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Photosynthesis Under Field Conditions. VIII. Analysis of Windspeed Fluctuation Data to Evaluate Turbulent Exchange Within a Corn Crop[1]

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ABSTRACT

Turbulent transfer within a crop of corn was characterized by an aerodynamic approach. The distributions of windspeed within an immature and a mature crop were measured using both cup and heated thermocouple anemometers. A combination of the statistical and mixing-length theories was employed to analyze the wind data for transfer coefficients.

Eulerian time scales of turbulence were calculated from the windspeed fluctuations of selected 30-second periods of semi-steady wind. Momentum transfer coefficients were determined from the scale of turbulence by equating it to the mixing length and assuming isotropy. The resulting values were as large as 8,000 cm^2 sec^{-1}. The shearing stress profiles calculated with these values had unrealistically sharp maximums just below the top of the crop. This anomaly was considered an artifact of the method resulting from extreme anisotropy in the turbulent shear flow.

The K values obtained by the statistical mixing length method were approximately ten times larger than those determined by logarithmic profile analysis. The latter values were considered more nearly correct and were used as a basis for correcting the other values.

The results showed that the magnitude of turbulent transfer is several orders of magnitude greater than molecular diffusion even at levels deep within the crop. The transfer coefficient showed a marked attenuation with depth below the top of the corn but remained a function of windspeed at all heights.

THE RAPID mixing of air by turbulence accounts for a large part of the diffusion of such entities as heat, momentum, water vapor, and carbon dioxide within the microclimate of the plant community. Turbulence, therefore, has a large role in determining the environmental conditions of the plants and thereby influences their physiological processes. Of these processes, the loss of water vapor by evapotranspiration and the fixation of carbon dioxide by photosynthesis are of major importance. A determination of turbulent transfer makes possible an evaluation of this exchange of water vapor and carbon dioxide between the

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plants and the atmosphere under natural field conditions. An understanding of the nature of turbulence and its interactions with the plant community is not only of basic interest, it is also of pragmatic importance in the management of crops for increased production.

Until recently most of the micrometeorological studies on the nature of turbulence near the earth's surface were restricted to the surface-air-layer above the vegetation. The early investigations of the wind field above the surface, and in a few cases within the vegetated layer, were determinations of wind profiles (windspeed distributions with height). Geiger (3) has discussed some of this early work. The work of Thornthwaite and Holzman (21) and Thornthwaite and Halstead (20), initiated the use of wind measurements to calculate the turbulent transfer of various molecular quantities from vegetated or bare soil surfaces. Sheppard (14) has reviewed much of the work on turbulent transfer through the air layer near the earth's surface. Several others have been very active in studying turbulence and turbulent transfer over cultivated fields (4, 5).

Although a few determinations of wind profiles within and above crops or trees were conducted some time ago (2, 10), the intensive study of the wind structure and turbulence within the crop is very recent (9, 17, 22). Penman and Long (12) in their rather complete study of the weather in wheat measured wind speeds within the crop but did not use these data to characterize the turbulent transfer. Stoller and Lemon (15) and Tan and Ling (18) in their preliminary wind investigations were some of the first to use turbulence theory and wind measurements to calculate turbulent transfer within the plant canopy.

The investigations reported in this paper were initiated in 1961 as a continuation of the initial preliminary studies. The objectives were to characterize the rate of vertical transfer resulting from turbulence within the crop by measuring the windspeed distributions and determining a momentum transfer coefficient. The transfer coefficient data and carbon dioxide profile data were used to calculate the flux of carbon dioxide and the distributions of net photosynthesis within the crop. We have discussed this portion of the study in an accompanying paper (18).

The distribution of evapotranspiration could also have been calculated from water vapor profile data. In some more recent studies the flux of water vapor has been calculated. The energy and momentum balance approaches have also been used to study the transfer within the crop. The results of these studies will be published separately.

Both the statistical and mixing-length theories of turbulence were used in this study to calculate the transfer coefficients. A brief statement of the theory is presented because it is not presented as used here in any single reference. The basic theories of turbulence are discussed in many texts and references, (6, 16).

