STATISTICS OF ATMOSPHERIC TURBULENCE WITHIN A NATURAL BLACK SPRUCE FOREST CANOPY

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Abstract. Turbulence statistics were measured in a natural black-spruce forest canopy in southeastern Manitoba, Canada. Sonic anemometers were used to measure time series of vertical wind velocity (w), and cup anemometers to measure horizontal wind speed (s), above the canopy and at seven different heights within the canopy. Vertical profiles were measured during 25 runs on eight different days when conditions above the canopy were near-neutral.

Profiles of s and of the standard deviation (σ_w) of w show relatively little scatter and suggest that, for this canopy and these stability conditions, profiles can be predicted from simple measurements made above the canopy. Within the canopy, a negative skewness and a high kurtosis of the w-frequency distributions indicate asymmetry and the persistence of large, high-velocity eddies. The Eulerian time scale is only a weak function of height within the canopy.

Although w-power spectra above the canopy are similar to those in the free atmosphere, we did not observe an extensive inertial subrange in the spectra within the canopy. Also, a second peak is present that is especially prominent near the ground. The lack of the inertial subrange is likely caused by the presence of sources and sinks for turbulent kinetic energy within our canopy. The secondary spectral peak is probably generated by wake turbulence caused by form drag on the wide, horizontal spruce branches.

1. Introduction

Statistics of atmospheric turbulence above and within plant canopies are needed to model mass and energy transfer among vegetation elements (e.g., Wilson *et al.*, 1981). Much of our knowledge of turbulence within plant canopies is based on measurements made within "model" canopies (Meroney, 1968; Seginer *et al.*, 1976; Raupach *et al.*, 1986) and within agricultural crops (Finnigan, 1979; Wilson *et al.*, 1982). Although turbulence above forests has been measured (Shaw *et al.*, 1974; Thompson, 1979; Anderson *et al.*, 1986), measurements within forest canopies are not as extensive. Much of the information of momentum transfer in forests has focused on profiles of the horizontal wind (Oliver, 1971; Pinker and Moses, 1982). Measurements of turbulence intensity (Cionco, 1972) and turbulence spectra (Allen, 1968; McBean, 1968) are more limited and pertain to specific forest types. More information is needed to allow a broader generalization of the turbulence regime in forests.

Our objective was to gather turbulence statistics within a natural forest canopy. The greater vertical height in forests, compared to agricultural crops, is an advantage for instrument placement. In addition, length scales are greater inside forests so that large instruments, such as sonic anemometers, can be used.

We studied a natural black-spruce forest canopy, typical of the Canadian

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boreal forest. We are interested in this forest type as part of an environmental research program studying the transport of radionuclides through the Canadian Precambrian Shield (Zach *et al.*, 1987). The turbulence statistics are needed for input to numerical models of atmospheric dispersion of contaminants within forest canopies (Davis, 1983).

2. Study Area

The study area is located near the Whiteshell Nuclear Research Establishment (50° 11′ N, 96° 04′ W) in southeastern Manitoba, Canada, about 100 km east-northeast of Winnipeg. It is situated on the edge of the Precambrian Shield and the general region is characterized by relatively flat terrain and mixed boreal forest. The experiment was conducted in a natural stand of black spruce (*Picea mariana*) covering a flat area of about 1 km^2. All runs were conducted with southerly winds, over a fetch of close to 1 km towards the south. The canopy was dense, averaging 7450 stems · ha^{-1} (average stem diameter = 8 cm), with tree heights of about 12 m. Because of the conical shape of the spruce crowns, the canopy was not fully closed above a height of about 9 m. The trees were even-sized and there were no openings in the canopy close to the experimental area. Below about 3 m, the canopy consisted mostly of dead spruce branches, and the ground cover was mostly sphagnum moss and sparse shrubs less than 0.3 m in height.

3. Methods

3.1. Instrumentation

Instruments were mounted on horizontal booms, about 0.5 m upwind of a light-gauge television tower. Horizontal wind speed, s, was measured with sensitive cup anemometers (Science Associates Inc., Princeton, NJ, USA, model 901). Vertical wind velocity, w, was measured with sonic anemometers similar to those described by Campbell and Unsworth (1979), but with smaller transducer heads (supplied by Campbell Scientific Inc. Logan, UT, USA). The sonic anemometers were always mounted a minimum of 0.5 m from the nearest vegetation element to prevent reflection of the sonic signal. Both the sonic and cup anemometers were calibrated over an open field before the experiment.

A three-dimensional (u, v, w) propeller anemometer (R. M. Young Co., Traverse City, MI, USA) was mounted above the canopy, at a height of 15.2 m. In addition, a fast-response thermocouple and sonic anemometer system (Campbell Scientific, Logan, UT, USA) was placed at a height of 13.7 m. Temperature gradients were estimated using small (12.5-μm diameter) thermocouples. The temperature gradient above the canopy was taken as the difference between the 14.9- and 11.9-m measurements, whereas the temperature gradient within the canopy was measured between the 6.2- and 1.4-m heights.

