-0.83\ \Gamma)$ for the normalized zero-plane displacement. These equations were evaluated from two constant parameters of $m = 0.68$ and $\beta = 0.29$ for a pasture canopy. Above relations mean that ζ_0 decreases and δ increases with the nondimensional rapidity Γ.

All of the spectrum provided a reasonably good fit comparing the relationship between the maximum frequency n_m and the wind speed $\bar{u}_h$. This was expressed by a relation $n_m = 0.71\ \bar{u}_h$. In the same way, the maximum reduced frequency f_m was evaluated by the nondimensional rapidity Γ as, $f_m = \exp[0.50\ (3.02\text{-}\Gamma)]$. The latter equation indicated that the decrease of the reduced frequency was in accordance with the drag coefficient C_D. Consequently, it was described that the appearance of the minimum value of C_D resulted from the waving of vegetation at the critical wind speed of $\bar{u}_h = 2.0$ m/s. In addition by introducing the effective roughness parameter η, an interesting relation, $f_m = \exp[0.50\ (3.02 + \frac{1}{k} \ln \eta)]$ was obtained.

The ordinary differential equation of the wind profile within a canopy was solved by foward integration beginning at the surface. From the results of the integration, close agreement between the observed and the calculated profiles was obtained. Consequently, results which supported the validity of the theoretical relationships between the physical quantities within a canopy were obtained.

ACKNOWLEDGEMENT

The author is greateful to Dr. M.M. Yoshino of the Institute of Geoscience, the University of Tsukuba, for many helpful suggestions and encouragement. The author is also greateful to Drs. T. Kawamura, T. Nishizawa, I. Kayane and K. Kotoda of the Institute of Geoscience, the University of Tsukuba, and Dr. T. Hanafusa of the Meteorological Research Institute for reviewing this paper. Thanks are due to Dr. M. Inokuchi, former Director of Environmental Research Center, the University of Tsukuba, for making available the observations of the present paper. The author indebted to Drs. K. Kotoda and T. Hanafusa for drawing his attention to this problem.

In preparing this presentation, the author had many supports with his colleagues, Dr. Y. Sakura of the Department of Earth Sciences, Chiba University, and Mr. K. Izumi of the Environmental Research Center. Thanks are also to Mr. Robert C. Backstrom, student of the University of Tsukuba, for English wording of the manuscript. The computation in the present study were performed with use of the FACOM M-200 computer at the Science Information Processing Center of the University of Tsukuba.

BIBLIOGRAPHY

Albini, F.A. (1981): A phenomenological model for wind speed and shear stress profiles in vegetation cover layers. *Jour. Appl. Met.,* **20**, 1325-1335.

Allen, L.H. (1968): Turbulence and wind speed spectra within a Japanese larch plantation. *Jour. Appl. Met., 7,* 73-78.

Busch, N.E. (1973): On the mechanics of atmospheric turbulence. In: *Workshop on micrometeorology.* ed. by Haugen, D.A., Amer. Met. Soc., 1-65.

Busch, N.E. and Panofsky, H.A. (1968): Recent spectra of atmospheric turbulence. *Quart. Jour. Roy. Met. Soc.,* **94**, 132-148.

Businger, J.A., Miyake, M., Dyer, A.J. and Bradley, E.E. (1967): On the direct determination of turbulent heat flux near the ground. *Jour. Appl. Met.,* **6**, 1025-1032.

Businger, J.A., Miyake, M., Inoue, E., Mitsuta, Y. and Hanafusa, T. (1969): Sonic anemometer comparison and measurements in the atmospheric surface layer. *Jour. Met. Soc. Japan,* **47**, 1-12.

Cionco, R.M. (1965): A mathematical model for air flow in a vegetative canopy. *Jour. Appl. Met.,* **4**, 517-522.

Cowan, I.R. (1968): Mass, heat and momentum exchange between stands of plants and their atmospheric environment. *Quart. Jour. Roy. Met. Soc.,* **94**, 523-544.

Deacon, E.L. (1949): Vertical diffusion in the lowest layers of the atmosphere. *Quart. Jour. Roy. Met. Soc.,* **75**, 89-103.

