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ON THE CANOPY FLOW INDEX
OF A TROPICAL FOREST

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Abstract. The usefulness of the canopy flow index concept is demonstrated for a two-story evergreen tropical forest. A sample of about 2500 wind profiles was utilized. It encompasses a large range of ambient wind conditions and spans the whole monsoon cycle in Southeast Asia.

It was found that the use of two canopy flow indices (one for the upper and one for the lower canopy) would be necessary to simulate the average canopy flow. For the upper canopy, an average value of 4.04 was obtained; for the lower canopy an index of 1.77 was computed. The indices seem to be independent of the ambient wind speed (if 2 m s^{-1} is exceeded), yet strongly dependent on wind direction.

1. Introduction

The structure of the turbulent air flow in vegetative canopies is quite complex. The turbulence within the stand is generated by the breakdown of the atmospheric flow into eddies (externally induced) and by eddies generated by the many inhomogeneous elements that comprise the canopy (internally induced). Historically, the approach to the problem of canopy flow proceeded along the following directions:

(a) theoretical – using basic equations of motion and continuity, supplemented by semi-empirical parameterizations;

(b) semi-empirical – based on wind tunnel studies and field experiments.

Most of the mathematical models assume steady state flow in a horizontally infinite canopy under neutral thermal stratification. The basic differential equation so derived is:

$$\partial/\partial z(K(z) + \nu)\frac{\partial U}{\partial z} = \frac{A(z)C_D U^2}{2} \tag{1}$$

where

$K(z)$ = eddy viscosity,
ν = molecular viscosity,
U = mean horizontal wind speed,
C_D = the form drag coefficient,
$A(z)$ = the leaf and branch area per unit volume.

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The left term represents the divergence of the Reynolds stress and the right term is equal to the fluid drag. This equation can be solved by numerical techniques and the methods used vary from investigator to investigator. Some use the eddy viscosity hypothesis (Tan and Ling, 1963) to parameterize the transport of momentum; some prefer the mixing-length hypothesis (Inoue, 1963; Cowan, 1968; Cionco, 1965); some use the second-order closure technique (Shaw, 1977) while others use the structured fluids approach (Silbert, 1970). An example of the empirical treatment is the work of Uchijama and Wright (1964) who postulated a wind speed function which included a term for the effect of the plant community on wind.

Considerable understanding of canopy flow was gained from controlled wind-tunnel studies conducted by various investigators such as Plate and Quraishi (1965), Sadeh *et al.* (1971), Seginer *et al.* (1976). Wind-tunnel studies in contrast to studies at natural sites allow one to simplify real situations.

The present study utilizes the formulation of Cionco (1965) who derived the following canopy flow equation:

$$\frac{2}{h}\frac{\partial U}{\partial x}\left[\frac{\partial U}{h^2\partial x}\frac{\partial(\ln l_c)}{\partial x}+\frac{\partial^2 U}{h^2\partial x^2}\right]=\frac{SU^2}{l_c^2} \tag{2}$$

where

$x = z/h$,
z = height above surface,
h = canopy height,
l_c = mixing length in canopy,
$S = 1/2\, C_D A(z)$.

Using the assumptions of an idealized canopy with a mixing length that is constant with height, this equation can be solved yielding:

$$U(z) = U(h)\exp\left[-a(1-z/h)\right] \tag{3}$$

where

a = extinction coefficient,
$(a/h)^3 = \dfrac{C_D A(z)}{2l_c^2}$,

i.e., the wind speed falls off exponentially with a depth scale proportional to $2^{1/3} l_c^{2/3}(C_D A(Z))^{-1/3}$, where $A(z)$ and C_D, or their product, are assumed constant with height.

2. The site

The experimental site is a tropical dry evergreen forest of about 80 km^2, situated at 14°31′ N, 101°55′ E in Thailand at elevations between 300 and 600 m. The region is under a monsoonal regime with two distinct seasonal circulations: a dry winter outflow from a cold continental anticyclone, and a moist summer inflow into a continental heat low. The climate is classified as tropical savannah with annual rainfall of 1500 mm.

The wind speed data utilized in this study were collected along a 50 m high tower. The tower was instrumented for temperature, dew point, wind speed and direction, rainfall and radiation measurements. Figure 1 illustrates the location of the measurement levels of the wind speeds along the tower.