The sonic anemometer signals were low-pass filtered with an RC filter of 0.09 s time constant and then sampled by a datalogger (Campbell Scientific Inc., Logan, UT, USA, model CR7X) at 10 samples s^{-1}. The raw data were stored for subsequent analyses. The experimetal runs were done during the summer and autumn of 1986.

3.2. Horizontal spatial variability

We tested for horizontal spatial variability of s and w at five locations and at two heights (1.5 and 3 m). Towers were subjectively placed about 10 m apart to sample a range of tree spacings. However, we could not test "holes" because of the closed nature of the canopy. Pairs of w and s sensors were mounted at each location for runs of about 10-min duration.

3.3. Vertical profiles

Vertical profiles of turbulence characteristics were measured at a single location in runs of about 20-min duration. The instruments were located on a 15-m tower erected in the canopy and no trees were removed around the tower. In each run, pairs of sonic and cup anemometers were mounted at four heights within the canopy (either 1.5, 3.7, 5.3, 6.7, 7.7, 8.7, or 9.4 m). A fifth sonic anemometer-thermometer was always operated above the canopy at 13.7 m. Instruments were switched from position to position between runs to remove any consistent bias; typically, three to four runs were done on a given day.

3.4. Data analysis

The mean cup wind speed (s) and the standard deviation of the vertical velocity (σ_w) were calculated from the time series. The propeller-anemometer measurements of wind velocity were cosine-corrected (Horst, 1973) and rotated into u, v, and w components. The horizontal wind velocity at the 15.2-m height ($u_{15.2\,\mathrm{m}}$) was then calculated, as was the friction velocity above the canopy, u_*, from

$$u_* = (\overline{u' \cdot w'})^{1/2} . \tag{1}$$

The prime superscripts in Equation 1 denote deviations from the mean value; the overbar denotes an average. The sensible heat flux above the canopy, H, was calculated from the fast-response measurements of w and temperature (T) at the 13.7-m height as

$$H = \rho C_p \cdot \overline{w' \cdot T'} , \tag{2}$$

where ρC_p is the volumetric heat capacity of air. A positive w' represents an updraft. Stability above the canopy was characterized by the Monin–Obukov length, L, as

$$L = -u_*^3 \cdot \frac{\rho C_p \cdot \bar{T}}{k \cdot g \cdot H} , \tag{3}$$

where $\bar{T}$ is mean air temprature, g is acceleration due to gravity, and k is the von Karman constant (assumed = 0.4).

We calculated Eulerian time scales, τ, as

$$\tau = \int_0^\infty R(\xi)\, d\xi \,, \tag{4}$$

where $R(\xi)$ is the Eulerian autocorrelation function at lag time ξ,

$$R(\xi) = \frac{\overline{w'(t) \cdot w'(t+\xi)}}{\sigma_w^2} \,. \tag{5}$$

In practice, we chose the upper limit of integration to be the time at which $R(\xi)$ first reached zero. We also define two length scales based on τ,

$$l_w = \tau \cdot \sigma_w \tag{6}$$

$$l_s = \tau \cdot s \,. \tag{7}$$

Power spectra of w were calculated using a fast Fourier transform (Welch, 1967). The time-series data were determined, and divided into eight blocks (nominally 2048 data points each). The average power spectrum was calculated from the eight spectra for frequencies (n) greater than about 0.005 Hz. Lower frequency spectra were generated using the total time series modified with a low-pass filter. The high and low frequency spectra were combined to form a composite power spectrum. The spectra were truncated at $n = 2.5$ Hz, above which signal filtering and averaging over the anemometer path length (0.1 m nominal) caused a loss of energy.

4. Results and Discussion

4.1. Horizontal Spatial Variability

We determined the representativeness of vertical profile measurements at a single location by measuring horizontal spatial variability. Horizontal heterogeneity

TABLE I

Horizontal variability of cup wind speed (s)

Date	July 24	July 29	Aug. 5	Aug. 12	Aug. 29
Height (m)	1.5	1.5	1.5	1.5	3
Number of runs	1	4	3	6	2
			Mean s ($m \cdot s^{-1}$)		
Location A	0.60	0.19	0.13	0.52	0.52
Location B	0.46	0.17	0.15	—	—
Location C	0.66	0.19	0.15	0.53	0.51
Location D	0.55	0.18	0.14	0.49	0.52