Emmanuel, C.B. (1975): Drag and bulk aerodynamic coefficients over shallow water. *Bound. Lay. Met.,* **8**, 465-474.

Hanafusa, T., Fujitani, T., Kobori, Y. and Mitsuta, Y. (1982): A new type sonic anemometer-thermometer for field operation. *Pap. Met. Geoph.,* **33**, 1-19.

Hayashi, Y. (1980): The numerical solution of wind profile in vegetated canopy layer. *Geogr. Rev. Japan,* **53**, 389-395. *

Hayashi, Y. (1982): Wind of an air layer characterized by vegetations. *Geogr. Rev. Japan,* **55**, 51-64. *

Hayashi, Y. and Kotoda, K. (1980): Some characteristics of roughness length and zero-plane displacement above a canopy. *Tenki,* **27**, 35-41. **

Hicks, B.B. (1976): Wind profile relationships from the 'Wangara' experiment. *Quart. Jour. Roy. Met. Soc.,* **102**, 535-551.

Hicks, B.B. and Wesely, M.L. (1981): Heat and momentum transfer characteristics of adjacent fields of soybeans and maize. *Bound. Lay. Met.,* **20**, 175-185.

Inoue, E. (1952): Interrelations between the structure of wind near the ground and its observations. *Jour. Met. Soc. Japan,* **30**, 255-264.

Inoue, E. (1963): On the turbulent structure of airflow within crop canopies. *Jour. Met. Soc. Japan.* **41**, 317-326.

Inoue, K. and Uchijima, Z. (1979): Experimental study of microstructure of wind turbulence in rice and maize canopies. *Bull. Nat. Inst. Agri. Sci.,* A, **26**, 1-88.

Isobe, S. (1964): Zero-plane displacement in relation to extinction of momentum flux in crop. *Bull. Nat. Inst. Agri. Sci.,* A, **11**, 1-18.

Kaimal, J.C. and Haugen, D.A. (1967): Characteristics of vertical velocity fluctuations observed on a 430-m tower. *Quart. Jour. Roy. Met. Soc.,* **93**, 305-317.

Kaimal, J.C., Wyngaard, J.G., Izumi, Y. and Coté, O.R. (1972): Spectral characteristics of surface-layer turbulence. *Quart. Jour. Roy. Met. Soc.,* **98**, 563-589.

Kawatani, T. and Meroney, R.N. (1970): Turbulent and wind speed characteristics within a model canopy flow field. *Agri. Met.*, 7, 143-158.

Kotoda, K. (1979): Wind profile and aerodynamic parameters above and within a plant canopy. *Ann. Rep. Inst. Geosci.*, Univ. of Tsukuba, 5, 11-14.

Kotoda, K. and Hayashi, Y. (1980): On the wind profile above plant canopies and its aerodynamical properties. *Jour. Agri. Met. Japan*, **35**, 221-228. *

Kotoda, K., Sakura, Y., Hayashi, Y. and Kai, K. (1978): On the observation and data acquisition system for the heat and water balance studies of ERC experimental field. *Bull. Envi. Res. Cen.*, Univ. of Tsukuba, 2, 65-90. **

Kondo, J. (1971): Effect of radiative heat transfer on profiles of wind, temperature and water vapor in the atmospheric boundary layer. *Jour. Met. Soc. Japan*, 49, 75-94.

Legg, B.J. and Long, I.F. (1975): Turbulent diffusion within a wheat canopy: II. Results and interpretation. *Quart. Jour. Roy. Met. Soc.*, **101**, 611-628.

Lemon, E.R., Wright, J.L. and Drake, G.M. (1969): Photosynthesis under field conditions. XB. origins of short-time CO_2 fluctuations in a cornfield. *Agron. Jour.*, **61**, 411-413.

Lettau, H. (1969): Note on aerodynamic roughness-parameter estimation on the basis of roughness-element description. *Jour. Appl. Met.*, 8, 828-832.

Long, I.F. Monteith, J.L., Penman, H.L. and Szeicz, G. (1964): The plant and its environment. *Met. Rdsch.*, **17**, 97-101.