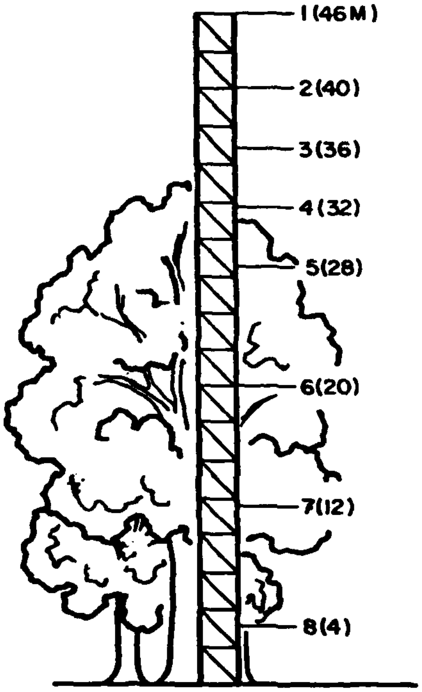


Fig. 1. The distribution of the wind speed measurement levels along the forest tower.

The wind speed sensors were Climet three-cup anemometers having a threshold velocity of 0.3 m s^{-1}. A totalizing signal was read every 10 s. The instruments were calibrated before and after the experiment at the National Bureau of Standards (NBS), Washington, D.C. in 1968 and 1970. The uncertainty of the wind speed measurements prior to the experiment was reported as follows:

Air Speed, m s^{-1}	>13.4	4.5	2.2	1	0.5
Uncertainty	0.4%	0.8%	1%	5%	14%

The calibration record of 8/22/70 after the experiment reports allowable error of 1%.

Based on a detailed inventory of vegetation conducted by the Thai Forestry Department (Smitinand *et al.*, 1968) in a 1-ha plot centered on the forest tower, a vertical

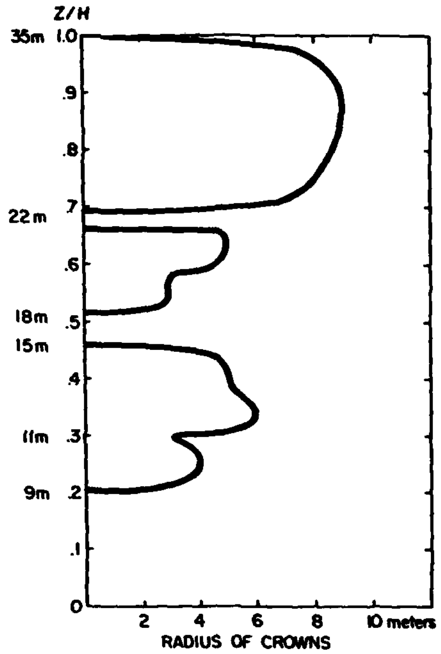


Fig. 2. The vertical distribution of the canopy crown radii, after Cionco (1980).

distribution of canopy crown radii (Figure 2) was constructed (Cionco, 1980). The tallest trees are 20–35 m high with a dense crown canopy of *Hopea ferrea*; the tops of the second

TABLE I

Two-week averaged wind velocities at selected levels along the forest (FT) and clearing (CT) towers (V_1 – at the 46 m level, V_2 – at the 32 m level)

Period (in 1970)	Level m	CT		FT	
		V m s^{-1}	v_1/v_2	V m s^{-1}	v_1/v_2
January	46	2.84	1.17	2.200	3.88
	32	2.42		0.566	
February	46	6.47	1.18	4.84	2.15
	32	5.47		2.25	
April	46	4.75	1.17	3.63	2.40
	32	4.06		1.51	
June	46	5.73	1.15	4.17	2.20
	32	4.98		1.85	
July	46	6.49	1.14	4.70	2.20
	32	5.67		2.13	
September	46	5.16	1.08	3.93	2.27
	32	4.77		1.73	

story canopy are 5–17 m tall. The species here were *Hydrocarpus ilicifolius, walsura trichostemon*, and *Memecyclon ovatum*. The undergrowth is composed of seedlings 2–3 m tall.

3. Data

Wind speed data for January, February, April, June, July, and September were used. Approximately ten days of observations were available for each month. Each day had 48 wind profiles averaged half hourly; each half-hourly value was based on 180 10-s data points. The average wind speeds at about 20 m above the forest canopy are presented in Table I. Similar information obtained along a tower in a nearby clearing is also included, to illustrate the drag effect of the forest canopy on the ambient wind field. The average wind direction frequency distribution in the region is illustrated in Figure 3.