THEORY

In contrast to laminar flow, turbulent flow is very irregular. Both the magnitude and the direction of the instantaneous velocity are functions of time as well as of space. This important irregular feature of turbulence makes it impossible to describe the motion in all details, but fortunately certain aspects of turbulent motion can be described by laws of probability and mean quantities. In addition, in contrast to laminar flow, the shearing stress between two fluid layers in highly turbulent flow is not due to molecular viscosity (friction), but rather to momentum transfer by motions of macroscopic bodies of fluid normal to the main direction of flow.

The characteristic fluctuation velocity of turbulent flow is defined for a given averaging period as

$$u' = u_i - u \qquad [1]$$

where u′ is the horizontal fluctuation velocity (cm sec^{-1}), u_i is the instantaneous velocity component in the direction of flow, and u is the average velocity.

Historically two theories concerning the nature of turbulence have developed, viz., Prandtl's mixing-length theory (13) and Taylor's statistical theory (19).

Mixing-Length Theory

Prandtl defined the mixing length as the distance a particle of fluid moved transverse to the mean flow before it lost its identity and mingled with other particles. When two layers of fluid with different velocities are moving adjacently, any transfer of parcels of fluid from one layer to the other will result in the transfer of momentum. (It will also result in a transfer of the molecular constituents.) The turbulent shearing stress between the two layers resulting from the transfer of momentum is the rate of momentum exchange per unit area. In terms of the turbulent shear components this is given as

$$\tau = \rho\, \overline{u'w'} \qquad [2]$$

where τ is the shearing stress (dynes cm^{-2} sec^{-1}), ρ is the fluid density (g cm^{-3}), and $\overline{u'w'}$ is the mean shear component (Reynolds stress) (cm^2 sec^{-2}), and w′ is the vertical fluctuation velocity (cm sec^{-1}).

Assuming u′ and w′ to be of the same order of magnitude, Prandtl used his definition of the mixing length and Equation [2] to obtain the following expression for the mean turbulent shearing stress:

$$\tau = \rho\, (l\,du/dz)^2 = \rho\, K_m\, du/dz \qquad [3]$$

where l is the mixing length (cm), z is the vertical height measured above ground (cm), and K_m is the eddy diffusivity or momentum transfer coefficient (cm^2 sec^{-1}). The coefficient K_m is somewhat analogous to the kinematic viscosity of laminar flow and the molecular diffusion coefficients in that it relates the rate of transfer to a gradient. However, since turbulent mixing is a type of mass transfer, K_m is nearly independent of the entity being transferred, especially in the case of fully developed turbulence near the surface. This is a very important feature; it means that K_m characterizes the effectiveness of the turbulent mixing more than any other single parameter.

A second Prandtl mixing length l′ is given by

$$K_m = l'\, \overline{(w'^2)}^{1/2} \qquad [4]$$

The two lengths l and l′ are not necessarily equal nor exactly independent of the entity being transferred. Evidence gathered from the study of turbulent fluids indicates that they must be of the same order of magnitude (16).

Velocity Profile

Since the shearing stress may be taken without serious error to be independent of height for a shallow layer above the roughness elements, and thus equal to its value τ_0 at the surface, a characteristic velocity u* can be defined as

$$u^* = (\tau_0/\rho)^{1/2} \simeq (\tau/\rho)^{1/2};\ \text{for } \tau_0 \simeq \tau \qquad [5]$$

Thus u* is the velocity of shear most often called the *friction velocity.* It is indicative of the amount of turbulence.

Above the surface where neither viscosity nor surface roughness has any appreciable effect on the position being considered, the mixing length is given as

$$l = kz \qquad [6]$$

where k, known as the von Karman constant, has a value of 0.4 for many conditions. Using this relationship Prandtl derived the well-known logarithmic velocity distribution for fully rough flow:

$$u = (u^*/k)\ \ln(z/z_o) \qquad [7]$$

where z_o, called the roughness length, is a function of the size of the roughness elements. The validity of this equation has been demonstrated in laboratory trials.

