Wind Structure in and above a Tropical Forest[1]

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ABSTRACT

Winds were measured in and above a tropical rain forest in northern Colombia. Wind speeds below the canopy are only 1 to 5 per cent of that measured 50 ft above the canopy. Wind directions below the canopy appear to be disorganized.

1. Introduction

Early in 1962 a team of meteorologists from Bendix Systems Division and The University of Michigan carried out a micrometeorological investigation of a tropical rain forest in northern Colombia. A complete account covering all aspects of the investigation is contained in the final project report (Bendix Systems Division, 1963). This paper describes the observed winds above and below the canopy and relates the findings to earlier studies of wind structure in other forests.

The forest is located in a broad flat valley drained by the Rio Atrato and the smaller Rio León. The test site was near 7°40′N, 76°45′W. The main geographic features of the region are shown in Fig. 1 (in which longitude is given in degrees west of Bogota).

The principal physical features of the rain forest are as follows:

1) An undulating crown surface reaches locally to 150 to 160 ft with a main canopy at 120 to 130 ft.

2) There is some indication of an intermediate layer at 70 to 80 ft and a lower layer around 40 ft, but an overall impression that layers are unimportant.

3) From the air, one can occasionally see through openings down to palms at 40 to 50 ft, but actual ground is not visible. Daylight reaches the ground only as diffuse light and occasional sun flecks.

4) The number of stems ⩾4 inches in diameter at breast height averages about 160 per acre and these stems provide an average basal area of about 365 ft² per acre.

5) The boundary nearest to the sensors was the narrow Rio León one mile to the east.

Fig. 2 is typical of the dense, lush growth within the forest.

The study was conducted primarily during the dry season, January to April, when northerly winds persist. At Turbo, 30 mi north-northeast of the site, the frequency of north-northwest, north, and north-northeast winds is about 53 per cent from December through February, still 45 per cent from March through May, but only about 19 per cent during the balance of the year (U. S. Hydrographic Office, 1945).

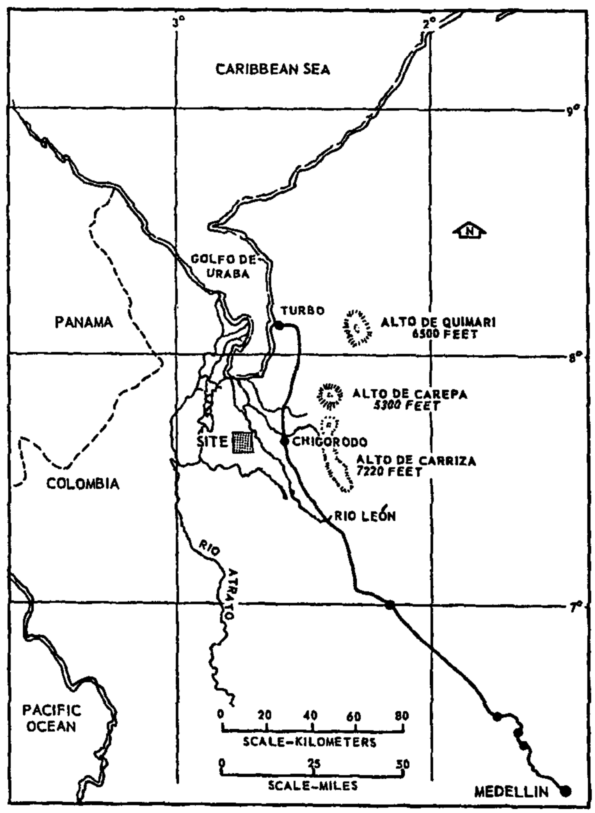

FIG. 1. Site of jungle meteorological study.

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FIG. 2. Typical lower growth in the study area.

2. Earlier studies of winds in the forest

Research into the influence of forests on winds have included studies in tropical rain forests (Allee, 1926; Hales, 1949; Latimer, 1950) and temperate latitude forests (Fons, 1940; Reifsnyder, 1955). The latter studies, which dealt with conifer forests having considerable bare trunk space, are not particularly relevant.

Allee measured winds in the rain forest on Barro Colorado Island in Gatun Lake, Panama Canal Zone. Scattered emergents rose above a dense main canopy at 90 ft; lower growth was rather open. The forest was thus at least 40 ft shorter and possessed less dense lower growth than the Rio León forest. Total wind passage was measured by 1924-vintage cup anemometers installed at 6.5 and 75 ft on the north (upwind) side of a tall tree.