Maitani, T. (1977a): Verical eddy transport of momentum in the surface layer over a paddy field. *Nōgaku kenkyū*, Okayama Univ., **56**, 119-131. **

Maitani, T. (1977b): Vertical transport of turbulent kinetic energy in the surface layer over a paddy field. *Bound. Lay. Met.*, **12**, 405-423.

Maitani, T. (1977c): On the downward transport of turbulent kinetic energy in the surface layer over plant. *Bound. Lay. Met.*, **14**, 571-584.

Maitani, T. (1979): Vertical eddy transport of momentum in the surface layer over a paddy field (2). *Nōgaku Kenkyū*, Okayama Univ., **58**, 19-30. **

Maitani, T. (1981): Measurements of vibration of rice plants during the period of passaging typhoon (1912) at Kurashiki area. *Jour. Agri. Met. Japan*, **36**, 251-255. *

Maki, T. (1969): On the zero-plane displacement and roughness length in the wind velocity profile equation over a corn canopy. *Jour. Agri. Met. Japan*, **25**, 13-18. *

Maki, T. (1975): Interrelationships between zero-plane displacement, aerodynamic roughness length and plant canopy height. *Jour. Agri. Met. Japan*, **31**, 7-15. *

Maki, T. (1976): Aerodynamic characteristics of wind within and above a plant canopy interrelationship between aerodynamic parameters and plant canopy height. *Bull. Nat. Inst. Agri. Sci.*, A, **23**, 1-67.

Monteith, J.L. (1973): *Principles of environmental physics*. Edward Arnold, 241p.

Monteith, J.L. (1975): *Vegetation and the atmosphere*. Vol. 1, Academic Press, 273p.

Monteith, J.L. (1976): *Vegetation and the atmosphere*. Vol. 2, Academic Press, 439p.

Oikawa, T. (1978): Wind characteristics of the model canopy demonstrated with wind-blow computer experiments. In: *Ecophysiology of photosynthetic productivity*. ed. by Monji, M. and Saeki, T., Univ. of Tokyo Press, 159-168.

Oke, T.R. (1978): *Boundary layer climates*. Methuen & Co., 372p.

Oliver, H.R. (1971): Wind profiles in and above a forest canopy. *Quart. Jour. Roy. Met. Soc.*, 97, 548-553.

Paltridge, G.W. (1970): A model of a growing pasture. *Agri. Met.*, 7, 93-130.

Panofsky, H.A. and McCormick, R.A. (1960): The spectrum of vertical velocity near the surface. *Quart. Jour. Roy. Met. Soc.*, **86**, 495-503.

Pasquill, F. (1974): *Atmospheric diffusion.* Ellis Horwood, 429p.

Penman, H.L. and Long, I.F. (1960): Weather in wheat: An essay in micrometeorology. *Quart. Jour. Roy. Met. Soc.*, **85**, 16-50.

Plate, E.J. (1971): *Aerodynamical characteristics of atmospheric boundary layers.* ACE Critical Review Series, U.S. Depertment of Commerce, 190p.

Rider, N.E. (1954): Evaporation from an oat field. *Quart. Jour. Roy. Met. Soc.*, **80**, 198-211.

Sato, T., Maitani, T. and Ohtaki, E. (1980): Measurements of vibration of plants by strain gauges. *Jour. Agri. Met. Japan,* **36**, 103-107. **

Saito, T. (1964): On the wind profile within plant communities. *Bull. Nat. Inst. Agri. Sci.,* A, **11**, 67-73.

Saugier, B. and Ripley, E.A. (1978): Evaluation of the aerodynamic method of determining fluxes over natural grassland. *Quart. Jour. Roy. Met. Soc.*, **104**, 257-270.

Sellers, W.D. (1965): *Physical climatology.* Univ. of Chicago Press, 272p.

Shaw, R.H., Hartog, G., King, K.M. and Thurtell, G.W. (1974): Measurements of mean wind flow and three-dimensional turbulence intensity within a mature corn canopy. *Agri. Met.*, **13**, 419-425.

Stanhill, G. (1969): A simple instrument for the field measurement of turbulent diffusion flux. *Jour. Appl. Met.*, **8**, 509-513.

Sutton, O.G. (1953): *Micrometeorology.* McGraw-Hill, 333p.