TABLE II

Horizontal variability of σ_w

Date	July 24	July 29	Aug. 5	Aug. 12	Aug. 29
Height (m)	1.5	1.5	1.5	1.5	3
Number of runs	1	4	5	6	1
u_* ($m \cdot s^{-1}$)	0.89	0.51	0.52	0.62	0.76
	Mean σ_w ($m \cdot s^{-1}$)				
Location A	0.166	0.087	0.111	0.121	—
Location B	0.126	—	0.111	0.104	0.239
Location C	0.130	—	—	—	0.212
Location D	0.159	0.074	0.112	0.111	0.206
Location E	0.143	0.079	0.114	0.101	0.202
Spatial standard deviation (%)	12%	8%	1%	8%	8%

might be expected in a natural forest canopy where trees are not distributed uniformly. We measured s at four locations within the canopy and, except for the single run on July 24, the spatial variability at 1.5 m is about 5% (Table I). Comparisons of runs on July 29 with those of August 12 indicate that the spatial variability is not affected greatly by the magnitude of s. The cup anemometer threshold speed was $11.5\,cm \cdot s^{-1}$ and the measurements of August 5 included periods when the cups stalled. This was not a problem during the vertical profile runs because s was always greater than $0.3\,m \cdot s^{-1}$. The measurements on August 29 at the 3-m height showed little spatial variability.

We tested for horizontal variability of σ_w at five locations (TableII). Again, the single run on July 24 showed the most variability, and the other runs varied by less than 10%. Our calibration and mounting techniques were sufficiently rigorous to ensure a measurement error of only a few percent (±S.D.). In addition, measurements of $|\bar{w}|$ taken by combining results from two successive runs, in one of which the sonics were flipped upside down, were generally smaller than $0.05\,m \cdot s^{-1}$ and did not show a unidirectional vertical flow in the canopy (Amiro and Davis, 1987). These tests indicate that our canopy is relatively homogeneous and that vertical profiles measured at a single site are probably representative of the canopy as a whole.

4.2. Vertical profiles

Vertical profile measurements were made during September and October, 1986, on eight different days. Meteorological conditions were close to neutral with a southerly wind, except for October 16 when conditions were unstable (Table III). There was always a lapse above the canopy, and an inversion within the canopy between the 1.4- and 6.2-m heights.

TABLE III

Meteorological conditions during vertical profile measurements

Date	Number of runs	u_* ($m \cdot s^{-1}$)	$u_{15.2\,m}$ ($m \cdot s^{-1}$)	H ($W \cdot m^{-2}$)	$1/L$ (m^{-1})	Wind direction (° from N)	Air temperature (°C)	Temperature gradient (°C · m^{-1})	
								Above canopy	Inside canopy
Sept 11	3	0.35	1.8	73	−0.017	183	21	−0.08	0.16
Sept 22	3	0.84	3.9	195	−0.003	132	18	−0.08	0.31
Sept 23	2	0.54	3.0	63	−0.004	114	19	−0.11	0.34
Oct 9	3	0.64	3.4	192	−0.007	153	7	−0.03	0.40
Oct 15	3	0.59	3.7	67	−0.006	113	12	−0.10	0.24
Oct 16	3	0.27	1.4	187	−0.105	208	11	−0.03	0.41
Oct 20	4	0.46	2.4	92	−0.010	112	18	−0.12	0.48
Oct 24	4	0.48	2.3	186	−0.019	164	11	−0.04	0.40

4.2.1. *Wind Velocities*

Under neutral conditions, we assumed a logarithmic wind profile above the forest canopy (Plate and Quraishi, 1965):

$$u = \frac{u*}{k} \ln\left(\frac{z - d}{z_0}\right), \tag{8}$$

where z is the measurement height, d is the zero-plane displacement height, and z_0 is the roughness length. Letting $s = u$, we determined that under near-neutral conditions, $d = 6$ m and $z_0 = 1.1$ m. Assuming $d = 0.7 \cdot h$ (Cionco, 1983), and $z_0 = 0.13 \cdot h$ (Monteith, 1973), the canopy height, h, is about 8.5 m. We have indicated this height in Figures 1 to 5.

The profile of horizontal wind speed (s) within canopies usually follows an exponential relationship (Cionco, 1965):

$$s = s_h \exp\left[a\left(\frac{z}{h} - 1\right)\right], \tag{9}$$

where s_h is the speed at the canopy-top height (h), and a is the attenuation coefficient. Figure 1 shows the normalized s profile, including equation (9) with a equal to its best fit value of 2.4. The exponential relationship only holds between heights of h and about $0.6 \cdot h$, as also summarized by Cionco (1978). A lower rate of decrease of s with height occurs closer to the ground, as in other forest

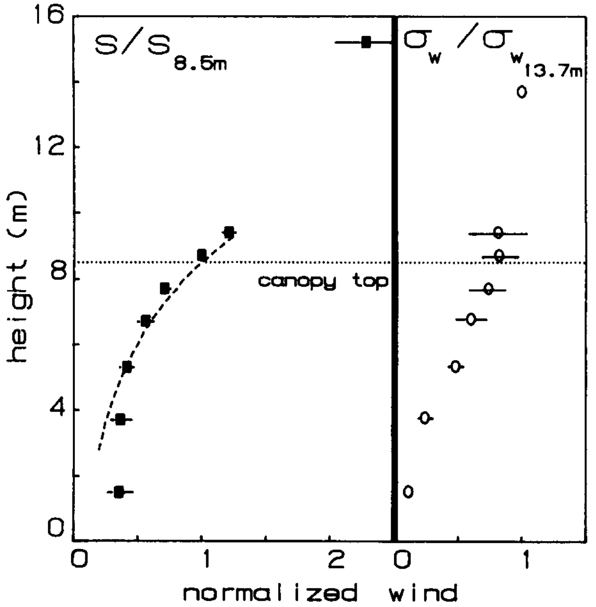


Fig. 1. Normalized vertical profiles of cup wind speed ($s/s_{8.5\,m}$) and $\sigma_w(\sigma_w/\sigma_{w\,13.7\,m})$. Means (±S.D.) are shown; on average, 14 runs are represented at each height. The curve is given by Equation (9) with $a = 2.4$.