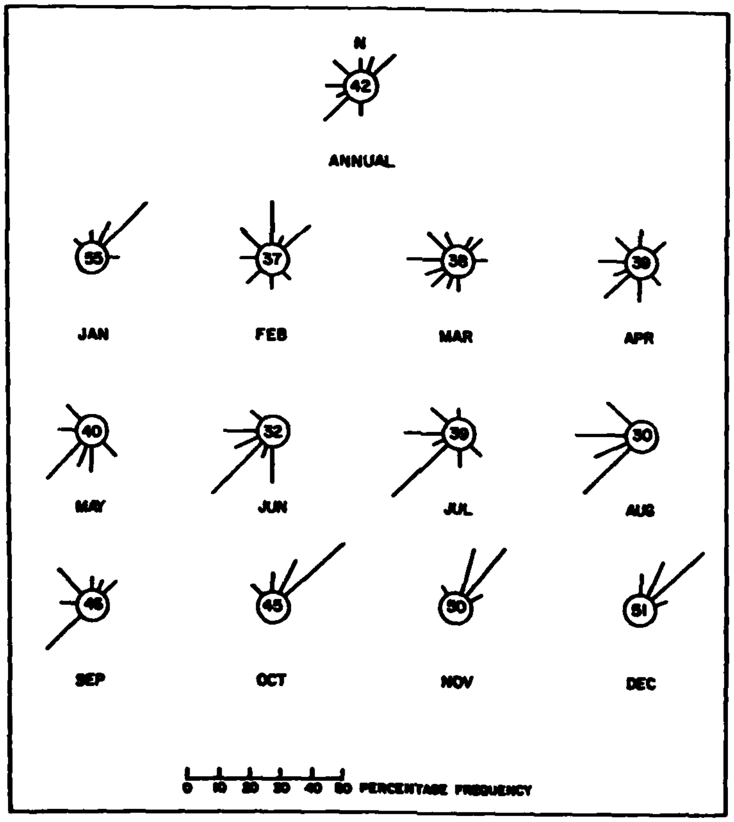


Fig. 3. Wind-rose diagram for Nakhon Ratchasima situated 60 km north from experimental site for 1956–1960, from ASRCT (1967). The number in center represents percentage frequency of calms.

During the winter monsoon (November–February), the prevailing winds are from the NE, while during the summer monsoons (May–September) the prevailing winds are from the SE; the steadiest SE flow occurs in June–July.

4. Procedures and Results

Before adopting a unified approach to represent the canopy flow, numerous profiles for each season were computer plotted. It became evident that the profiles fit into one of the following categories:

(1) an exponential-type decrease from canopy top to the lowest measurement level, with lower rate of decrease for $z/h < 0.4$ (i.e., Figure 5a, July, 1970).

(2) an exponential-type decrease down to $z/h = 0.6$; an increase in wind speed at $z/h = 0.4$; a lower rate of decrease for $z/h < 0.4$ (i.e., Figure 5b, April, 1970).