Tajchman, S.J. (1981): Comments on measuring turbulent exchange within and above forest canopy. *Bull. Amer. Met. Soc.*, **62**, 1550-1559.

Takeka, K. (1966): On roughness length and zero-plane displacement in the wind profile of the lowest air layer. *Jour. Met. Soc. Japan,* **44**, 101-107.

Tani, N. (1963): The wind over the cultivated field. *Bull. Nat. Inst. Agri. Sci.*, A, **10**, 1-99.*

Tani, N., Inoue, E. and Imai, K. (1954): Some measurements of wind over the cultivated field (3). *Jour. Agri. Met. Japan,* **10**, 105-108. *

Tani, N., Inoue, E. and Imai, K. (1956): Some measurements of wind over the cultivated field (5). *Jour. Agri. Met. Japan,* **12**, 17-20.

Thom, A.S. (1968): The exchange of momentum, mass, and heat between an artificial leaf and the airflow in a wind-tunnel. *Quart. Jour. Roy. Met. Soc.*, **94**, 44-55.

Thom, A.S. (1971): Momentum absorption by vegetation. *Quart. Jour. Roy. Met. Soc.,* 97, 414-428.

Uchijima, Z. (1976): Maize and rice. In: *Vegetation and the atmosphere.* ed. by Monteith, J.L., Academic Press, 33-64.

Uchijima, Z. and Wright, J.L. (1964): An experimental study of air flow in a corn plant-air layer. *Bull. Nat. Agri. Sci.,* A, 11, 19-66.

Udagawa, T. (1966): Variation of aerodynamical characteristics of a barley field with growth. *Jour. Agri. Met. Japan,* **22**, 7-14.

Yoshino, M.M. (1957): The structure of surface winds crossing over a small vally. *Jour. Met. Soc. Japan,* **35**, 184-195.

Yoshino, M.M. (1958): Wind speed profiles of the lowest air layer under influence of micro-topography. *Jour. Met. Soc. Japan,* **36**, 174-186.

Yoshino, M.M. (1975): *Climate in a small area.* Univ. of Tokyo Press, 549p.