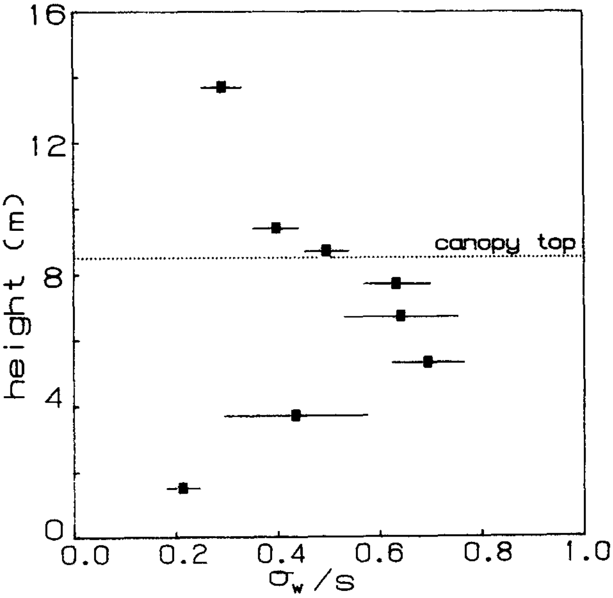


Fig. 2. Vertical profile of turbulence intensity, σ_w/s. Means (±S.D.) are shown; on average, 14 runs are represented at each height.

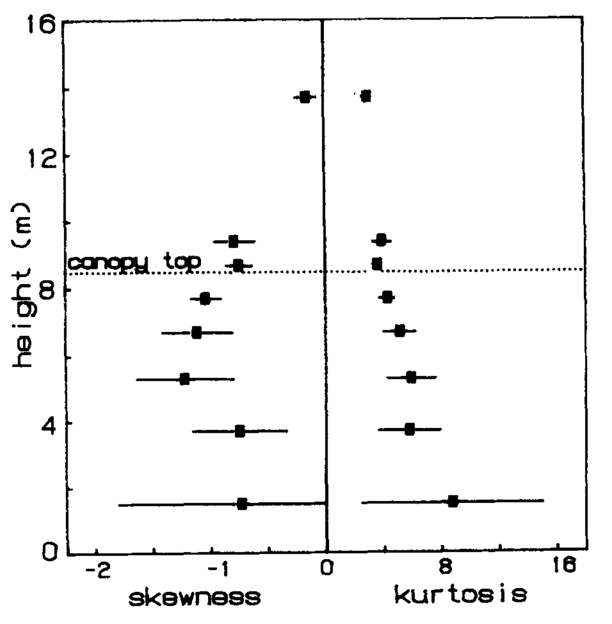


Fig. 3. Vertical profiles of skewness and kurtosis of w. Means (±S.D.) are shown; on average, 14 runs are represented at each height.

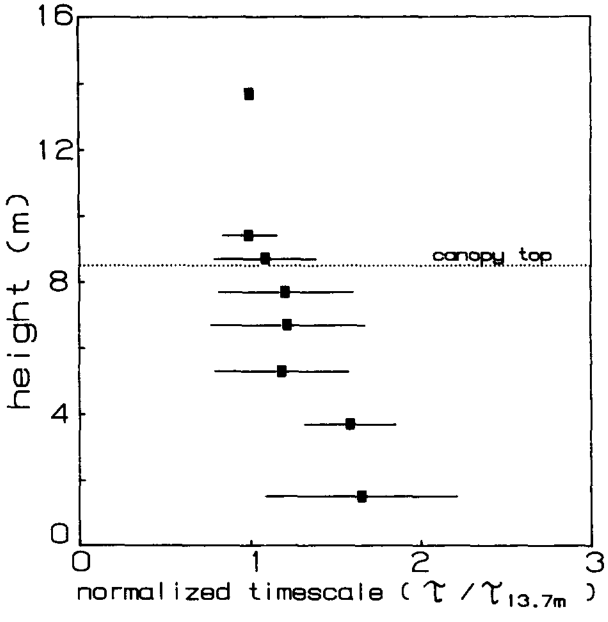


Fig. 4. Normalized vertical profile of Eulerian time scale ($\tau/\tau_{13.7\,m}$). Means (±S.D.) are shown; on average, 12 runs are represented at each height.

