SOME OBSERVATIONS OF TURBULENCE AND TURBULENT TRANSPORT WITHIN AND ABOVE PLANT CANOPIES

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Abstract. Observations have been made of the structure of turbulence and turbulent exchange within plant canopy layers. A new three-dimensional anemometer was used to measure the eddy fluxes of heat and momentum, and the related cospectra, within and above a corn crop and above a red pine forest. Measured values of momentum and heat fluxes, at each height within the corn canopy, were relatively constant proportions of the flux above the canopy, for the period of a day's observation. Extensive regions obeying a $-\frac{2}{3}$ power relation were found. Isotropy was found above the forest at high frequencies while above and within the corn crop, the ratios of the lateral and vertical spectral densities to the longitudinal component were less than the expected value in the $-\frac{2}{3}$ region. In all situations, the vertical velocity spectra were more peaked than a 'universal' curve, particularly a vertical velocity spectrum from above the forest. It is suggested that the additional variance results from the mixing caused by the individual roughness elements. As expected, the spectra could not be normalized using the height above the soil surface to calculate a non-dimensional frequency, but scaling heights were estimated by matching the frequencies of the peak of each curve with that of the 'universal' curve. Cospectra of uw and wT within the corn canopy were of similar shape and frequency regime, and were basically similar in shape to cospectra above the crop. All of the cospectra were more sharply peaked than 'universal' cospectral curves.

1. Introduction

The structure of turbulent flow and transport within a plant canopy cannot be accurately predicted from present knowledge of turbulent exchange processes in the free airstream above the surface. In addition, instrument limitations so far have prevented accurate measurements of the three-dimensional wind structure within plant canopies.

A quantitative description of the transport processes within plant layers is an essential part of plant community models since turbulent transfer directly affects the exchanges of carbon dioxide, water vapour, sensible heat and momentum between the air and both biomass and soil surfaces. Plant canopies vary widely in structure and each creates a very distinct environment. One example might be the micro-environment of the forest floor where solutions to problems of forest fire and seedling growth will result only from a sound understanding of the exchange processes.

The interest in this area over the last few years has led to the development of various models which are usually dependent on an assumption of one-dimensionality and on assumptions about the turbulent structure within the canopy. Examples of such models have been described by Brown and Covey (1966) and by Waggoner and Reifsnyder (1968) but in each one, reliance is placed upon flux-gradient relationships, the validity of which can be seriously questioned when distributed sources and sinks are contained in the volume being considered.

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The turbulent characteristics of the horizontal or total wind flows within vegetation canopies have been measured by Allen (1968) in a Japanese larch plantation and by Wright and Lemon (1966) within a corn crop using omnidirectional heated thermocouple anemometers. In wheat, Baines (1972) has measured turbulence with a single constant-temperature hot-wire anemometer positioned to minimize the effect of the crosswind component. Meroney (1968) conducted comparable studies in model canopies using a single constant-temperature hot-wire anemometer of unspecified directional sensitivity. Analyses of the turbulent structure of individual velocity components have been undertaken by McBean (1968) using a vertical propeller anemometer within two pine forests and by Isobe (1972) using two unidirectional sonic anemometers inside a corn canopy. Isobe shows the cross-correlation of vertical or horizontal velocity components at two different heights and power spectra of the two velocity components, but does not report any attempt at momentum flux measurement or cospectral analysis. In McBean's study, simultaneous measurements of temperature and humidity from relatively fast response instruments were correlated with the vertical wind to estimate the vertical fluxes of heat and water vapour, and their cospectra. The energy flux obtained (sensible plus latent heat) did not approximate the net radiation but the results indicated that the shape of the wT cospectrum might be different from that measured over open ground. McBean suggested that instruments with a response of at least 10 Hz are required for such studies and that spatial averaging is necessary.

In this study, we present data taken in the Fall of 1971 with a fast-response, miniature anemometer (Shaw *et al.*, 1973) designed specifically to investigate the three-dimensional characteristics of turbulent flow and eddy transport within vegetation canopies. Four such instruments were constructed and operated within and above a corn canopy, and one unit was operated above a red pine forest.

Eddy-correlation flux density measurements depend upon the continuous monitoring of eddy transport by the sensing instruments. Thus, both the instruments and the analysis technique must be able to respond over the entire frequency band in which transport occurs and, to be useful, measurements made at a reasonable number of sampling points must provide a satisfactory representation of the flux density for the area being studied. This requires that the flux density must not vary significantly with horizontal position and that divergence or very low frequency transport must be minimal. Experience has shown that when the measurements are made several metres above a relatively smooth surface, only one eddy-correlation measurement, averaged over 15 or 30 min, can often provide very useful information. No such experience exists for measurements within and a short distance above plant canopies.

It is likely that homogeneity in biomass distribution does not exist for all scales of turbulence within a vegetation canopy and single point estimates may not provide adequate descriptions of the transport and turbulence characteristics for the entire canopy. The canopies of different types of vegetation probably differ greatly in this respect; for example, an agricultural field crop such as corn might be considered to be far more homogeneous than a natural or managed forest with large open spaces between densely leaved crowns. An important feature is the manner in which the scales of the homogeneity relate to the scales of the turbulent eddies that contribute to the total energy or to the transport.

2. Description of the Sites

The experimental study began late in September 1971 in a cornfield at the Elora Research Station, Elora, Ontario, Canada. Although cutting operations reduced the fetch during the period of study, it was never less than 115 m in any direction. Corn (*Zea mays*) had been planted in 76-cm rows; at the start of the experiment the crop was about 290 cm tall and was starting to senesce. The crop progressively deteriorated until at the end of the experiment, in the middle of October, few leaves showed any areas of green, the stand was noticeably less dense, and tassel or stem breakage had reduced the crop height to about 260 cm. The row direction was SE-NW and practically all the data presented were collected on days when the mean wind direction was from the SW, i.e., across the rows.

At the end of October 1971, the equipment was transferred to a tower in a stand of uniformly spaced red pine at Waterloo County Forest, Elmira, Ontario. The canopy was fairly uniform and about 11 m tall. Trees were spaced about 2.5 m apart in a square plantation. The fetch was approximately 160 m to the east, north and west but to the south, it was in excess of 400 m; no data are included for periods when the wind did not have a large southerly component. Because poor weather conditions caused a cancellation of the experiment before any measurements had been made within the canopy, only data from above the vegetation can be presented.