The concept has also been applied to the wind profile in the lower atmosphere. However, for the case of the wind profile over a tall vegetated surface it is necessary to introduce a new datum plane representing the level above which active turbulent exchange exists. The modified form of Equation [7] is

$$u = (u^*/k)\ln[(z - z_d)/z_o];\ z_d = (z_s - z_o) \qquad [8]$$

where z_s is the height at which the wind profile extrapolates to zero velocity and z_d is the height measured above ground at which the exchange coefficient K_m extrapolates to zero. The effective roughness length z_o, therefore, represents the height above z_d to the zero point displacement. Many field trials have shown Equation [8] to hold for nearly adiabatic conditions and for the region above the surface where the divergence of the shearing stress with height is very small compared with its value at the surface.

By Equations [3] and [6], considering also z_d, K_m is given by

$$K_m = lu^* = k(z - z_d)u^* \qquad [9]$$

This is a very useful expression for determining the transfer coefficient above the surface.

Both z_s and z_d, as used here, have sometimes been designated by a capital D; z_d has often been denoted by a small d (7, 8). Because of this confusion and sometimes incorrect use of the terms D and d, z_s and z_d will be used in this paper. Equations [8] and [9] are illustrated for a hypothetical, ideal case in Fig. 1.

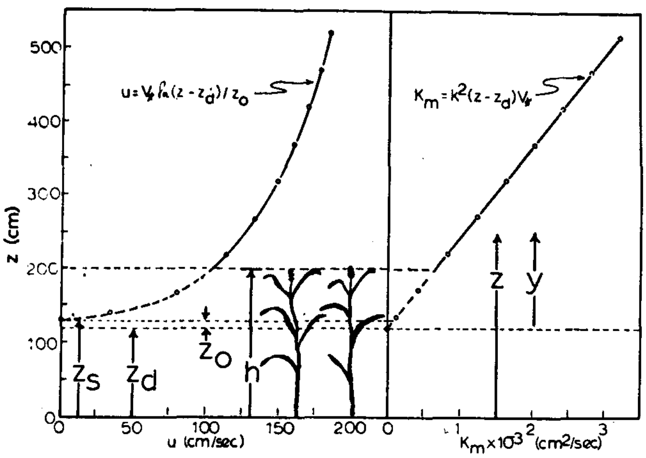

Fig. 1. Profiles of windspeed u and transfer coefficient K_m for a hypothetical case where $V^* = 50$ cm ($u^* = 20$ cm), $z_d = 120$ cm, $z_o = 10$ cm, $h = 200$ cm, and $k = 0.4$.

Statistical Theory

The statistical theory of turbulence as introduced by Taylor (19) has been treated by many writers, but inasmuch as the notation is generally quite complex a simplified version of the theory will be stated here. In contrast to the mixing-length theory which considers discrete particles as retaining their identity over a certain distance, the statistical theory regards turbulent motion as continuous.

Taylor introduced the theory utilizing the Lagrangian view but he later extended it to the Eulerian description of the spatial structure of turbulence. He utilized the correlation functions in an effort to define a length which would represent in some way the "size of an eddy."

The Eulerian spatial correlation is defined as

$$R(\Delta x) = \frac{\overline{u'_1(x,t)\ u'_2(x+\Delta x,t)}}{\overline{(u'^2_1)}^{1/2}\ \overline{(u'^2_2)}^{1/2}} \qquad [10]$$

where u_1' and u_2' are values at the same instant at points 1 and 2 separated by a distance Δx along the x axis. When points 1 and 2 are close together, $R(\Delta x)$ is nearly unity; but it tends to zero when they are taken far apart. A plot of $R(\Delta x)$ against x, where $R(\Delta x)$ has been determined for various values of x, gives the distribution of u along the x axis. Using this kind of a distribution, Taylor showed that if $R(\Delta x)$ went to zero at some value of x, say at $x = x_1$, then a length l_2 could be defined such that

$$l_2 = \int_0^\infty R(\Delta x)\ dx = \int_0^{x_1} R(\Delta x)\ dx \qquad [11]$$

which, ". . . may be taken as a possible definition of the average size of eddies. . ."