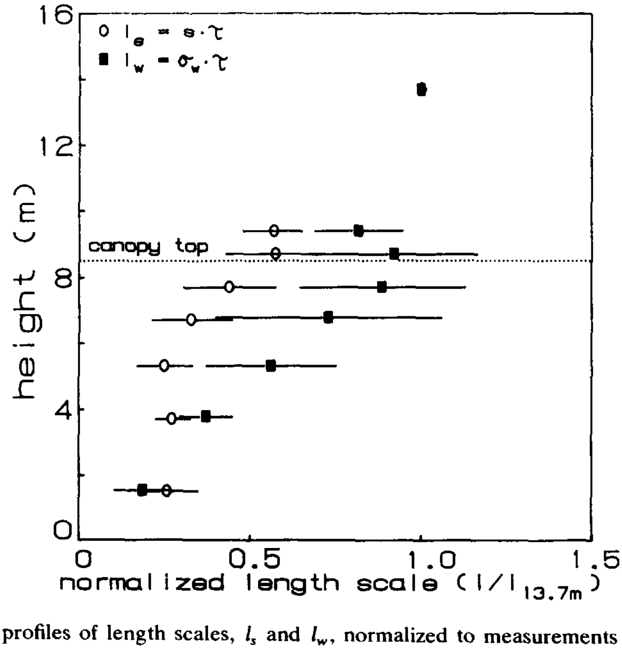


Fig. 5. Vertical profiles of length scales, l_s and l_w, normalized to measurements at 13.7 m. Means (±S.D.) are shown; on average, 12 runs are represented at each height. At the 13.7 m height, $\bar{l}_s = 4.4$ m; $\bar{l}_w = 1.4$ m.

canopies (Pinker and Moses, 1982). Our attenuation coefficient (a) is slightly less than the value (2.74) for a spruce canopy reported by Cionco (1978), based on data of Shinn.

The normalized profile of σ_w shows a decrease in σ_w within the canopy (Figure 1). This pattern is similar to that found in a corn canopy by Wilson *et al.* (1982). Profiles of σ_w/u_*, where u_* is measured above the canopy, show a similar pattern (data not shown).

The vertical profile of turbulence intensity, σ_w/s, has a maximum at about the 6-m height in the canopy (Figure 2). This is because σ_w decreases less rapidly than s with depth in the canopy (Figure 1). This profile pattern has been observed in both model (Seginer *et al.*, 1976) and natural canopies (Wilson *et al.*, 1982). The magnitude of σ_w/s with height is very similar to the pine forest data of Bradley *et al.* (as reported by Wilson *et al.*, 1982) with a maximum at about $0.7 \cdot h$.

The definite patterns and relatively low scatter in Figures 1 and 2 indicate that it may be possible to predict vertical profiles of σ_w and s in this canopy from measurements taken above the canopy.

4.2.2. *Higher Moments*

We calculated skewness ($\overline{w'^3}/(\overline{w'^2})^{3/2}$) and kurtosis ($\overline{w'^4}/(\overline{w'^2})^2$) to study the contributions of relative gust size to turbulence (e.g., Shaw and Seginer, 1987). Skewness is most negative in the densest part of the canopy, between 5 and 8 m (Figure 3). This pattern implies asymmetry of the contributions to turbulence originating from above and below this part of the canopy. Negative skewness is caused by larger scale motions aloft being carried downward (negative w), whereas inside the canopy, there is no corresponding source of large updrafts (positive w). Symmetry is observed both above the canopy and in most runs near the ground where skewness approaches zero. However, large negative skewness (< -1.8) in three of the 14 runs analyzed at the 1.5-m height caused the high standard deviation and relatively large negative mean shown in Figure 3. Time traces of these three runs showed large, but infrequent, unidirectional velocity variations from the mean as if, occasionally, a large eddy penetrated the canopy.

Increasing kurtosis close to the ground (Figure 3) indicates a greater relative contribution of larger $|w'|$, suggesting that larger gusts are more prevalent in the w-frequency distribution. Near the ground, we observed much greater variability in kurtosis between runs than was observed at higher heights (Figure 3). Kolmogorov-Smirnoff tests for normality indicated that the w-frequency distributions were not normal, but we could not make any satisfactory transformations to achieve normality.

4.2.3. *Time and Length Scales*

The normalized profile of Eulerian time scale ($\tau/\tau_{13.7\,\mathrm{m}}$) shows a slight decrease in τ with height above 1.5 m (Figure 4). The relationship within the canopy is approximately linear, with a slope of about $-0.075\ m^{-1}$. Normalization of the τ data to an average day, as done by Wilson *et al.* (1982), did not decrease the scatter. Time scales typically ranged between 1 and 4 s, although τ was about 7 s during runs with light winds.