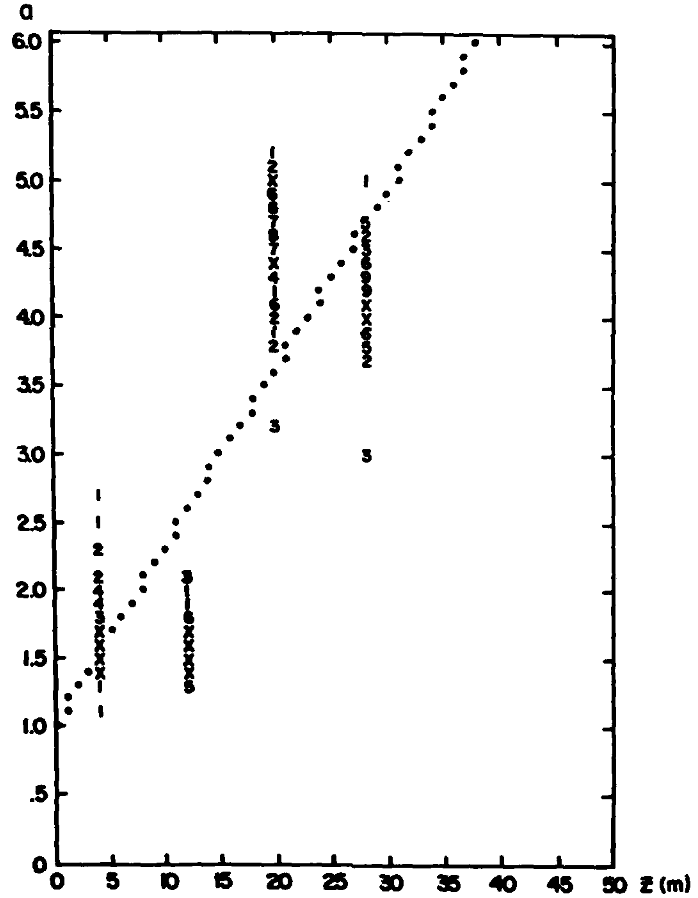


Fig. 4a. Computer printed least-square fit to the computed canopy flow index a for June 1970, using profiles for which the wind speed at the highest measurement level exceeded 5 m s^{-1}. The number of cases with equal a is represented by a numeral X was used when the number of cases exceeded ten.

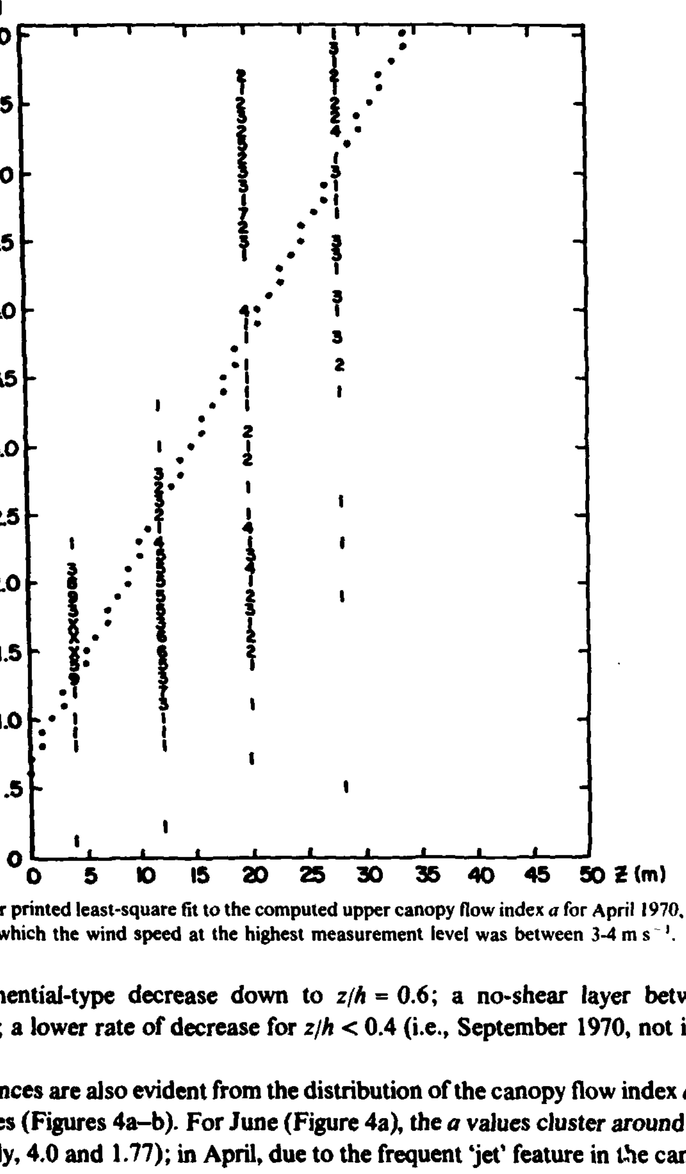


Fig. 4b. Computer printed least-square fit to the computed upper canopy flow index *a* for April 1970, using profiles for which the wind speed at the highest measurement level was between 3-4 m s^{-1}.

(3) an exponential-type decrease down to $z/h = 0.6$; a no-shear layer between $0.4 \leq z/h \leq 0.6$; a lower rate of decrease for $z/h < 0.4$ (i.e., September 1970, not illustrated).

These differences are also evident from the distribution of the canopy flow index *a* for the various cases (Figures 4a–b). For June (Figure 4a), the *a* values cluster around two 'centers' (namely, 4.0 and 1.77); in April, due to the frequent 'jet' feature in the canopy flow at $z/h \approx 0.4$ level, the *a*'s are less uniform in magnitude, resulting in high standard deviations. Consequently, the following procedure was adopted.