The Eulerian time correlation is defined as

$$R(\Delta t) = \overline{u'(x,t)\ u'(x,t + \Delta t)}/\overline{(u'^2)} \qquad [12]$$

where $u'(x,t)$ and $u'(x, t + \Delta t)$ are values at times t and $t + \Delta t$ at some point in space x. It is usually referred to as an autocorrelation coefficient. If the sequence of variations of u at a fixed point is assumed to be determined by the passage over the fixed point of an unchanging pattern of turbulence, it follows that

$$R(t) = R(x);\ \text{when } x = u\ t. \qquad [13]$$

Following the concepts of Taylor as given by Equation [11], the scale of turbulence L can be defined as

$$L = \int_0^X R_x(T)\ d(\Delta x) = L_x(T) \qquad [14]$$

$$= a \int_0^T R_t(T)\ d(\Delta t) = a\ L_t(T) \qquad [15]$$

where $L_x(T)$ and $L_t(T)$ are the space and time scales of turbulence, respectively, and (T) is written to emphasize dependence on averaging time T. X is the distance in the direction of measurement over which significant nonzero values of R_x exist, and "a" is the constant of proportionality relating the scales.

The time correlation lends itself to instrumentation much better than does the spatial correlation because it is easier to follow the fluctuations of the windspeed with time at one point than to measure them at two different points when the mean wind direction is constantly changing. By field measurements it has been shown (1) that for fully developed turbulence the constant "a" can be replaced by the mean windspeed u so that

$$L_x(T) = u\,L_t(T). \quad [16]$$

The Prandtl mixing length may also be regarded as a scale of turbulence and compared with L_x.

According to the Kolmogoroff similarity hypothesis, in the inertial subrange of eddy sizes

$$(1 - R) \sim \Delta t^{2/3} \quad [17]$$

where R is the autocorrelation coefficient, and Δt is the lag time. Field measurements have verified this (1).

Turbulence in the Vicinity of Plants

As the wind passes over a vegetated surface, the plants create small disturbances in the wind flow which become a part of the total turbulent regime. The effect of a single small disturbance is soon dissipated but a succession of these imposes a sequence of oscillations upon the mean motion. The intensity and character of the turbulence are a result of the disturbance pattern, or roughness of the surface, and the internal properties of the air mass already present when the vegetated surface is encountered.

Because there is no upper limit to the periods of motion, the mean quantities calculated will be a function of the averaging time. However, an averaging time can be chosen which will include nearly all of the variation. Durations of 5 minutes are considered adequate for heights of 1 meter.

In an analysis of wind in the vicinity of plants, Tan and Ling (18) found that for flow over a crop, an averaging period of 30 seconds smoothed out the high frequency fluctuations. Such short-period averaging gave satisfactory results when selected sampling was used to eliminate extreme variation as well as nonlinear effects.

PROCEDURES

Apparatus[3]

A rather inexpensive, commercially available type of heated thermocouple anemometer (Hastings–Raydist Model R-2 air meter with Model N-7 omnidirectional probe) was used to obtain continuous windspeed measurements. The probe is designed to eliminate the effect of ambient temperature fluctuations. It has a relatively fast response, a 10-millivolt output suitable for recording, and a high sensitivity at low velocities. The signal from each Hastings was amplified by a chopper stabilized DC amplifier and was recorded with a single pen recording milliammeter (Esterline Angus type AW, 0 to 1 milliamp range) at a chart speed of approximately 4.75 inches per minute.

A cup anemometer system (Beckman & Whitley model K 113) with a 35 mm recording camera was used to obtain windspeed profile measurements above the crop. The cup revolutions were registered by a bank of electro-mechanical counters.

Field Studies

Windspeed measurements were made on two clear days, August 1 and September 10, 1961, within a dense 10-acre crop of corn at Ithaca (Ellis Hollow), N. Y. The corn was planted in north-south, 29-inch rows at a density of 26,000 plants per acre. The crop was well fertilized and the soil favorable for luxurious growth.

Four cup anemometers were mounted above the crop. One Hastings probe was mounted alongside the uppermost cup as a reference and another Hastings probe was sequentially placed at several heights within the crop. Measurements were taken by all anemometers for 10 minutes at a time. The sequence of heights was traversed once each hour. The recording camera was set to record at 30-second intervals.