Two length scales were plotted, l_s and l_w (Figure 5). The shape of the profiles of l_s and l_w are similar to those of s and σ_w (Figure 1), respectively, because τ is only a weak linear function of height (Figure 4). Our length-scale profiles are similar to those of Wilson *et al.* (1982) in a corn canopy. Our data suggest that $l_w \approx 0.14 \cdot z$, compared to $l_w \approx 0.1 \cdot z$ in the corn canopy. Above a height of about 7 m in our forest, the slope l_s/z is about 0.5 (an identical slope to that found by Wilson *et al.* (1982)), but between 1.5 and 7 m, l_s varies little with height (Figure 5).

4.3. Power Spectra

We calculated a non-dimensional spectral density, $n \cdot S(n)/\sigma_w^2$, where $S(n)$ is the power spectrum, and a non-dimensional frequency, $n \cdot z/s$ (e.g., Silversides, 1974).We assumed that the eddies scale linearly with height (supported by l_w in Figure 5), and that Taylor's hypothesis holds so that measurements in the time domain can be converted to the space domain (Taylor, 1938). This last assumption is unlikely to be true within the canopy but our scaling method is consistent throughout the profile. We did not account for stability.

Figure 6 presents normalized spectra above the canopy (13.7 m) and at the three heights within the canopy. A $-\frac{2}{3}$ slope is evident in the inertial subrange (e.g., Kaimal *et al.*, 1972) in the spectra measured above the canopy (13.7 m). Here, the spectral pattern is similar to that found above other forests (Thompson, 1979; Anderson *et al.*, 1986) and in the free atmosphere.

A different pattern exists inside the canopy (7.7-, 3.7- and 1.5-m heights) where the spectra depart from a $-\frac{2}{3}$ slope (Figure 6). A "loss" of energy appears in the 7.7- and 3.7-m spectra relative to the pattern above the canopy and a "shoulder" develops at high frequencies. This is complicated further at the 1.5-m height where, despite greater scatter, a second peak is evident at high frequencies. The location of the primary peak (at about $n \cdot z/s = 0.3$ at 13.7 m) in the spectra differs slightly between measurement heights; this could be caused by the use of the height above ground as the normalizing length scale and by changes in stability. At frequencies >2.5 Hz (data not shown), all spectra have a slope steeper than $-\frac{2}{3}$ caused by the signal filtering and averaging over the sonic-anemometer path length. Spectra measured at other heights within the canopy are consistent with the pattern shown in Figure 6.

The appearance of "shoulders" developing into peaks inside the canopy (Figure 6) can be explained by the generation of wake-turbulence caused by form drag on canopy elements (Raupach and Shaw, 1982). A simplified representation of this process (following Shaw and Seginer (1985) and neglecting molecular

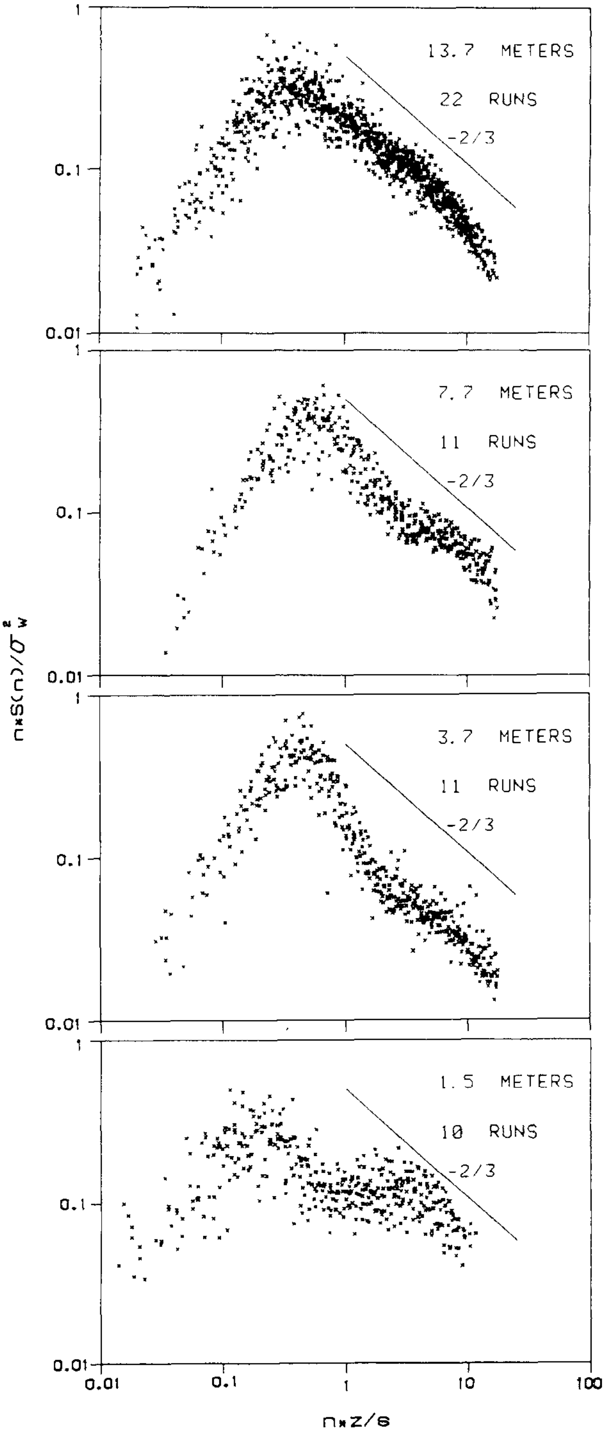
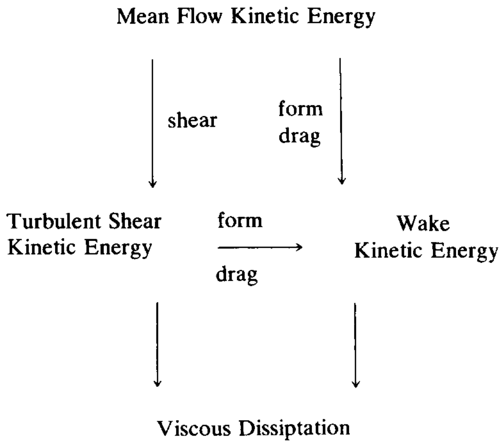