3. Experimental Methods

A new three-dimensional anemometer (Shaw *et al.*, 1973) was used to measure the three components of wind velocity. The instrument is basically a cylindrical hot-film anemometer which derives its directional sensitivity from the variation in local heat-transfer coefficient around its circumference. The film is split along its length, at the front and the back, to create two electrically isolated sensitive elements which together detect the angle of incidence of the instantaneous wind velocity. A horizontal element measures the total speed and elevation angle of the wind. It is kept facing the horizontal wind by a servo control system operated by a similar, vertically positioned, split-film. The servo system responds to frequencies of about 5 Hz while the hot-film elements follow fluctuations probably in excess of 100 Hz. A single-turn potentiometer monitors the horizontal position of the anemometer. The anemometer has no directional ambiguity and its sensitivity reduces to zero only as the elevation angle approaches plus or minus 90 degrees. Its spatial resolution is excellent, the sensing head fitting into a sphere of diameter 0.9 cm, and it is sensitive at velocities down to about 20 cm s^{-1}. The anemometer has been shown to compare well with a pressure-

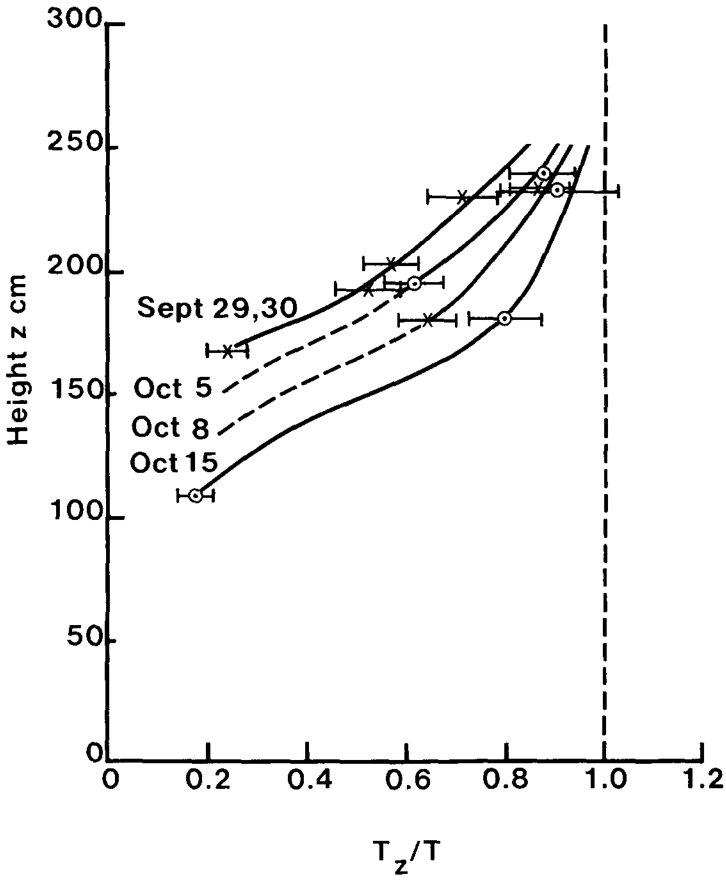

Fig. 1. Normalized momentum flux profiles within the corn canopy. The ratio of momentum flux T_z at height z to the momentum flux T above the canopy. Bars denote the standard deviations of the experimental values.

sphere anemometer in terms of wind component and shear-stress measurement over a grass surface.

Each anemometer was operated in conjunction with a fast-response fine-wire resistance thermometer located within approximately 5 cm of the hot films but upstream of the films with respect to the mean wind direction and positioned well below them. The thermometers were based on a design by Wesely *et al.* (1970) and the complete system including electronics is described by Silversides (1972).

Four anemometers were operated simultaneously in the field, each being mounted on an individual adjustable stand within a radius of approximately 4 m of the electronic control units.

Signals were analysed 'on line' by a Honeywell 316 digital computer* located in a

* Honeywell Controls Ltd., 740 Ellesmere Road, Scarborough, Ontario.

house trailer 150 m from the experimental site. Outputs from all anemometers and thermometers were sampled one hundred times per second. Each anemometer required four channels of data to specify fully the three wind components; two from the horizontal element for total speed and elevation, one from the horizontal wind direction potentiometer and a difference measurement from the vertical sensor to determine the error, at any instant, in the horizontal positioning of the servo system. A fifth channel was used for the temperature sensor at each site. Each of four parameters (u, v, w, T) was calculated at each sampling point together with its square and all cross-products. At the end of each 15-min sampling period, all means, variances and covariances were computed. No filtering was used in the calculations of the variances and covariances. A coordinate transformation to make $\bar{v}=\bar{w}=0$ was applied, as described by Tanner and Thurtell (1969), and the results (including both the heat and momentum fluxes) were printed out and punched onto paper tape. In

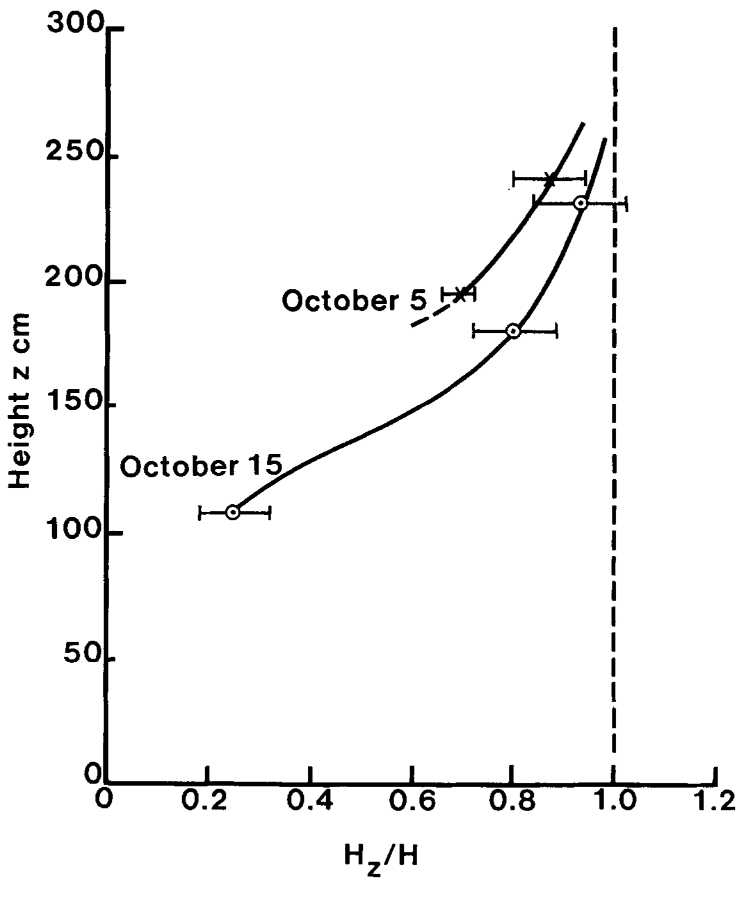

Fig. 2. Normalized heat flux profiles within the corn canopy. The ratio of heat flux H_z at height z to the heat flux H above the canopy. Bars denote standard deviations of the experimental values.