In treating his data, Allee extended the profiles roughly 40 ft above the canopy by estimating winds at 130 ft from an exposed anemometer at Gatun. He reported the following average profile:

Height above ground (ft)	6.5	80	130
Mean wind speed (mi day^{-1})	1	10	240

Since most cup anemometers have starting speeds of about 2 mph, up to 48 mi day^{-1} of wind could have passed Allee's anemometers without turning the cups. One must conclude that the true mean wind speed at 6.5 ft was probably several times that reported by Allee.

Hales described the site of his study as "well enclosed by tropical vegetation with trees rising to a height of 75 ft", but these trees are presumably the emergents since 45 ft is designated as the canopy on the figures in the report. Hot wire anemometers were raised and lowered up to 10 ft on lance poles, to 40 ft with the limb of a tree, and to 150 ft by balloon. One profile per hour was obtained from the average of the readings during ascent and descent. Two 24-hour runs, one in the dry season and one in the wet season, are reported by Hales. The average wind speeds at 2 ft and 150 ft were 0.7 mph and 6.5 mph. Thus the 2-ft wind speed was nearly 11 per cent of the wind speed 75 ft above the tallest trees.

Latimer discussed meteorological conditions in some unidentified jungle which is described as being fairly dense with a canopy of irregular height topped at 30 to 50 ft, moderate undergrowth, and little direct sun on the forest floor at noon. For this type of forest, which is about one third the height of the Rio León forest, Latimer's data showed the wind speed at 6 ft to be approximately 12 per cent of that observed 40 ft above the canopy.

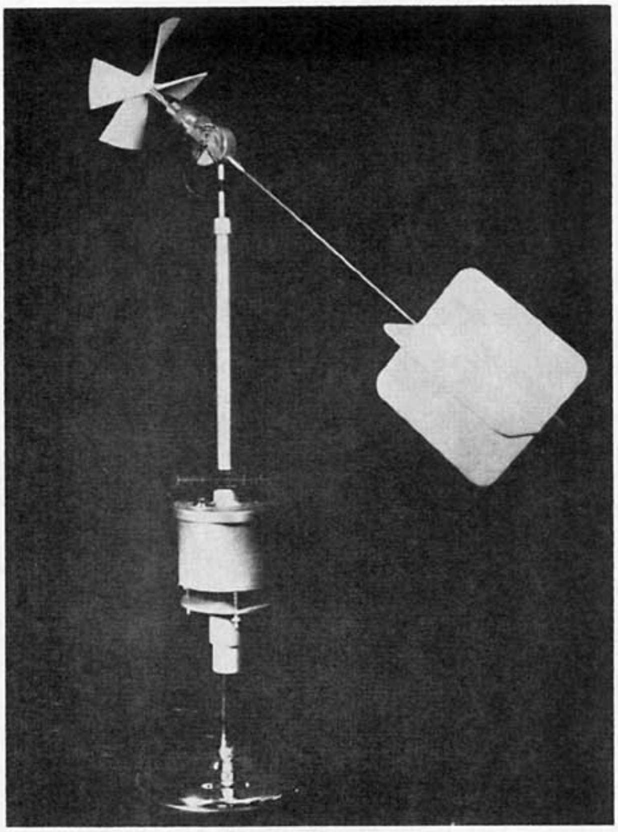

FIG. 3. Gill anemometer bivane.

The earlier studies show that winds are very light below the main canopy and that the fine details of the wind structure are determined mostly by the density of the undergrowth.

3. Instrumentation

A major concern in the present study was the selection of a sensor with a sufficiently low starting speed to measure winds within the forest. A special, sensitive, anemometer bivane was designed and built for the measurement of within-forest winds. The sensor, shown in Fig. 3, is a modification of the Gill bivane in which a propeller of molded polystyrene beads replaces the counterweight. The starting speed of the propeller is 0.3 ft sec^{-1} and its distance constant[6] is 2.4 ft. The vane is somewhat less sensitive. Complete details of the construction and dynamic characteristics of the sensor are available elsewhere (Bendix Systems Division, 1963).

Identical sets of sensors were installed on two 200-ft towers 1100 m apart on a north-south line. One of the towers is shown in Fig. 4. The sensors included a Beckman and Whitley vane and cup anemometer installed at 200 ft atop the tower, and anemometer bivanes at 6.5, 56, 74 and 146 ft. To minimize errors caused by the passage of wind through the tower (Moses and Daubek, 1961), the bivanes were all installed on the north or upwind side of the towers. The Beckman and Whitley system provided direction and speed outputs which were recorded continuously on strip charts for several weeks. The anemometer bivanes provided outputs of azimuth angle, elevation angle, and total wind speed which were recorded on magnetic tape. Details of the analog machine-processing of the magnetic tape records have been given by Brock (1963).