For each period of study, the data were stratified according to wind speed at the highest measurement level above the canopy; the attenuation coefficient *a* was computed for each such group separately using Equation (3). A least-square fit was obtained for the computed *a* values. Table II presents summaries of all the results, i.e., average *a* for upper

TABLE II

Statistical summary about the computed canopy flow index a

Period	# of Cases	Wind speed range 20 m above canopy (m s^{-1})	mean a a_u	mean a a_e	Standard deviation σ_u	Standard deviation σ_e	Correlation coeff.	Regression coeff.	Intercept
			28–20 m	12–4 m	28–20 m	12–4 m			
January	0	⩾ 5.0	–	–	–	–	–	–	–
	0	4.0–5.0	–	–	–	–	–	–	–
	30	3.0–4.0	–	–	–	–	–	–	–
	500	2.0–3.0	–	–	–	–	–	–	–
	500	0.0–2.0	–	–	–	–	–	–	–
February	468	⩾ 5.0	4.00	2.03	0.63	0.40	0.70	0.09	1.54
	296	4.0–5.0	4.10	2.00	0.52	0.44	0.74	0.09	1.52
	188	3.0–4.0	3.99	1.67	0.47	0.30	0.83	0.11	1.03
	40	2.0–3.0	4.05	1.39	0.50	0.25	0.88	0.13	0.51
	8	0.0–2.0	3.64	1.29	0.67	0.31	0.78	0.10	0.42
April	52	⩾ 5.0	4.63	1.81	1.39	0.25	0.63	0.12	1.27
	26	4.0–5.0	4.35	1.80	1.35	0.40	0.63	0.12	0.95
	51	3.0–4.0	4.21	1.64	2.51	0.70	0.64	0.16	0.52
	23	2.0–3.0	3.45	1.37	3.51	0.80	0.54	0.16	0.14
	20	0.0–2.0	2.74	1.13	3.27	0.63	0.41	0.10	−0.04
June	115	⩾ 5.0	4.31	1.65	0.51	0.26	0.82	0.13	0.93
	82	4.0–5.0	4.25	1.82	0.60	0.33	0.85	0.13	1.03
	57	3.0–4.0	4.21	1.77	0.80	0.31	0.86	0.13	0.90
	17	2.0–3.0	4.03	1.63	0.98	0.25	0.84	0.13	0.59
	18	0.0–2.0	3.36	1.42	1.35	0.39	0.26	0.03	0.85
July	251	⩾ 5.0	3.27	1.74	0.73	0.28	0.85	0.09	1.05
	190	4.0–5.0	3.38	1.85	0.73	0.30	0.83	0.09	1.21
		3.0–4.0	3.67	1.86	0.85	0.22	0.80	0.10	1.20
	16	2.0–3.0	3.80	1.88	0.45	0.23	0.81	0.09	1.34
	8	0.0–2.0	3.01	1.79	0.85	0.81	0.86	0.07	0.86
September	142	⩾ 5.0	2.69	1.66	1.32	0.30	0.84	0.12	0.64
	120	4.0–5.0	4.16	1.62	1.99	0.40	0.77	0.16	0.26
	184	3.0–4.0	4.45	1.67	2.20	0.35	0.78	0.18	0.12
	42	2.0–3.0	4.97	1.60	2.82	0.32	0.78	0.22	−0.31
	64	0.0–2.0	4.27	1.39	2.31	0.33	0.79	0.18	−0.29

and lower canopy; correlation coefficients; intercepts and slopes. As evident from Table II, the highest frequency of wind speeds in January is in the low range of 0–2.0 m s^{-1}. Thompson and Pinker (1975) analyzed the stability conditions for this site and showed that January was the most unstable period and as such, least suitable to the application of a canopy model based on neutral stratification. Therefore, no a's are presented for this period. For all the months treated, there does not seem to be a dependence of a on ambient wind speed as long as winds of 2 m s^{-1} are exceeded. The average value of a for the lower canopy seems to be half of that for upper canopy. The standard deviations seem to be related to the variability of wind direction. As illustrated in Figure 3, April and September are among the most variable in wind direction and the standard deviations in a during these periods are 3 times those for the other months. Strong dependence on wind direction was also reported by Cionco (1978).