Fig. 6. Normalized *w*-spectra above the canopy (13.7 m), and within the canopy (7.7, 3.7 and 1.5 m).

diffusion and energy lost doing work) is:



Above the canopy, kinetic energy of the mean flow is transferred to kinetic energy in the turbulent shear that eventually dissipates. This process also happens within the canopy, but in addition, form drag on canopy elements causes energy transfer from both the mean flow and turbulent shear to the turbulent wakes, which then dissipate.

Some of these processes effectively interrupt the normal eddy cascade, so an inertial subrange is not observed. The concept of an inertial subrange assumes no sources or sinks for turbulent kinetic energy, a condition that does not hold within the canopy. The shapes of our spectra are not due simply to energy transfer from low frequencies to higher frequencies caused by form drag. This is evident in the spectra at the 3.7-m measurement height (Figure 6), where the departure from a $-\frac{2}{3}$ slope represents a greater energy loss than can be accounted for in the secondary peak. An apparent sink of turbulent kinetic energy, causing the absence of an inertial subrange, has been observed in the free atmosphere under stable conditions (Lumley and Panofsky, 1964). The environment within our canopy is very stable (Table III) and may not be able to support an inertial subrange. Above the 1.5 m height, our spectral slopes become less steep with increasing height in the canopy. This is consistent with decreasing stability and more suitable conditions for the existence of an inertial subrange. The lack of an inertial subrange has also been observed in spectra measured in a model canopy under conditions of low Reynold's number (Seginer *et al.*, 1976).

Our spectra are similar to those obtained within model canopies inside wind tunnels (Seginer *et al.*, 1976; Raupach *et al.*, 1986). The data of Seginer and coworkers showed that turbulence, generated inside the canopy, imposed a secondary peak in the spectra at frequencies about an order of magnitude greater than the primary-peak frequency. This secondary peak is not noticeable in spectra measured within corn canopies (Shaw *et al.*, 1974; Wilson *et al.*, 1982) but it does appear in the data presented by Allen (1968) for a larch plantation. The appearance of a secondary peak in the w-spectrum depends, in part, on the orientation of the vegetation elements (Seginer *et al.*, 1976). Horizontal elements likely shed more vortices in the w dimension that do vertical elements, and the wide, horizontal, tree branches in our spruce canopy are likely candidates to generate wake-turbulence.

We estimated the size of the canopy elements (D) that might cause the secondary peak at the 1.5-m height. Wake-turbulence theory indicates that, at Reynolds' numbers (Re) between 600 and 6000, the Strouhal number for cylinders ($\mathrm{St} = n \cdot D/u$) is approximately constant at $\mathrm{St} = 0.21$ (Schlichting, 1968). We chose n to be our secondary peak frequency, assumed that our elements were cylindrical, and assumed that the horizontal wind was the