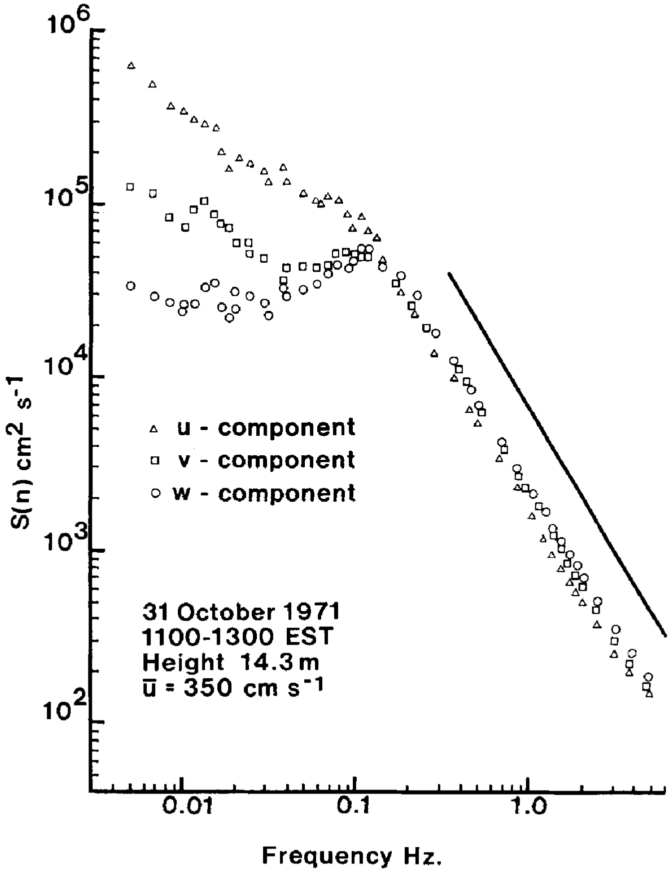

Fig. 3. Power spectra of *u*, *v* and *w* above a forest canopy. Solid line indicates $-\frac{5}{3}$ slope.

order to retain all the original information, prior to the coordinate transformation, the mean horizontal and mean elevation angles were included in the output.

In addition to the 'on line' analysis, selected periods of data from one site were stored on magnetic tape using a Sangamo model 3562 FM tape recorder* operating at 4.76 cm s^{-1}. Data stored in this manner could be reproduced with a high degree of accuracy, the means and cross-products differing by only a few percent from the 'on line' analysis. The recorded signals were used for variance spectral and co-spectral analysis of *u*, *v*, *w* and *T*. All spectral analysis was completed on the Honeywell 316 computer using the techniques described by Silversides (1972) and based upon the procedures outlined by Blackman and Tukey (1958), and Jenkins and Watts (1968). Sampling periods for the spectral analyses were 105 and 120 min in duration.

* Sangamo Electric Co., Springfield, Illinois, U.S.A.

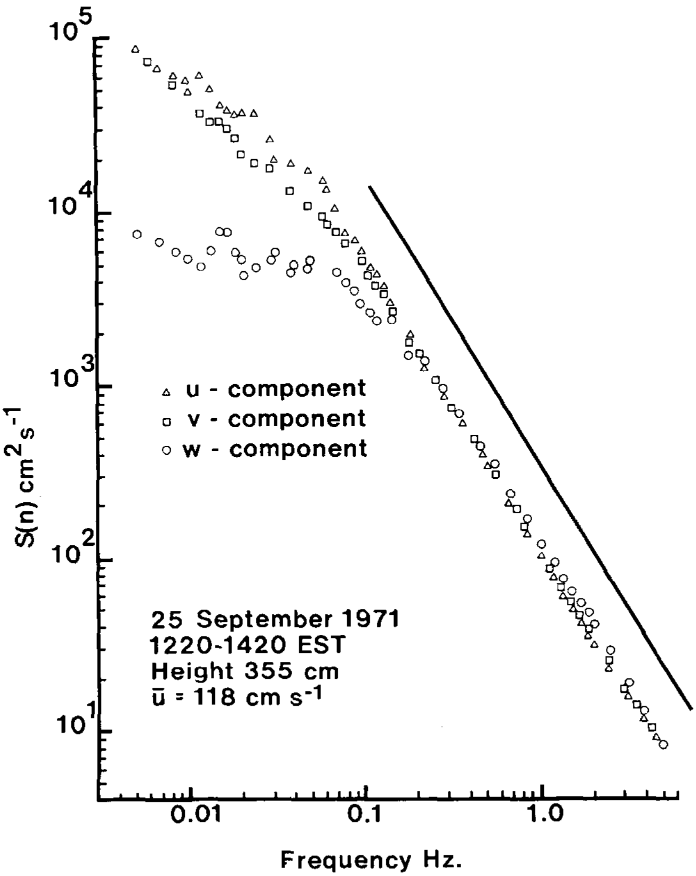

Fig. 4. Power spectra of *u*, *v* and *w* above a corn canopy. Solid line indicates −5/3 slope.

4. Results and Discussion

Elevation angles of mean wind velocity measured by the anemometer, above and within the corn crop, during a 7-h period on 15 October 1971, are shown in Table I along with standard deviations of the twenty-eight 15-min mean values. A positive mean elevation angle indicates net upflow.

The variation with height of the measured mean elevation angle is no greater than has been observed between all four instruments operating side by side above the canopy. The standard deviation of the 15-min means increases with depth into the canopy but it is not known whether this is a real variation or whether it reflects the decrease in angular sensitivity of the anemometer with decreasing wind speed. Regions with a significant mean vertical component were, therefore, not found, but this evidence is not conclusive.

These results suggested that local convergence was small in this canopy and it was

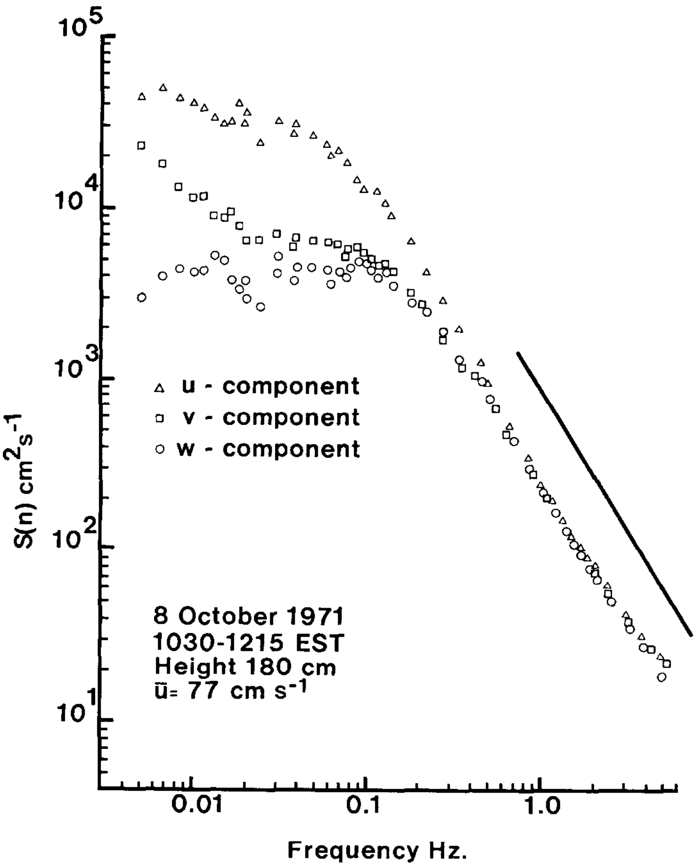

Fig. 5. Power spectra of u, v and w within a corn canopy. Solid line indicates $-\frac{5}{3}$ slope.