* In Japanese with English abstract

** In Japanese

APPENDIX A

LIST OF DATA OBSERVED IN 1978

Case No.	$\overline{u}_1$ (m/s)	$\overline{u}_2$ (m/s)	$\overline{u}_3$ (m/s)	$\overline{u}_4$ (m/s)	$\overline{u}_5$ (m/s)	Ri	$\overline{u}_h$ (m/s)	u_* (m/s)	d (m)	z_0 (m)
1	1.8	2.4	2.9	3.4	3.8	−0.026	1.7	0.26	0.16	0.02
2	1.7	2.3	2.8	3.3	3.8	−0.018	1.6	0.26	0.16	0.03
3	2.2	3.0	3.7	4.5	5.2	−0.012	2.1	0.43	0.02	0.06
4	2.6	3.6	4.3	5.1	5.6	−0.020	2.5	0.39	0.21	0.02
5	2.5	3.4	4.0	4.8	5.6	−0.016	2.4	0.38	0.15	0.03
6	2.5	3.3	3.9	4.6	4.9	−0.013	2.4	0.35	0.14	0.02
7	2.0	2.8	3.4	3.9	4.6	−0.011	1.9	0.27	0.29	0.01
8	2.2	3.1	3.8	4.6	5.1	−0.006	2.1	0.41	0.13	0.04
9	2.6	3.7	4.3	4.9	5.6	−0.007	2.4	0.27	0.37	0.01
10	2.4	3.1	3.7	4.3	5.0	−0.002	2.3	0.32	0.13	0.02
11	1.6	2.3	2.7	3.3	4.1	−0.006	1.5	0.26	0.20	0.03
12	1.8	2.4	3.0	3.5	4.0	0.002	1.7	0.29	0.12	0.03
13	1.4	1.9	2.2	2.6	3.0	0.014	1.4	0.18	0.23	0.01
14	1.4	2.0	2.4	2.9	3.2	0.003	1.3	0.24	0.19	0.03
15	1.3	1.8	2.3	2.7	3.1	0.006	1.2	0.24	0.15	0.04
16	2.0	2.7	3.1	3.7	4.2	0.006	1.9	0.26	0.20	0.02
17	0.8	1.2	1.5	1.8	2.2	−0.010	0.7	0.15	0.23	0.03
18	0.9	1.4	1.6	1.9	2.2	0.008	0.8	0.11	0.38	0.01
19	1.0	1.4	1.6	2.0	2.4	−0.007	1.0	0.17	0.09	0.04
20	0.8	1.1	1.3	1.5	1.8	−0.014	0.8	0.10	0.29	0.01
21	1.0	1.4	1.7	2.1	2.5	0.011	1.0	0.20	0.04	0.06
22	1.2	1.9	2.4	3.0	3.3	0.007	1.1	0.29	0.16	0.07
23	1.1	1.6	1.9	2.3	2.5	0.022	1.1	0.18	0.23	0.02
24	1.4	2.1	2.6	3.0	3.2	−0.002	1.3	0.21	0.32	0.01
25	1.4	2.0	2.5	2.9	3.4	−0.011	1.3	0.22	0.25	0.02
26	2.6	3.6	4.4	5.1	5.6	−0.000	2.4	0.37	0.24	0.02
27	2.0	2.7	3.2	3.8	4.4	−0.014	1.9	0.29	0.16	0.02
28	3.1	4.2	5.0	5.7	6.5	−0.019	2.9	0.36	0.29	0.01
29	2.2	3.1	3.9	4.8	5.8	−0.011	2.1	0.49	0.15	0.08
30	2.3	3.1	3.9	4.6	5.2	−0.023	2.2	0.41	0.10	0.04
31	2.4	3.3	4.1	4.8	5.2	−0.017	2.3	0.39	0.18	0.03
32	2.9	4.0	4.8	5.7	6.5	−0.009	2.8	0.44	0.19	0.02
33	2.4	3.3	3.9	4.6	5.2	−0.020	2.3	0.33	0.23	0.02
34	2.6	3.7	4.5	5.2	5.9	−0.019	2.4	0.36	0.29	0.01

Case No.	$\overline{u}_1$ (m/s)	$\overline{u}_2$ (m/s)	$\overline{u}_3$ (m/s)	$\overline{u}_4$ (m/s)	$\overline{u}_5$ (m/s)	Ri	$\overline{u}_h$ (m/s)	u_* (m/s)	d (m)	z_0 (m)
35	2.3	3.2	4.0	4.7	5.3	−0.013	2.2	0.39	0.18	0.03
36	3.0	4.0	4.7	5.4	6.3	−0.026	2.9	0.35	0.26	0.01
37	2.5	3.5	4.3	5.0	5.9	−0.013	2.3	0.37	0.24	0.02
38	2.6	3.6	4.3	5.0	5.8	−0.014	2.4	0.35	0.26	0.01
39	2.0	2.8	3.5	4.2	4.8	−0.012	1.9	0.38	0.12	0.05
40	2.5	3.4	4.2	5.0	5.4	−0.014	2.4	0.44	0.11	0.04
41	2.4	3.3	4.2	4.9	5.5	−0.014	2.2	0.42	0.16	0.04
42	2.4	3.2	4.1	4.8	5.4	−0.017	2.3	0.44	0.08	0.05
43	2.0	2.7	3.4	4.0	4.3	−0.019	1.9	0.35	0.11	0.04
44	2.1	2.8	3.2	3.7	4.3	−0.019	2.0	0.22	0.29	0.01
45	1.7	2.5	3.1	3.7	4.3	−0.009	1.6	0.30	0.23	0.03
46	2.0	2.8	3.3	4.1	4.5	−0.011	2.1	0.38	0.06	0.05
47	1.7	2.4	2.9	3.3	3.5	−0.020	1.6	0.21	0.32	0.01
48	1.7	2.5	3.0	3.6	4.0	−0.016	1.6	0.24	0.32	0.01
49	1.7	2.4	3.1	3.7	4.2	−0.014	1.6	0.35	0.11	0.06
50	1.3	1.8	2.3	2.7	3.3	−0.013	1.2	0.24	0.15	0.04
51	1.5	2.1	2.6	3.1	3.6	−0.015	1.4	0.26	0.16	0.04
52	1.5	2.1	2.7	3.2	3.5	−0.010	1.4	0.29	0.12	0.05
53	1.8	2.5	3.0	3.6	4.1	−0.008	1.7	0.29	0.16	0.03
54	1.2	1.8	2.2	2.6	3.0	0.009	1.1	0.19	0.29	0.02
55	1.6	2.2	2.7	3.3	3.9	0.002	1.6	0.32	0.02	0.06
56	1.7	2.2	2.7	3.2	3.7	0.005	1.5	0.27	0.15	0.03
57	1.7	2.4	2.9	3.4	3.8	0.000	1.6	0.25	0.25	0.02
58	1.2	1.7	2.1	2.5	3.0	−0.002	1.1	0.21	0.18	0.03
59	1.7	2.4	3.0	3.5	3.8	−0.001	1.6	0.28	0.22	0.02
60	1.3	1.8	2.3	2.7	3.2	−0.002	1.2	0.24	0.15	0.04
61	1.1	1.6	2.0	2.4	2.4	−0.005	1.0	0.21	0.18	0.04
62	0.6	0.9	1.1	1.4	1.6	−0.009	0.6	0.14	0.05	0.08