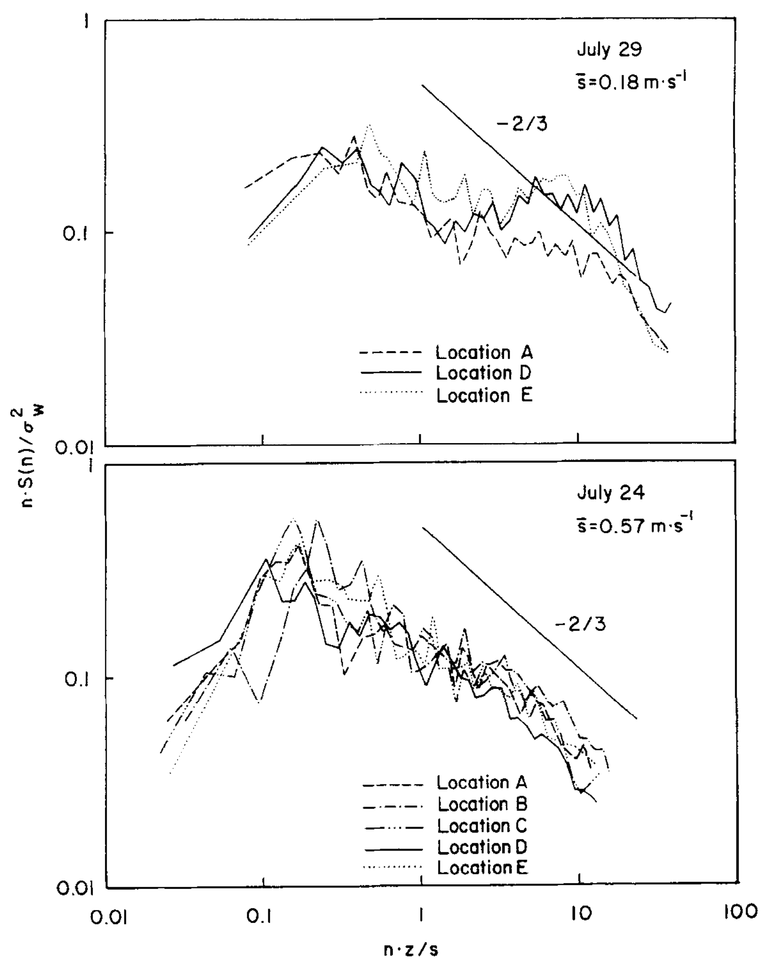


Fig. 7. Normalized w-spectra at different locations at the 1.5-m height on days with light winds (July 29) and strong winds (July 24).

dominating velocity contributing to turbulence generation ($\sigma_w/s \approx 0.2$ at 1.5 m, Figure 2). The calculated mean element size was 0.13 m (standard deviation = ± 0.04 m, 14 runs) corresponding to Re ≃ 4000. Whole branches in our canopy have sizes in the range of 0.1 to 0.3 m, supporting the thesis that the wake turbulence is induced by whole spruce-canopy branches. Individual spruce twigs would produce wake effects at higher frequencies than we observed (Grant, 1983), and would only persist very close to the twigs. Our measurements were made at least 1 m away from the nearest vegetation element, and it is likely that wake effects are seen for distances of at least 10 to 20 element sizes.

Simultaneous measurements of spectra at different locations at the 1.5-m height showed that the spectra were independent of horizontal location within the canopy (Figure 7). However, the primary peaks in the spectra occur at different non-dimensional frequencies on different days. Increased stability should shift the primary peak to higher normalized frequencies (Kaimal *et al.*, 1972). Our data are consistent with this, assuming that days with lighter winds impose a stronger inversion within the canopy (Figure 7). In addition, spectra measured on a windy day (July 24) do not express as strong a secondary peak as on a calmer day (July 29); on windy days, greater momentum penetration through the canopy may mask wake generation. These complications at the 1.5-m height likely contribute to some of the scatter in the spectra shown in Figure 6 for this height.

5. Summary and Conclusions

Our natural spruce canopy was quite homogeneous in structure, and our tests showed little horizontal spatial variability of s, σ_w, and spectral characteristics. Therefore, we believe that our vertical profiles are representative of this canopy type as a whole. Our profiles of s, σ_w, and turbulence intensity (σ_w/s) are consistent with data from other canopies, and they are sufficiently repeatable to make it possible to predict profiles within the canopy from measurements above, at least under near-neutral conditions.

Analysis of the higher moments shows a negative skewness within the canopy complemented by a higher kurtosis. Non-normality of the w-frequency distributions should be considered in numerical models of mass and energy transfer inside such canopies.

The Eulerian time scale is only a weak function of height within the canopy, and this dictates that the length scales, l_s and l_w, have profiles similar to those of s and σ_w, respectively.

Power spectra measured above the forest are typical of those in the free atmosphere. However, within the canopy, an inertial subrange is not observed and a secondary peak is present at higher frequencies. The second peak is caused by wake-turbulence generation and its frequency roughly corresponds to the size of the horizontal spruce branches. This peak is not as evident during higher wind speeds when, presumably, it is masked by greater momentum transfer through the canopy. The primary peak in the spectra measured near the ground does not scale well with wind speed alone and is likely dependent on stability. In addition, the primary peak does not scale well with height from the ground and it is likely that the non-dimensional scaling is incorrect.

The spectral analyses show that the turbulence characteristics inside our spruce canopy are complex. An inertial subrange is not observed, and the processes of eddy cascading and wake-turbulence generation are difficult to describe quantitatively. Without additional measurements of the energy budget, we are unable to develop relationships to describe the energy cascade from the shear or the wake-turbulence energy that was superimposed on our canopy spectra. The turbulence structure in other complex forest canopies is likely different than that presented here for a spruce canopy. Numerical modelling of energy and mass dispersion within other natural canopies would likely require site-specific turbulence measurements.

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