The correlation coefficients of the regression equations are above 0.8 except for April and for the low wind speed range during other months. The average values for all periods studied are summarized in Table III. The range of the standard deviations during the various periods is indicated. The values of a as compiled by Cionco (1978) are summarized for comparison.

TABLE III

Average canopy flow index a for forest canopies after Cionco (1978) and Shinn (1971) and for present study

Forest canopy	a mean ± st. dev.	
Gum-maple	4.42 ± 1.05	
Maple-fir	4.03 ± 0.65	
Jungle	3.84 ± 1.52	
Spruce	2.74 ± 1.29	
Oak-gum	2.68 ± 0.66	
Tropical-evergreen	mean ± st. dev. range	
	upper canopy	lower canopy
$\geqslant$ 5.0[a]	3.98 ± (0.25–1.32)	1.77 ± (0.25–0.40)
4.0–5.0	4.05 ± (0.52–1.95)	1.81 ± (0.30–0.44)
3.0–4.0	4.11 ± (0.47–3.51)	1.72 ± (0.30–0.70)
2.0–3.0	4.06 ± (0.45–3.51)	1.57 ± (0.23–0.80)
0.0–2.0	3.4 ± (0.67–3.25)	1.40 ± (0.31–0.60)

[a] Wind speed range 20 m above canopy.

To test the suitability of the computed canopy flow index a to actual conditions, average profiles for each period investigated were compared to the model profile using the appropriate canopy index. The results are illustrated for selected cases in Figures 5 and 6.

Figures 5a–b illustrate a normalized daily average profile on a log-log scale for June and April and the corresponding predicted profiles using the appropriate a value from Table II. Figure 6 represents an all-season average and the scatter obtained with $a \pm \sigma_a$.

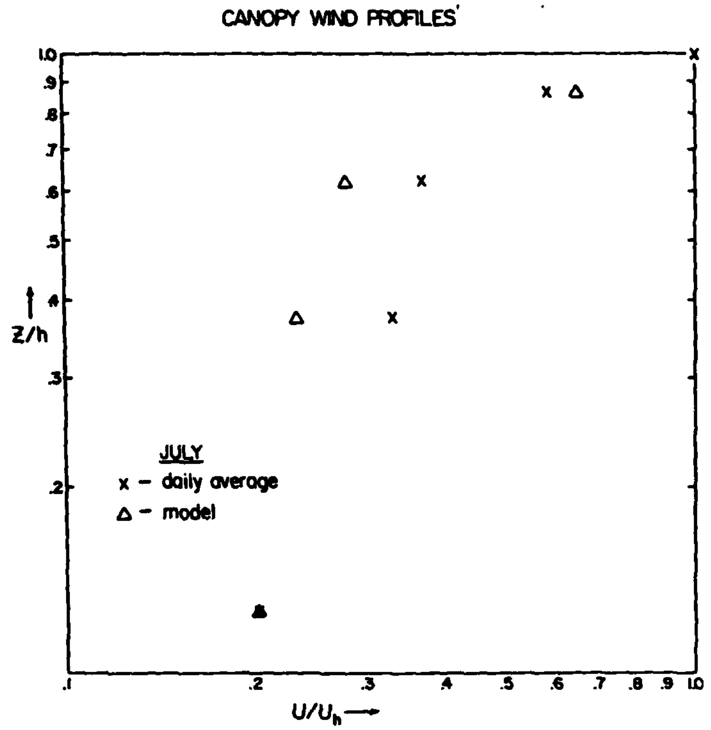
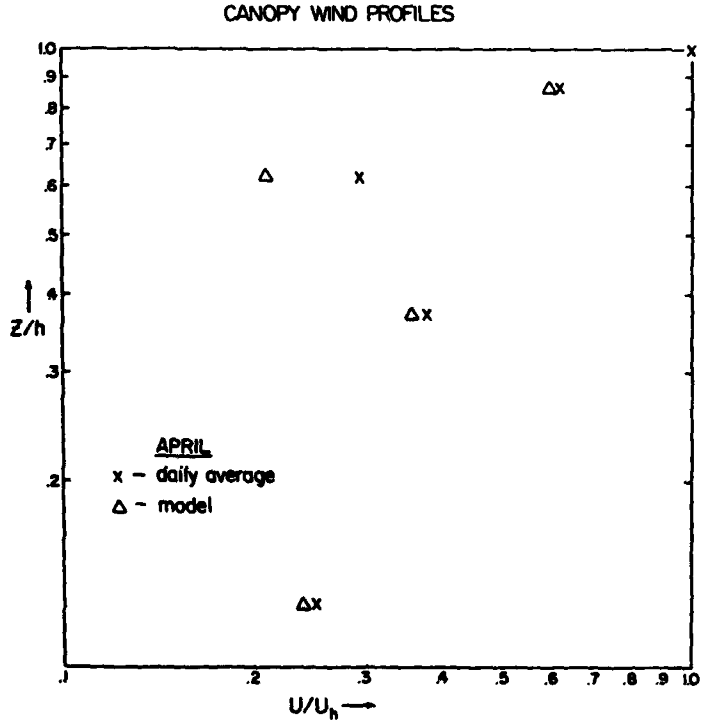