In accordance with the discussion on the nature of turbulence in the vicinity of plants, periods of semi-steady wind trace (periods preceded and followed by approximately the same time average) of 30-second duration were selected. Windspeeds were read from the trace at 1-second intervals. Reduction and subsequent correlation analysis of the data were accomplished with the aid of an electronic computer.

[3] Any trade names or manufacturers listed do not imply endorsement by the U. S. Department of Agriculture but are mentioned for reference only.

RESULTS AND DISCUSSION

An example of a Hastings trace for a probe placed just above the top of the crop is shown in Fig. 2. The root mean square of the fluctuations typically is about 50% of the mean velocity.

Windspeed Profiles

A normalizing procedure was used to obtain continuous windspeed profiles from the Hastings data taken sequentially at the various heights. The mean windspeeds for the variable heights were divided by the appropriate reference mean windspeeds. The resulting normalized (fractional) values were then grouped for comparable reference windspeeds. Four continuous profiles with height were the constructed from these data, see Figs. 3 and 4.

Hourly mean windspeed profiles for above the crop were calculated from the cup anemometer data. The corresponding within crop portions of the profiles were determined by graphic interpolation of the normalized profiles determined as mentioned above. The resulting profile values are given in Table 1. The shape of the profiles above the crop obtained from the cup data and from the 30-second periods was very similar. This indicated that the normalizing procedure yielded satisfactory results.

The crop heights indicated refer to the tallest portion of the crop. Between the two dates the elongation of the upper internodes increased the vertical distance between leaves in the upper portion of the crop, thus decreasing the effective drag surface at a given height. The less rapid attenuation of windspeed below the top of the crop on September 10 is a result of this difference.

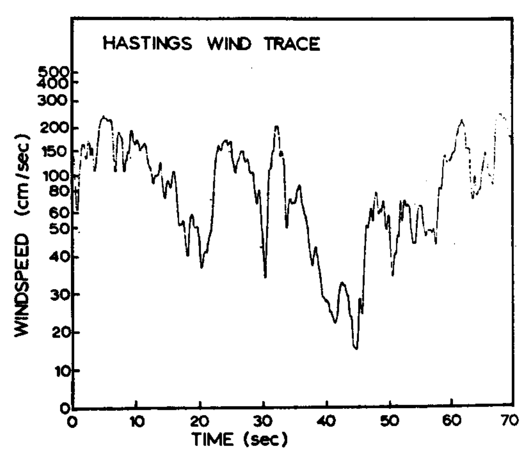

Fig. 2. Windspeed fluctuation record obtained from heated thermocouple anemometer probe placed just above top of crop as recorded by a null-balancing potentiometer (10 mv scale).

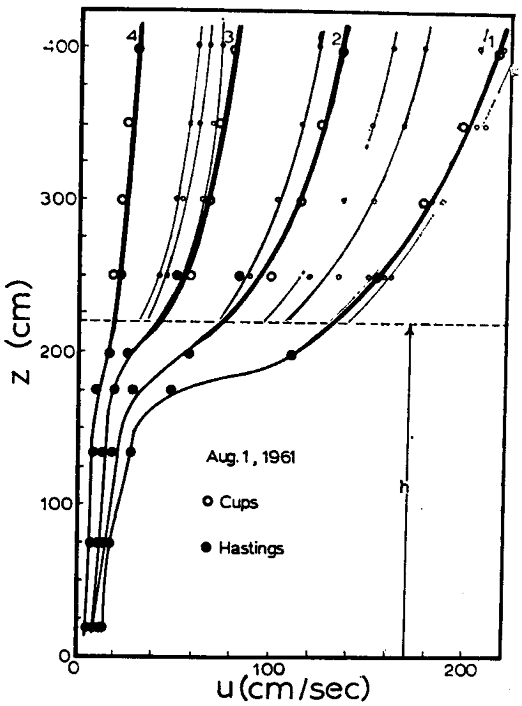

Fig. 3. Normalized windspeed profiles obtained from cup and Hastings anemometer data for an immature corn crop (Ellis Hollow).