Subscripts 1, observed at 0.5 m
2, observed at 1.0 m
3, observed at 2.0 m
4, observed at 4.0 m
5, observed at 8.0 m

APPENDIX B

LIST OF DATA OBSERVED IN 1980

Run name – Case No.	ζ	$\bar{u}_h$ (m/s)	u_* (m/s)	σ_w (m/s)	n_m (l/s)	$\frac{n_m S_w(n_m)}{\sigma_w^2}$	λ_m (m)	f_m
A – 8	−0.025	1.48	0.26	0.34	1.0	0.40	1.48	0.23
A – 14	−0.029	1.05	0.24	0.27	1.2	0.40	0.88	0.50
A – 16	−0.021	1.06	0.20	0.19	0.8	0.38	1.85	0.28
A – 19	−0.011	1.41	0.22	0.26	0.4	0.46	3.53	0.07
A – 21	−0.015	1.10	0.19	0.21	0.6	0.45	1.83	0.18
A – 23	−0.011	1.23	0.22	0.25	0.3	0.42	4.10	0.08
A – 24	−0.010	1.20	0.20	0.20	1.8	0.33	0.67	0.47
A – 25	−0.017	0.89	0.18	0.18	0.5	0.47	1.78	0.22
A – 27	−0.010	1.60	0.26	0.27	0.7	0.46	2.29	0.12
A – 33	−0.009	1.29	0.24	0.22	0.5	0.35	2.87	0.12
A – 41	−0.009	2.15	0.37	0.40	1.4	0.64	1.54	0.21
A – 48	−0.010	1.94	0.30	0.34	0.9	0.56	2.16	0.12
A – 55	−0.029	1.42	0.24	0.27	1.1	0.51	1.30	0.24
A – 56	−0.024	1.46	0.23	0.26	1.9	0.35	0.77	0.35
A – 57	−0.027	1.45	0.21	0.26	1.4	0.48	1.04	0.22
A – 58	−0.028	1.25	0.20	0.23	0.3	0.46	4.17	0.07
A – 62	−0.010	1.92	0.34	0.34	0.9	0.60	2.13	0.16
A – 76	−0.024	1.07	0.15	0.20	1.1	0.73	0.97	0.20
A – 81	−0.016	0.94	0.18	0.18	0.4	0.43	2.35	0.16
A – 99	−0.022	1.01	0.16	0.18	0.5	0.51	2.24	0.13
A – 101	−0.007	1.38	0.22	0.23	1.3	0.43	1.10	0.25
A – 102	−0.013	1.33	0.20	0.22	0.7	0.40	1.90	0.12
A – 111	−0.014	1.60	0.27	0.27	0.4	0.42	4.00	0.08
A – 137	−0.023	1.39	0.21	0.21	0.5	0.34	2.78	0.09
A – 138	−0.027	1.15	0.22	0.21	0.8	0.51	1.44	0.27
A – 142	−0.029	1.22	0.19	0.20	1.3	0.66	0.94	0.27
A – 150	−0.027	1.11	0.20	0.20	1.0	0.40	1.11	0.30
B – 1	−0.013	1.79	0.30	0.32	0.6	0.49	2.98	0.10
B – 8	−0.025	1.42	0.27	0.25	1.3	0.42	1.09	0.34
B – 11	−0.017	2.09	0.31	0.37	1.0	0.57	2.09	0.12
B – 13	−0.007	2.06	0.36	0.38	1.4	0.52	1.47	0.23
B – 15	−0.007	2.17	0.35	0.37	1.5	0.48	1.45	0.20
B – 23	−0.023	1.82	0.29	0.30	3.0	0.42	0.61	0.43
B – 25	−0.015	2.16	0.34	0.42	1.7	0.59	1.27	0.21