Fig. 5a. The normalized average profile on a log-log scale for July 1970 (*x*), and the predicated profile (Δ), using appropriate upper canopy a_u and lower canopy a_l values from Table II.



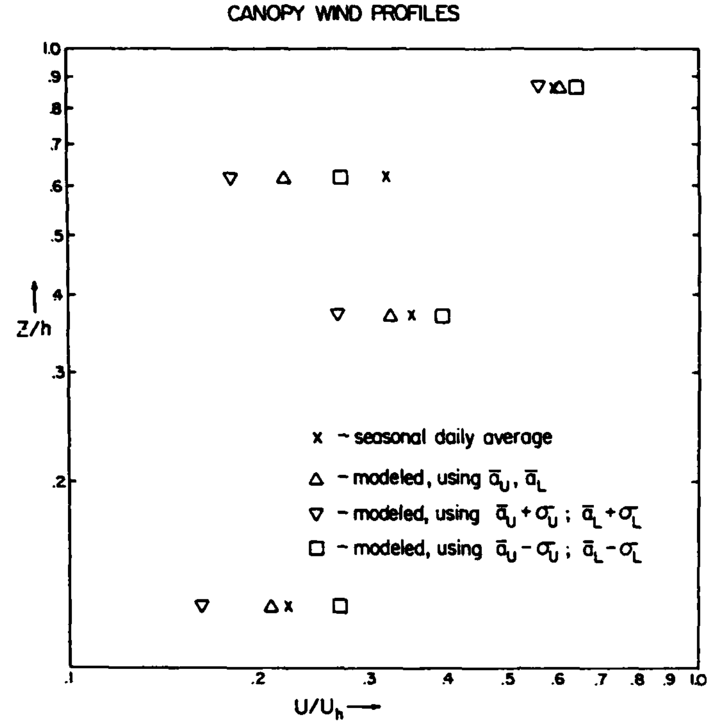


Fig. 6. A seasonal daily average normalized wind profile on a log-log scale (x), the predicted profile (Δ), and the scatter around the predicted mean obtained with a_u, a_l, and $a_u \pm \sigma_u$, $a_l \pm \sigma_l$ (∇), (□), as given in Table II.

The largest discrepancies were found in the upper canopy in April and September (same level) and might be related to the large wind direction variability during these two months.

5. Summary

The canopy flow in a two-story evergreen tropical forest was investigated using a large sample of wind profiles which span the whole monsoon cycle in Southeast Asia. Each of the wind profiles was an half-hourly average based on 180 data values for each measurement level. Inspection of the profiles led to the adoption of the canopy flow index concept as a possible way to model the canopy flow. Numerous experiments were conducted to identify the most appropriate model for this two-story canopy. It was found suitable to use two indices; an average value of 4.04 was found for the upper canopy ($0.6 < z/h < 1$) and an average value of 1.77 for the lower canopy ($0 < z/h < 0.4$). The comparison of the modeled profiles with the measured averaged profiles, seemed in good agreement. The computed a for the upper canopy is close to the canopy index reported for Gum-maple (4.42 ± 1.05) and Maple-fir (4.03 ± 0.65) forests.

Due to the large number of profiles available, this study could address one of the still unresolved issues regarding canopy flow, namely, the dependence of a on the ambient wind speed. No dependence seemed evident if winds of 2 m s^{-1} above the canopy were exceeded. However, dependence on wind directions seems to be a plausible reason for the large variability in the index as indicated by the increased standard deviation of a for periods of less steady ambient flow.

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