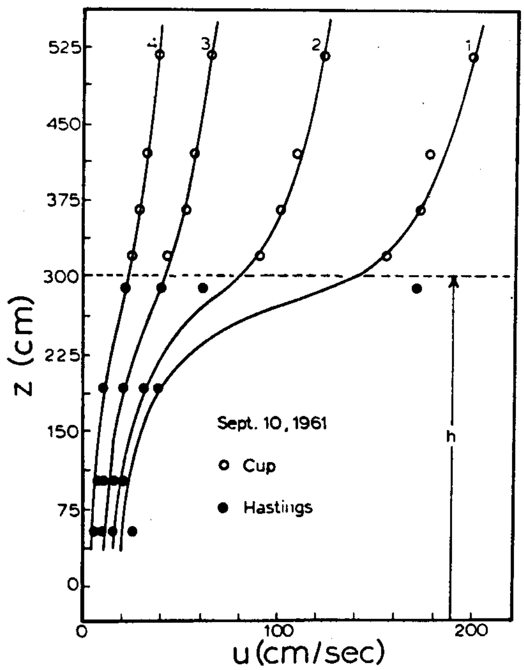

Fig. 4. Normalized windspeed profiles obtained from cup and Hastings anemometer data for a mature corn crop (Ellis Hollow).

Characterizing the Turbulence

Analysis of Windspeed Fluctuation. The 1-second windspeed values for each of the 30-second periods were used in an autocorrelation analysis to obtain R_t, the Eulerian time correlation coefficient (Equation [12]). The values were displaced 1 second for each time increment up to a maximum lag time of 10 seconds. The values of R_t were plotted against time t_n (t_n was less than 3 seconds) necessary for R_t to go to zero. The time scale of turbulence L_t was obtained by graphically integrating the area under this plot.

Table 1. Hourly mean windspeed profiles for a corn crop, Ellis Hollow, New York.

Height (cm)	Mean windspeed, cm/sec, at various times (hours, EST)									
	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21
					August 1, 1961					
400		206	177	217	223	161	123	67	60	73
350		198	166	204	208	150	115	62	57	69
300		175	151	181	187	136	102	53	51	64
250		152	134	159	166	119	88	46	47	56
250*		149	125	158	160	112	84	47	42	51
200*		106	86	114	118	75	51	23	20	25
175*		45	38	49	50	34	26	16	15	17
135*		25	20	29	30	18	15	13	13	14
20*		18	16	20	21	14	14	12	12	13
					September 10, 1961					
520	127	106	128	85	156	116	65	77		
420	111	96	115	76	139	101	56	63		
370	106	91	107	72	132	95	50	56		
320	93	81	97	64	116	80	42	50		
320*	96	79	96	62	119	87	46	51		
285*	70	57	71	45	90	63	33	36		
250*	48	41	48	34	56	44	26	30		
190*	33	30	33	26	36	31	20	22		
100*	16	15	16	14	17	15	13	13		

* Windspeed values obtained from graphic interpolation of the normalized profile data.

The values of R_t were checked against the two-thirds power law (Equation [17]). The fit was good in most cases, indicating fully-developed turbulence. It was evident, however, from this analysis that as the windspeed decreased at a given height or with depth into the crop the values increasingly deviated from the two-thirds relationship. This result agrees with that of others (1, 4, 9).

The horizontal root mean square velocity $\overline{(u'^2)}^{1/2}$ as determined from the 1-second values for each of the 30-second periods was found to be highly proportional to the mean windspeed for the respective height. The regression correlation coefficients ranged above 0.9.

The length scale of turbulence L_x was calculated using L_t and the mean windspeed u by Equation [16]. A different vertical distribution of L_x was obtained for each of the normalized windspeed profiles. The fact that the distribution of L_x was influenced by windspeed and not a function of height alone could well have been due to the effect of the wind on the roughness characteristics of the crop. Results of others (15) indicate that the roughness properties of a crop are markedly affected by windspeed.

Determination of the Transfer Coefficient. Equation [15] was used as the basis for calculating the vertical distribution of the transfer coefficient within the crop from the windspeed fluctuation data. However, since w′ was not measured directly, it was necessary to assume the condition of isotropic turbulence and equate the horizontal to the vertical fluctuation component. Stoller and Lemon (15) also assumed isotropy in this regard. The assumption is frequently made in studies of turbulence. However, in a zone of high shear flow such as exists near the earth's surface, the turbulence is far from isotropic.