TABLE I

Mean elevation angles

Instrument height, cm	355	231	180	107
Mean elevation angle, degrees	0.8	−1.1	−0.9	0.2
Standard deviation, degrees	0.6	0.8	1.3	4.3

TABLE II

uw correlation coefficients

Instrument height, cm	355	231	180	107
$\overline{u'w'}/\sigma_u\sigma_w$	−0.40	−0.45	−0.57	−0.36

decided to use a coordinate transform which made $\bar{w}=\bar{v}=0$ in the analysis procedure. If regions of preferred updraughts or downdraughts were present, and contributed to the spatially averaged vertical transport, it is believed that significant differences in flux density would be observed between sampling points, at the same height but at different locations within the canopy.

Observations have been made of the horizontal variations in momentum flux density, within distances of a few row spacings, inside a corn crop. Differences of only about 10% were observed in the upper portion of the canopy while differences of 25% occurred between sampling points in the central portion. These measurements were made late in September 1971 and probably relate fairly well to measurements that might be made earlier in the season in an actively growing crop. Furthermore, fluxes measured at a point were relatively constant proportions of the fluxes measured above the vegetation (Section 4.2). These results are very encouraging and suggest that eddy-correlation measurements of transport, within some homogeneous plant canopies, are a feasible proposition. It is felt that more measurements of this type are badly needed. In particular it will be necessary to compare fluxes at more widely separated locations. Byrne and Rose (1972) have identified regions of non-horizontal

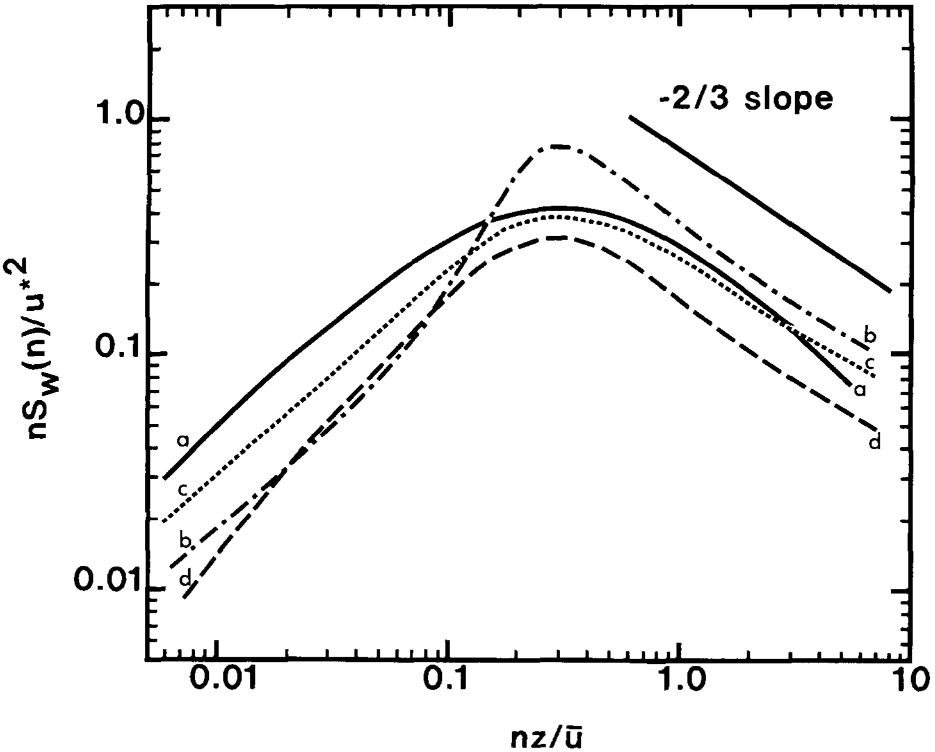

Fig. 6. Normalized spectra of vertical velocity. (a) Busch and Panofsky (1968); (b) above the forest; (c) above the corn crop; (d) within the corn canopy.

mean wind motions in a field of Townsville stylo using non-buoyant smoke sources. They ascribe such conditions to spatial variations in the degree of water stress and to non-uniformity in crop height.

Because no fast-response humidity sensor was available, an energy balance comparison with the canopy could not be made and no direct evaluations of the canopy flux measurements are included in this report.

4.1. Non-spectral statistics within and above the canopy

Above open terrain, the standard deviation of the vertical velocity σ_w has been shown to be independent of height in neutral atmospheres and to be proportional to the friction velocity u^*. The constant of proportionality is believed to be a universal constant (Lumley and Panofsky, 1964). Above the corn at Elora, a mean value for σ_w/u^* of 1.26 ± 0.01 was derived from 106 observations, when the stability parameter z/L lay between $+0.02$ and -0.15, while above the forest, a mean value of 1.25 ± 0.02 was obtained from 21 near-neutral runs. These values are in excellent agreement with the 1.25 for σ_w/u^* found by Thurtell *et al.* (1970) over a grass surface using a pressure-sphere anemometer, and they compare with a value of 1.3 obtained by Haugen *et al.* (1971) using sonic anemometers over a surface of wheat stubble.

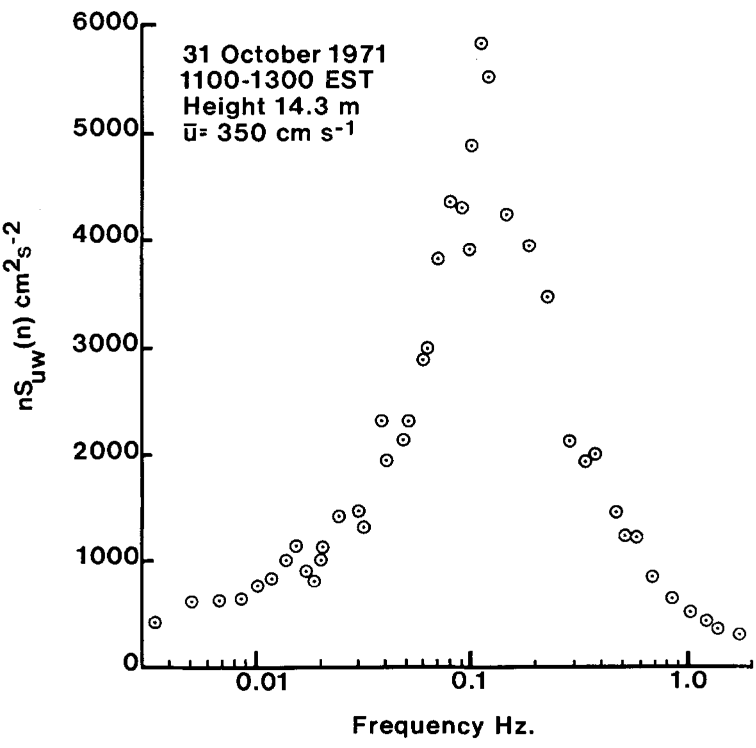

Fig. 7. Cospectrum of u and w above a forest canopy.

The relationship between σ_w and u^* within the corn canopy was investigated. In the upper portion of the canopy σ_w/u^* was smaller than the value observed above the vegetation and 172 results from three different probes located in the upper third of the canopy yielded a mean value of 1.12 ± 0.01. Deeper into the canopy, the reverse was true with σ_w/u^* equalling 1.45 ± 0.03 from 28 runs at a height of 107 cm. These results suggest that the degree of correlation between the vertical and longitudinal components of the wind velocity is a function of height inside the crop.