4. Observed winds in the rain forest

200-ft winds. In a later section it is shown that 200-ft wind directions at the north and south towers were well correlated. Accordingly this analysis has been performed on the data from one tower only, a series of measurements made at the north tower between 19 February and 21 April 1962. Available for analysis were 2257 mean half-hourly observations, representing approximately 80 per cent of the total time interval. The data were analyzed to yield relative frequency of different wind directions, and average speed for each direction and hour of the day.

From Table 1 it is apparent that the northerly trade winds dominated the weather of early 1962. The frequency of winds from 330° to 030° was 69 per cent compared to a climatological norm of about 50 per cent.

FIG. 4. Instrumented 200-ft tower in the jungle.

[6] For 63 per cent of a step change in wind speed.

TABLE 1. Relative frequency, and mean speed of 200-ft wind as observed from 19 February to 21 April 1962, by 30 degree sectors (35–01 includes winds from 345° to 015°).

Sector	35–01	02–04	05–07	08–10	11–13	14–16	17–19	20–22	23–25	26–28	29–31	32–34
Frequency (per cent)	41.8	11.9	1.9	1.0	2.0	2.3	6.6	1.8	2.3	3.3	4.6	20.3
Mean speed (mph)	9.9	7.6	4.5	2.2	4.1	4.5	5.2	4.0	3.5	2.3	4.2	8.5

TABLE 2. Hourly mean speed of 200-ft wind, 19 February to 21 April 1962.

Hour ending	01	02	03	04	05	06	07	08	09	10	11	12
Speed (mph)	6.7	6.3	6.2	6.3	5.9	6.0	5.9	5.7	6.5	7.3	8.5	8.7
Hour ending	13	14	15	16	17	18	19	20	21	22	23	24
Speed (mph)	9.2	9.5	9.5	9.5	9.4	9.2	9.4	8.8	8.8	8.4	7.7	7.2

Some influence of the broad north-south valley in which the site is located is also revealed in the data of Table 1. This is manifested in two ways. First, a secondary maximum in both frequency and speed appears at the sector 17–19 directly opposed to the primary maximum at 35-01. Secondly, minima of speed appear at the two cross-valley sectors 08–10 and 26–28 and of direction also at the sector 08–10. Mean hourly wind speeds in Table 2 resemble the normal daily course of surface wind speeds.

Wind speed profiles. The quantity of reliable data from the anemometer bivanes was small due to difficulties with their associated electronics and with the tape recorders. The authors believe, however, that uniqueness of these data justifies a brief discussion of profiles of wind speed. Wind speeds as measured at widely separated times were converted to a percentage of the simultaneous 200-ft wind speed before being combined. The mean profile is indicated in Table 3 where speeds are expressed first as a percentage of the 200-foot wind speed, and then in ft sec^{-1} by equating the 200-foot wind speed to 11.4 ft sec^{-1} which was its average value for the entire period of record, 19 February through 21 April 1962.

Any inferences from such a small sample must be regarded as tentative. It may be remarked, however, that the mean speeds given in Table 3 are consistent with the observation that the propellers at 6.5 ft were often stationary and that those at 56 and 74 ft were usually turning. The starting speed of the propellers, as noted earlier, was 0.3 ft sec^{-1}. Although Hales and Latimer had reported surface winds equal to 11 and 12 per cent of that above the jungle, they had described a less dense vegetation than that of the present study.

The mean wind-speed profile is also presented graphically in Fig. 5 by constructing approximately a one-seventh power-law profile between 200 and 160 ft assuming the interface to be at tree-top level, and at lower levels employing a smooth curve to intersect

TABLE 3. Profile of mean wind speed for the León rain forest and sample size for each height.

Height above ground (ft)	6.5	56	74	146	200
Mean speed (per cent of 200 foot wind)	0.8	5.1	4.5	29.3	100
Mean speed (ft sec^{-1})	0.1	0.6	0.3	3.3	11.4
Hours of data	30	35	55	65	65