In addition, because l′ was not measured directly, it was necessary to further assume that the space scale of turbulence was equal to the second mixing length. Accordingly, by analogy with equation [4], a special transfer coefficient was calculated by

$$S_K = L_x \overline{(u'^2)}^{1/2} \qquad [18]$$

where the special symbol S_K is used to distinguish between the true transfer coefficient defined by Equation [3]. The calculated values of S_K for the normalized windspeed profiles are given in Table 2.

Determination of the Vertical Flux of Momentum. An estimation of the shearing stress or vertical flux of momentum was defined by analogy with Equation [3] as

$$T_S = \rho S_K \, du/dz \qquad [19]$$

The distributions of T_s with height are given in Figs. 5 and 6. The decrease in T_S with depth below the top of the crop represents the amount of momentum extracted by the plants from the windstream. The nose, a sharp maximum, on the T_S profiles occurring in the upper part of the crop is probably unreal. A marked acceleration of the air in this region would be required to produce such an effect. It is possibly a result of extreme anisotropy in this region of high shear and thus an artifact of the method of determining S_K.

Comparison with Logarithmic Profile Results. Transfer coefficients were also calculated for the region above the crop by Equation [9]. A comparison of these values with the respective values of S_K showed S_K to be higher by nearly one order of magnitude. This was not surprising because of the assumptions required in the calculation of S_K. Even though the values of K_m were calculated for daylight periods when conditions for the logarithmic profile relationships were not rigorously met, they were taken to be the more nearly correct ones. Evidence indicates that

Table 2. Values of the special transfer coefficient S_K determined from fluctuating windspeed data in a corn crop.

Height cm	S_K ($cm^2 \, sec^{-1}$)			
	Profile			
	1	2	3	4
		August 1, 1961		
400	23,500	12,200	4,260	373
250	6,090	2,930	908	110
200	4,610	1,280	226	39
175	1,100	262	82	30
135	278	65	33	22
75	137	60	29	13
20	144	75	25	8
		September 10, 1961		
520	14,800	5,340	1,550	520
285	6,860	2,340	740	215
190	730	400	140	55
100	295	190	60	20
50	140	90	20	5

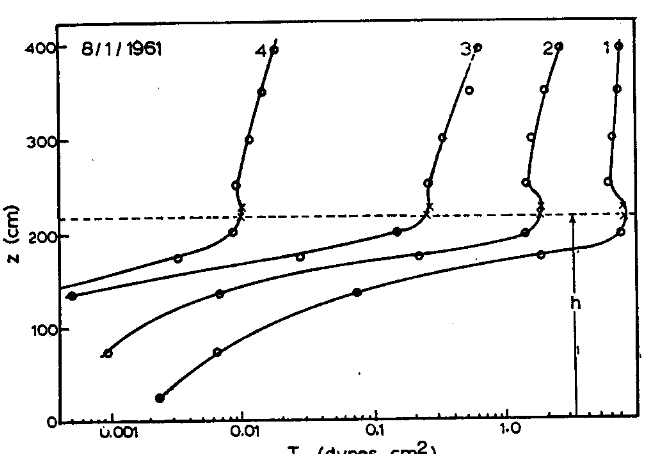

Fig. 5. Height distribution of momentum flux (shearing stress) T_S calculated from statistical transfer coefficients S_K corresponding to 4 normalized wind profiles (corn crop, Ellis Hollow).