Table II shows the *uw* correlation coefficients derived from twenty-eight 15-min sampling periods on 15 October 1971 at four different locations, the highest anemometer being about 95 cm above the top of the crop.

The results show an increased correlation coefficient between *u* and *w* in the upper part of the canopy and a corresponding decrease at lesser heights. These changes undoubtedly account for the observed differences in the ratio of the standard deviation of the vertical wind to the friction velocity.

In contrast, vertical wind and temperature appeared to be equally well correlated above and within the upper portion of the canopy (Table III). Fluctuations of *w* and *T* in the lower half of the canopy were again more poorly correlated.

It is not clear why the *uw* correlation coefficient should increase in the canopy but it would seem to imply that the presence of the vegetation has a significant effect on the structure of the turbulent flow through the stand.

4.2. Profiles of Momentum and Heat Flux inside the Canopy

Daytime heat-flux and shear-stress values measured within the canopy were relatively constant proportions, at each height, of the fluxes measured above the canopy for the period of each day's operation. Normalized mean profiles for five days of shear-stress and two days of heat-flux measurements have been hand drawn and are shown in Figures 1 and 2. The number of observations (15-min sampling periods), included in each point, ranges from 14 (8 October) to 28 (15 October) for momentum flux, and from 10 (5 October) to 23 (15 October) for heat flux. The bars around the mean values denote the standard deviations of the measured values at each height.

The heat-flux profiles were made on sunny days and no change in their shapes was detected with changing Sun elevation. This seems to be a little surprising but its

TABLE III

wT correlation coefficients

Stability z/L	No. of samples	Instrument height in cm 355	231	180	107
-0.15 to -0.10	4	0.42	0.42	0.45	0.30
-0.10 to -0.05	18	0.40	0.40	0.40	0.24
-0.05 to 0	3	0.23	0.24	0.20	0.08
0 to $+0.05$	3	0.12	0.15	0.14	0.11

significance in terms of the energy balance could not be assessed because of a lack of net radiation and latent-heat measurements within the crop. Similarly, the normalized shear-stress profiles did not appear to be a function of wind speed. Shear-stress measured above the corn canopy was found to be proportional to the square of the wind speed and, therefore, at any level within the canopy was also linearly related to the square of the wind speed above the crop. In addition, momentum flux at points inside the crop was proportional to the square of the velocity at instrument height, but the constant of proportionality depended on the structure of the canopy and on the height of the measurement. This means that the momentum lost in any small increment of height was also proportional to the square of the velocity at that level. It may be noted that the momentum balance procedure for evaluating canopy fluxes (e.g., Wright and Brown, 1967) assumes that the momentum sink strength, $d\tau/dz$, at any level in the canopy is proportional to the square of the wind speed and to the leaf area per unit height at that level. Our measurements confirm the velocity relationship and will be used to evaluate the adequacy of the above procedure using measured leaf area densities. This work will be presented elsewhere under different authorship.

The flux profiles reveal the vertical distributions of sink strength, $d\tau/dz$, for

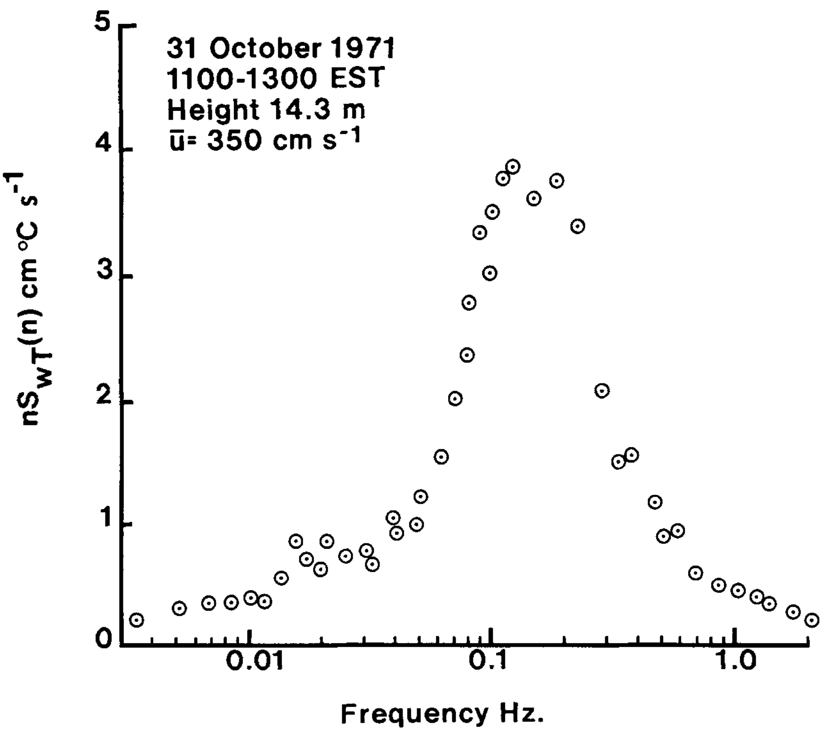

Fig. 8. Cospectrum of w and T above a forest canopy.

momentum and source strength, dH/dz, for sensible heat on the days in question. The progressive increase with time of the penetration of external air and solar radiation into the canopy is very apparent. During the period 29 September to 15 October, the momentum sink distribution shifted approximately 50 cm lower as the structure of the canopy gradually deteriorated.

The profiles of momentum and heat fluxes, for the same dates, do not appear to differ very greatly, being displaced in the vertical by 10 cm or less in all but the lowest portions of the curves. This implies that the relative sink and source strengths were similarly distributed within the canopy at these times. It is recognized that the structure of the canopy was then quite different from that of a healthy corn crop and our observations, concerning source and sink distributions, are not representative of a crop during the major portion of its growth cycle. No reversals of heat or momentum fluxes were found in the canopy, at least down to the levels of the lowest anemometer, and this might also be non-typical, particularly of vegetation with dense, elevated foliage.