Run name – Case No.	ζ	$\overline{u}_h$ (m/s)	u_* (m/s)	σ_w (m/s)	n_m (l/s)	$\frac{n_m S_w(n_m)}{\sigma_w^2}$	λ_m (m)	f_m
B – 30	–0.011	1.50	0.30	0.32	1.0	0.43	1.50	0.26
B – 34	–0.012	2.46	0.34	0.44	0.8	0.34	3.28	0.06
B – 36	–0.013	1.73	0.27	0.33	0.7	0.56	2.47	0.11
B – 37	–0.014	2.39	0.35	0.42	1.0	0.48	2.52	0.09
B – 38	–0.014	2.24	0.34	0.41	1.0	0.47	2.24	0.11
B – 39	–0.020	1.88	0.27	0.33	1.7	0.47	1.11	0.19
B – 40	–0.024	2.09	0.27	0.37	1.5	0.49	1.39	0.12
B – 48	–0.014	2.19	0.30	0.39	0.9	0.56	2.16	0.12
B – 49	–0.020	2.03	0.31	0.40	0.8	0.47	2.54	0.10
B – 55	–0.014	2.23	0.30	0.35	1.5	0.63	1.49	0.12
B – 57	–0.013	1.94	0.34	0.36	0.8	0.45	2.43	0.14
B – 58	–0.013	1.81	0.34	0.37	0.7	0.36	2.59	0.14
B – 59	–0.017	1.87	0.29	0.30	1.0	0.50	1.87	0.13
B – 60	–0.017	1.94	0.31	0.38	1.1	0.37	1.76	0.15
B – 65	–0.026	1.59	0.29	0.33	1.2	0.41	1.33	0.27
B – 67	–0.030	1.65	0.29	0.33	0.7	0.63	2.36	0.14
B – 72	–0.014	1.75	0.27	0.28	0.8	0.39	2.20	0.11
B – 76	–0.020	2.14	0.28	0.34	1.5	0.73	1.43	0.12
B – 79	–0.020	1.81	0.31	0.31	2.1	0.54	0.86	0.36
B – 80	–0.016	1.81	0.27	0.31	0.9	0.48	2.01	0.12
B – 81	–0.014	1.93	0.33	0.36	1.1	0.66	1.75	0.18
B – 83	–0.011	2.28	0.36	0.39	2.1	0.38	1.09	0.25
B – 84	–0.019	1.69	0.28	0.31	1.8	0.50	0.94	0.32
B – 90	–0.016	1.60	0.27	0.28	0.8	0.48	2.00	0.16
B – 92	–0.011	2.27	0.35	0.38	1.5	0.45	1.51	0.17
B – 93	–0.014	1.63	0.33	0.32	1.6	0.46	1.02	0.39
B – 95	–0.007	2.15	0.37	0.37	1.1	0.44	1.95	0.16
B – 101	–0.024	1.67	0.29	0.33	0.6	0.45	2.78	0.12
B – 103	–0.014	1.83	0.30	0.32	0.6	0.45	3.05	0.10
B – 104	–0.011	2.14	0.35	0.39	1.1	0.55	1.95	0.15
B – 105	–0.012	1.77	0.29	0.31	1.4	0.49	1.26	0.23
B – 107	–0.016	1.97	0.28	0.32	1.3	0.45	1.52	0.13
B – 108	–0.013	2.13	0.34	0.37	0.7	0.38	3.04	0.09
B – 109	–0.022	1.57	0.25	0.30	0.8	0.39	1.96	0.15
B – 110	–0.026	1.21	0.25	0.25	1.7	0.63	0.71	0.57
B – 112	–0.013	2.20	0.31	0.38	1.0	0.46	2.20	0.09
B – 114	–0.008	2.39	0.34	0.41	0.8	0.62	2.99	0.07
B – 117	–0.028	1.89	0.24	0.36	0.9	0.43	2.10	0.08
B – 118	–0.027	1.99	0.27	0.34	1.9	0.43	1.05	0.17