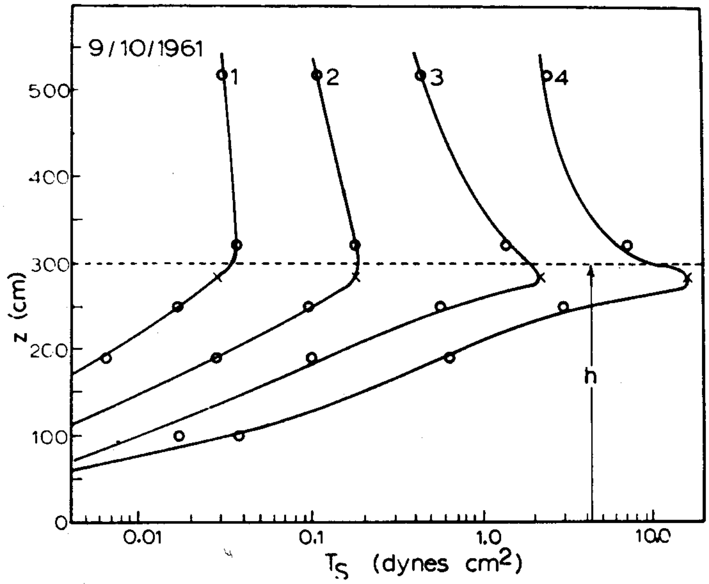

Fig. 6. Height distribution of momentum flux (shearing stress) T_S calculated from statistical transfer coefficients S_K corresponding to 4 normalized wind profiles (corn crop, Ellis Hollow).

even under nonneutral conditions the logarithmic profile gives reasonable results if the profile very near the surface is used where the effects of buoyancy are minor. Furthermore, the condition of the crop on both dates favored high evapotranspiration and thus decreased buoyancy.

To correct for the possible deviations from the stated assumptions, Equation [4] was rewritten:

$$K_m = b \, S_K = b \, L_x \, \overline{(u'^2)}^{1/2} \qquad [20]$$

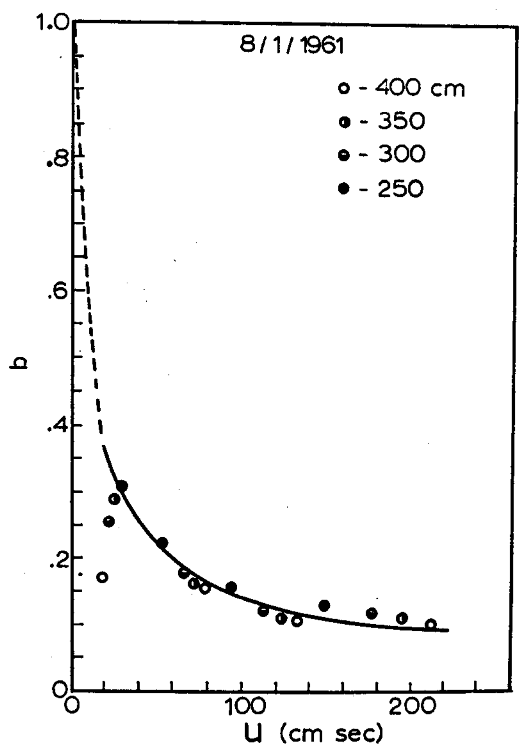

Fig. 7. The correction coefficient "b" as a function of the windspeed at 4 heights above the crop (corn crop, Ellis Hollow).

Table 3. Corrected values of transfer coefficient S_K for a corn crop, August 1, 1961.

Height cm	$K_m = b\,S_K$ (cm² sec⁻¹)			
	Profile			
	1	2	3	4
400	2,500	1,290	670	115
250	1,060	448	203	19
200	691	268	73	12
175	254	73	26	9
135	78	21	11	7
75	41	19	9	4
20	43	24	8	3

where b is the correction factor relating S_K to K_m. The relation of b to windspeed is shown in Fig. 7. The values of K_m obtained by correcting the S_K values of August 1 are given in Table 3.

It is true that the correction of the S_K values within the crop by the b values obtained above the crop is only an approximation. It was justified on the basis that b did not show an appreciable dependence on height above the crop. An independent method of evaluating b is necessary, or more fundamentally a direct measurement of w' and an evaluation of the relationship between l' and L_x is needed. In the absence of such information, the approximation did improve the data. The corrected values yielded shearing stress distributions without the nose.

CONCLUSION

The potential of the method used here in characterizing turbulent transfer will require further investigation. Both u' and w' need to be measured and the relationship between l' and L_x determined. Faster response recording instruments and a more automatic data extraction method to facilitate more frequent sampling than was used here are desirable.

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