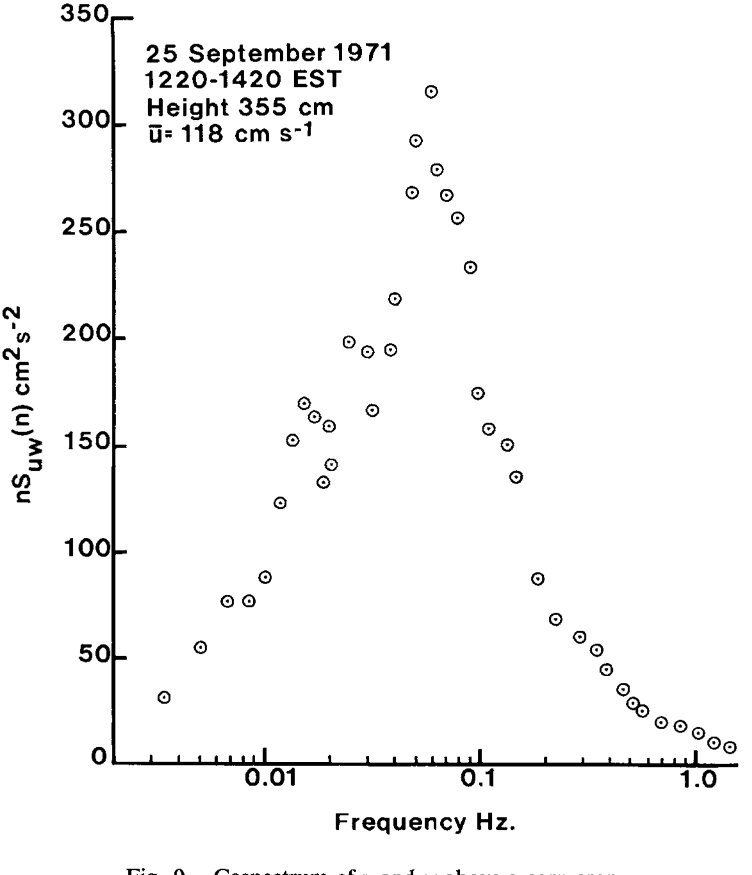

Fig. 9. Cospectrum of u and w above a corn crop.

4.3. Spectra of u, v and w

Power spectra of the three wind components from above the forest and from above and within the corn canopy are presented in Figures 3 to 5. Generally they form quite smooth curves, unlike those drawn by Isobe (1972) which exhibit a number of pronounced maxima. The differences probably result from the longer sampling period used in our analyses. Isobe analysed periods of only 10-min duration of data extracted manually from strip-chart recordings.

The concepts of local isotropy and of an inertial subrange of eddy sizes, in which there is an equilibrium transfer of energy from larger to smaller eddies, with no net loss due to viscosity, lead to the relationship

$$E(\kappa) = \alpha\varepsilon^{2/3}\kappa^{-5/3}$$

where $E(\kappa)$ is the energy spectrum function, ε is the dissipation rate, κ is wave number and α is a universal constant (e.g., Munn, 1966).

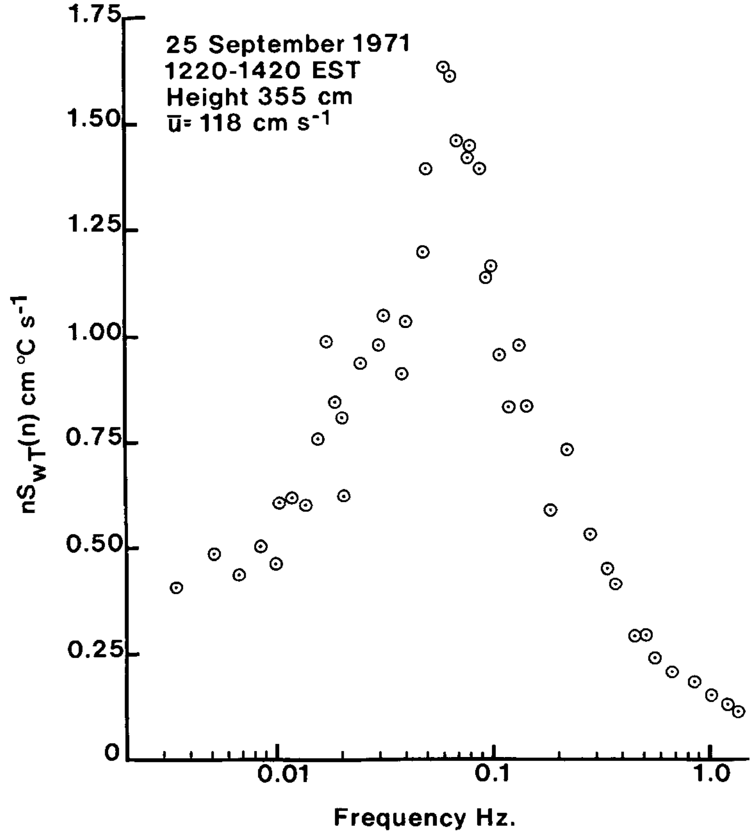

Fig. 10. Cospectrum of w and T above a corn canopy.

The relationship between transverse and longitudinal velocity correlations (e.g., Hinze, 1959) indicates that in the isotropic part of the $-\frac{5}{3}$ region, spectral densities of the lateral and vertical velocity components should be a factor $\frac{4}{3}$ greater than that of the longitudinal component.

A number of recent studies have presented data on the ratios of the one-dimensional velocity spectra but conclusive evidence of the presence of isotropy in the atmosphere still appears to be lacking. For example, Busch and Panofsky (1968) analysed Round Hill, Massachusetts data and found considerable scatter in the ratios of the lateral to longitudinal and vertical to longitudinal spectral densities in the high frequency portion of the spectra where a $-\frac{5}{3}$ power law could be distinguished. The ratio of the lateral to the longitudinal spectrum averaged to a value close to $\frac{4}{3}$ but the measured ratios of the vertical to the longitudinal spectrum were generally smaller than the expected value. Similarly, Miyake *et al.* (1970) found the vertical velocity spectra over water to have less energy than the longitudinal component in the $-\frac{5}{3}$ region.

TABLE IV

Ratios of velocity spectra in the $-\frac{5}{3}$ region

Location	$S_v(n)/S_u(n)$	$S_w(n)/S_u(n)$
Above the forest	1.27	1.36
Above the corn crop	1.06	1.25
Within the corn canopy	0.91	0.94

All of the power spectra measured with the split-film anemometer display extensive $-\frac{5}{3}$ regions. Ratios of the spectral estimates of the different velocity components, at the higher frequencies, were computed and the values for each situation averaged, usually over a frequency range of about one decade. The results are listed in Table IV.

The $\frac{4}{3}$ relationship, required by a condition of isotropy, was found to be approximated only above the forest. The ratios of the lateral and vertical spectra to the longitudinal component in the inertial subrange, above and within the corn crop, were smaller, especially those from inside the canopy.

In Figure 6, the vertical velocity spectral densities, multiplied by the frequency n and normalized by u^{*2}, are plotted against a non-dimensional frequency, $f = nz/\bar{u}$, and compared with a 'universal' curve drawn by Busch and Panofsky (1968) from Round Hill, Massachusetts data. Our curves have been subjectively smoothed. All observations represent slightly unstable conditions.

Plotted against the reduced frequency, the spectra should be functions only of stability (Lumley and Panofsky, 1964). The height is normally taken to be the distance above the surface but the presence of vegetation effectively shifts the zero plane as seen from above and complicates the spectral composition of the velocity component variances within its canopy.

A scaling height, z, was therefore chosen to match the frequencies of the peak of each curve with that of the 'universal' curve. The values of z necessary to accomplish this were 6.2 m above the forest (instrument height 14.3 m, tree-top height 11 m), 289 cm above the corn crop (instrument height 355 cm, crop height approximately 290 cm) and 108 cm within the corn canopy (instrument height 180 cm).