Run name – Case No.	ζ	$\tilde{u}_h$ (m/s)	u_* (m/s)	σ_w (m/s)	n_m (1/s)	$\frac{n_m S_w(n_m)}{\sigma_w^2}$	λ_m (m)	f_m
B – 125	−0.014	1.92	0.26	0.32	0.9	0.50	2.13	0.09
B – 131	−0.026	1.72	0.25	0.32	1.4	0.44	1.23	0.18
B – 133	−0.023	1.68	0.25	0.23	0.8	0.45	2.10	0.11
B – 135	−0.026	1.68	0.25	0.29	0.9	0.43	1.87	0.12
B – 137	−0.020	1.68	0.27	0.32	0.6	0.53	2.80	0.11
B – 141	−0.019	2.37	0.31	0.42	1.9	0.50	1.25	0.13
B – 150	−0.020	2.13	0.27	0.35	0.9	0.48	2.37	0.06
B – 151	−0.020	1.55	0.23	0.25	2.3	0.49	0.67	0.34
B – 153	−0.018	1.79	0.26	0.32	0.6	0.53	3.00	0.08
B – 155	−0.004	2.28	0.40	0.40	0.7	0.44	3.26	0.10
B – 156	−0.011	1.94	0.30	0.39	1.1	0.50	1.76	0.14
B – 157	−0.027	1.54	0.21	0.26	1.2	0.50	1.28	0.15
B – 159	−0.006	2.39	0.39	0.44	1.9	0.53	1.26	0.23
B – 164	−0.010	2.21	0.35	0.41	1.7	0.56	1.30	0.20
B – 168	−0.010	2.20	0.33	0.39	1.9	0.37	1.16	0.21
B – 169	−0.006	2.23	0.40	0.43	1.4	0.47	1.59	0.22
B – 170	−0.009	2.15	0.34	0.35	1.1	0.41	1.95	0.15
B – 175	−0.006	2.59	0.41	0.50	1.2	0.57	2.16	0.12
B – 177	−0.006	2.53	0.38	0.45	1.5	0.56	1.69	0.14
C – 1	0.000	2.24	0.38	0.47	1.8	0.65	1.24	0.26
C – 5	0.002	2.16	0.33	0.41	1.3	0.40	1.66	0.15
C – 7	0.002	1.79	0.27	0.36	1.2	0.56	1.49	0.16
C – 8	0.001	2.58	0.25	0.35	1.2	0.56	1.71	0.08
C – 9	0.001	1.95	0.24	0.35	1.1	0.55	1.77	0.08
C – 16	0.003	2.08	0.28	0.45	1.8	0.53	1.16	0.15
C – 19	0.001	1.74	0.26	0.32	1.8	0.61	0.97	0.24
C – 21	0.002	2.06	0.28	0.36	2.2	0.46	0.94	0.19
C – 30	0.002	2.24	0.33	0.39	1.4	0.47	1.60	0.15
C – 34	0.003	3.02	0.47	0.60	2.1	0.72	1.44	0.18
C – 35	0.003	2.63	0.41	0.45	3.0	0.53	0.88	0.30
C – 39	0.003	3.03	0.43	0.52	3.0	0.59	1.01	0.21
C – 42	0.003	2.75	0.42	0.49	1.9	0.53	1.45	0.18
C – 45	0.002	2.90	0.48	0.54	2.6	0.44	1.12	0.26
C – 48	0.003	2.11	0.35	0.40	1.3	0.57	1.62	0.18

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発行　　　昭和58年3月8日

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