The vertical velocity spectra from the cornfield are a little more peaked than the Round Hill curve and there is relatively less energy at low frequencies. The spectrum from within the canopy would have matched that from above the crop more closely had they both been normalized by the total variance of vertical velocity instead of by u^*. The difference in the ratio σ_w/u^* between these two locations has been noted in Section 4.1. The vertical velocity spectrum above the forest is quite different; it contains appreciably more energy in its peak but falls off rapidly at lower frequencies. A vertical propeller, operating a short distance from the hot-film anemometer, exhibited an almost identical spectrum over the same period (Shaw *et al.*, 1973), except at the higher frequencies where the response of the propeller fell off. The additional energy probably results from the mechanical mixing caused by the individual elements of the very rough surface. These same effects probably contribute to the

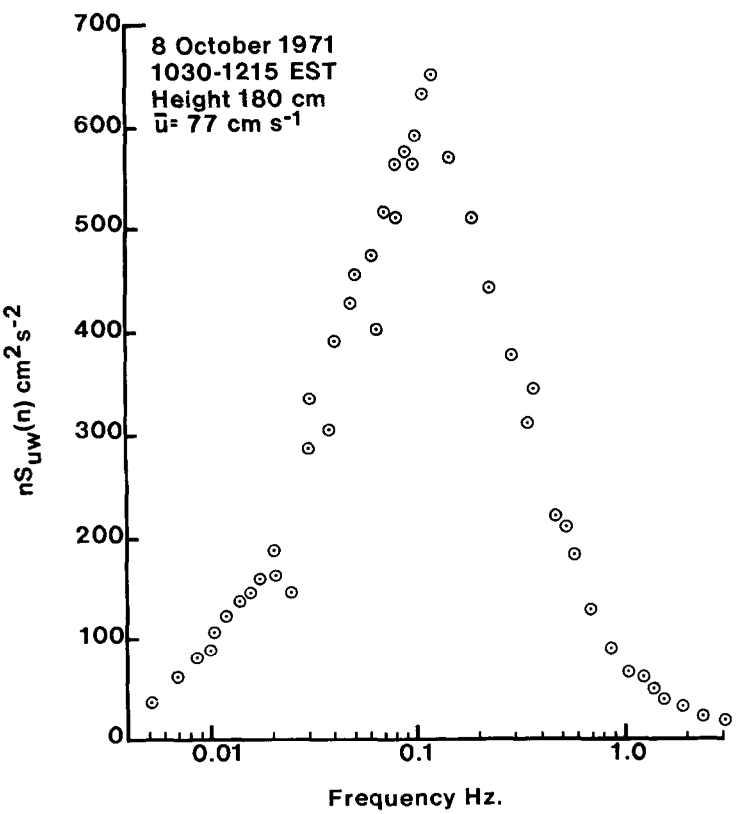

Fig. 11. Cospectrum of u and w within a corn canopy.

variance of the vertical velocity in and above the corn crop resulting in a slightly peaked nature of the spectra from these regions.

For a given canopy structure, there probably exists a unique relationship between the frequencies of the spectral peaks at different heights, at least under neutral conditions. Two factors, already mentioned, complicate the analysis; firstly, attempts to normalize the spectra using the height above the soil surface to compute a non-dimensional frequency, do not appear to be acceptable, and secondly, additional turbulent energy results from the presence of the individual elements of this vegetation. While the major portion of the variance might scale according to some unknown function of height and canopy structure, the additional mixing is probably a function of plant spacing. No attempt has been made to separate the two effects with the limited number of observations made to date.

4.4. Cospectra

Cospectra of u and w, and w and T are shown in Figures 7 to 12. Plotted in a semi-logarithmic form, in which areas are conserved, the two cospectra appear to be similar in shape and frequency regime in each situation, indicating that momentum

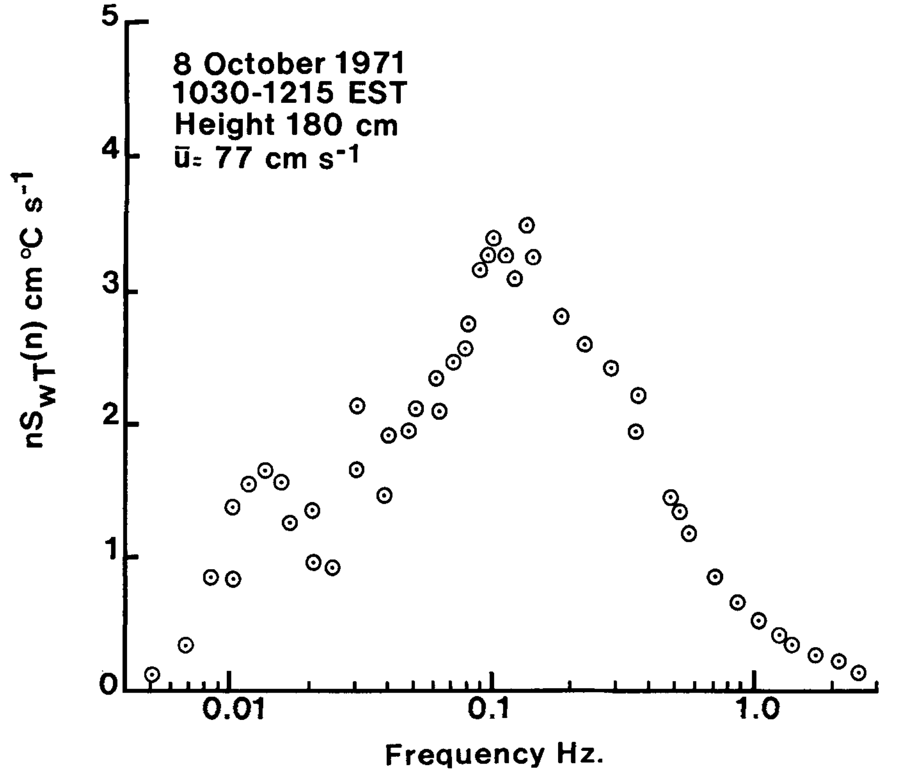

Fig. 12. Cospectrum of w and T within a corn canopy.

and sensible heat were being transported by eddies of similar size. If the sizes of eddies contributing to the covariance are estimated from $\bar{u}/n$ (i.e., an assumption of Taylor's hypothesis), the cospectral peaks are found to correspond to wavelengths of approximately 30 m above the red pine stand, 20 m above the corn crop and 6 m within the corn canopy.

The same data, but normalized according to the total covariance and subjectively smoothed, have been plotted on double logarithmic paper. They are presented in Figures 13 and 14, for momentum and heat flux, respectively. The abscissa is a non-dimensional frequency, $f = nz/\bar{u}$, where scaling heights, z, were selected to match the cospectral peaks with those of curves drawn by Panofsky and Mares (1968). These curves represent an average of several unstable runs during the experiments from which the comparison curve for the vertical velocity spectrum was obtained (Figure 6). Like the vertical velocity spectra, the cospectra from above and within the vegetation are more sharply peaked than the curves used for comparison. Again, the difference is most apparent above the forest.

The height, z, used to scale the frequency in each situation was much smaller than that used to scale the vertical velocity spectra (slightly less than 1/2 in the corn crop

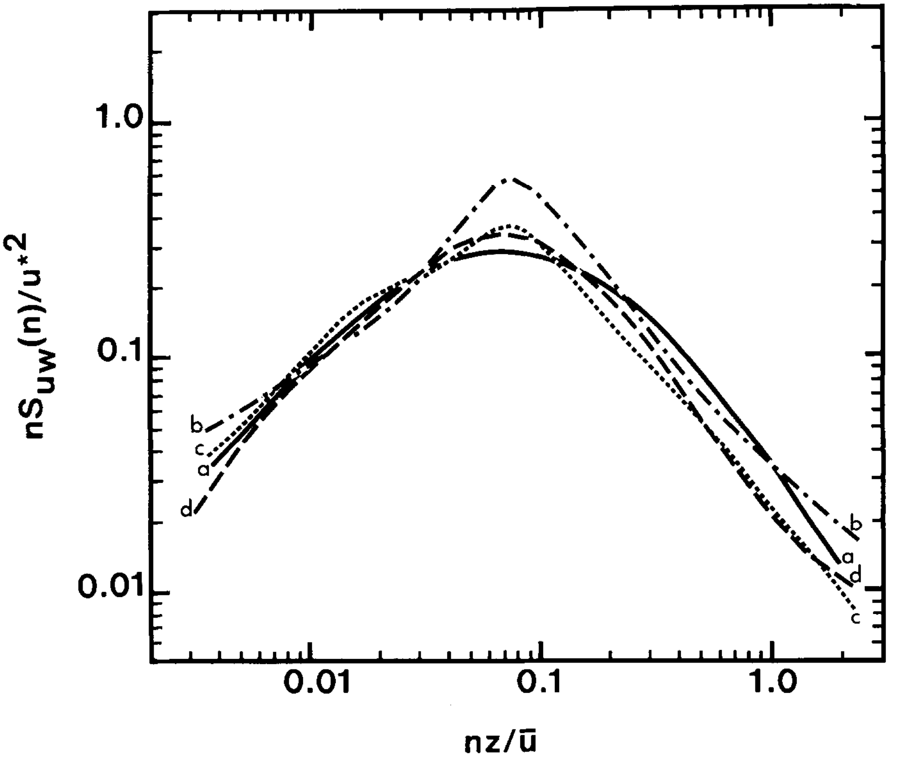

Fig. 13. Normalized *uw* cospectra. (a) Panofsky and Mares (1968); (b) above the forest; (c) above the corn crop; (d) within the corn canopy.

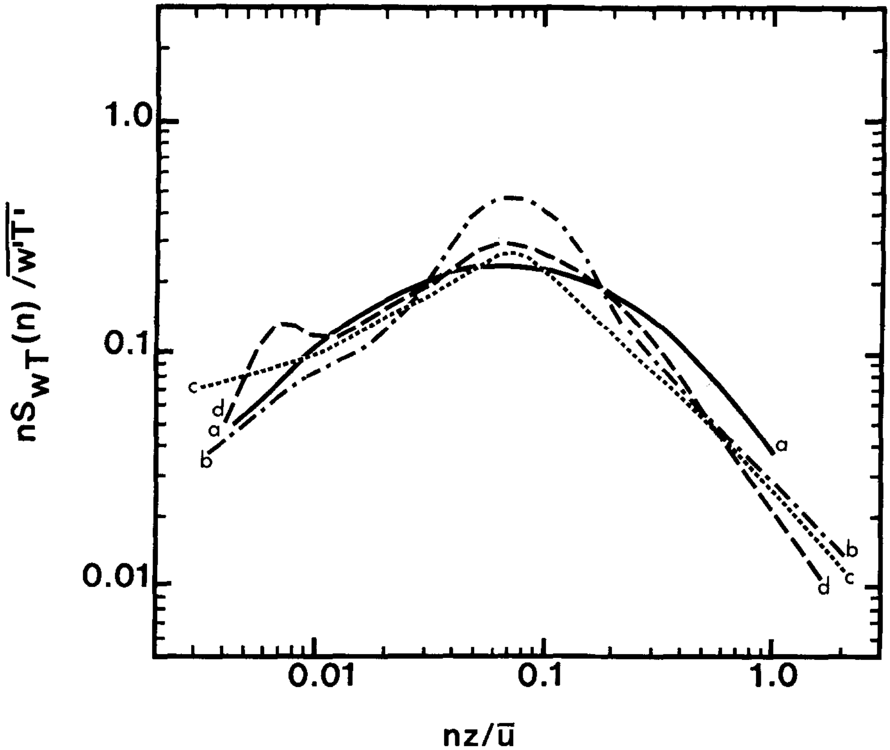

Fig. 14. Normalized wT cospectra. (a) Panofsky and Mares (1968); (b) above the forest; (c) above the corn crop; (d) within the corn canopy.

environment and about $\frac{1}{3}$ above the forest). Presumably, the relatively sharp peaks in the w-spectra were contributing significantly to the uw and wT cospectra, at the same frequencies, causing the peaks of the power spectra and the cospectra to be closer in frequency than is normally observed.

5. Summary

This appears to be the first time that shear-stress has been measured directly within a vegetation canopy and the first time that profiles of the flux density of heat and momentum have been measured by the eddy correlation technique in such a region. Measurements within the canopy seem to be quite self-consistent and horizontal variations in flux density do not appear to be excessive. It is hoped that in the future, latent heat fluxes can be included and an energy balance procedure used to provide additional proof that the instrument correctly measures 'in canopy' vertical fluxes.

Vertical velocity and temperature appeared to be equally well correlated above and within the upper portion of the corn canopy although the correlation was not as good at lesser heights. On the other hand, the vertical and longitudinal components of the wind speed had a higher correlation coefficient within the upper portion of the canopy. As a result, the ratio of the standard deviation of the vertical wind to the friction velocity (which above the canopy was in good agreement with recent measurements elsewhere) was somewhat smaller in the upper canopy. The significance of these observations is not fully understood.

During this experiment, heat and momentum fluxes at each height within the corn canopy were relatively constant proportions of the flux at the top of the canopy for each day. It is possible that some of the present canopy models can be evaluated in the light of these direct measurements but it must be pointed out that the corn canopy was rather open at this late time of year and the results that have been presented may not all be representative of the crop at earlier times in the season.

Extensive regions obeying a $-\frac{5}{3}$ power relation were found in all situations but isotropy was present only above the pine forest. Ratios of the spectral densities of the vertical and lateral velocity components to the longitudinal component were smaller, in the $-\frac{5}{3}$ region, than the expected value within and a short distance above the corn crop.

The similarity in the shape and frequency regimes of the wT and uw cospectra suggests that in these situations, heat and momentum were transported by eddies of the same size. Cospectra from within the corn canopy appear to be of similar shape to those computed above the vegetation surface but to date we do not have sufficient data to allow us to predict accurately the frequency domain of turbulent fluxes, either within the canopy or immediately above it. Neither the vertical velocity spectra nor the cospectra for heat and momentum could be normalized using the height of the instrument above the soil surface to calculate a non-dimensional frequency. The vertical velocity spectra and the cospectra were more sharply peaked than the 'universal' curves presented in the literature, and it is suggested that additional turbulent energy resulted from mechanical mixing due to the individual roughness elements.

It is believed that investigations of this type will help characterize the turbulent environment of the plant canopy and hopefully lead to more realistic predictive models of canopy environment conditions and of transport within these regions.

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