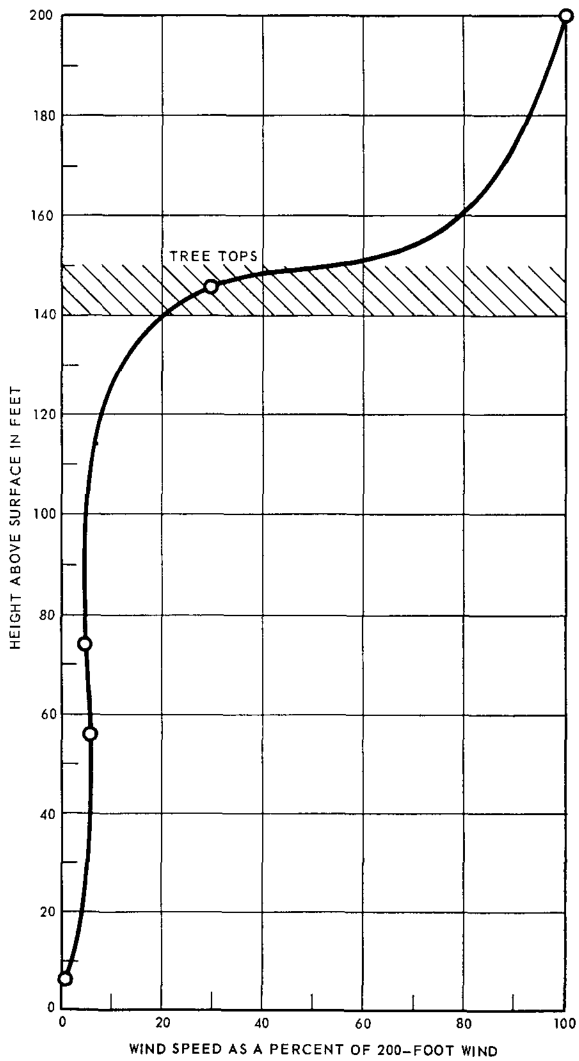

FIG. 5. Mean wind speed (per cent of 200-ft wind) as a function of height.

TABLE 4. The relationship between simultaneous wind directions on the two towers based on samples of 25 observations, by levels (r is the correlation coefficient).

Height in ft	6.5	56	74	146	200
r	0.47*	0.51**	−0.14	0.89**	0.95**
95% confidence limits for r	0.09 to 0.72	0.15 to 0.75	−0.50 to 0.27	0.74 to 0.95	0.87 to 0.98
Extent of randomness $=1-r^2$	78.3%	74.8%	97.9%	20.6%	9.3%

* 0.40 is significant at the 5 per cent level.
** 0.51 is significant at the 1 per cent level.

the four lowest points. No significance can be attached to the slight secondary maximum at 56 ft.

Correlation of wind direction between the north and south towers. It is desirable to know the extent to which the air flow over and within the forest is organized and the extent to which it is random. Since the orthogonal components of the wind vector are normally distributed the statistically rigorous way to get answers is to compute correlations among the components. A statistically less elegant way is to correlate directions only. Although the data are not normally distributed in the present case because of the dominance of a single climatic type, they do exhibit a central tendency. In a paper that should be read by all geophysicists, McDonald (1960) demonstrates that the researcher who applies conventional correlation techniques to non-Gaussian data will not be led into false inferences. Accordingly, simple correlations were computed, level by level, between wind directions at the two towers.

In general, the fact that directions of 360° and zero degrees represent the same angle gives some difficulty. By re-expressing the angles to take advantage of the prevailing northerly winds, this difficulty was minimized.

The first step in conditioning the data consisted of expressing each wind direction at the north tower in degrees from true north, positive for clockwise and negative for counterclockwise from true north. A scale from -180 to $+180$ is obtained for the north tower directions. Now each direction at the south tower can be at most 180° from that at the north tower and must be coded to indicate that the small angle between the directions requires clockwise (positive) or counterclockwise (negative) rotation.

The procedure used to accomplish this is best illustrated with an example. Assume that the wind direction at the south tower is 90° clockwise from that at the north tower. Then one must add 90 to the direction at the north tower. Now if the north-tower wind is from 160°, the south-tower wind direction will be coded $160+90=250$. If the north-tower wind is from 200° (i.e., 160° counterclockwise from north) the north-tower wind is expressed as -160, and the south tower wind becomes $-160+90=-70$.

Using the above procedure, twenty-five half-hourly mean wind directions were compared for the four bivane levels and for 200 ft. The results of the correlations are summaried in Table 4. Confidence limits are also given for the correlation coefficients, and in the last line, the quantity $1-r^2$ is given as an estimate of the extent of randomness in half-hourly mean winds at each level, since this quantity measures the percentage of variance that is unaccounted by the correlation between the two sets of wind directions.

Although significant correlations were obtained at all levels except 74 ft, the last line of the table shows most clearly the extent to which randomness is present within the forest. It is concluded that air currents below the canopy are primarily random, and above the canopy are well organized, on the scale implied by half-hourly averages of wind direction.

5. Conclusions

The conclusions drawn from the several analyses performed on the wind data are as follows:

1) The year 1962 was normal with respect to a high frequency of northerly trades during the dry season.

2) The 200-ft winds revealed some evidence of steering by the broad north-south valley.

3) Wind speeds at 200 ft exhibit a rather normal diurnal pattern of afternoon maximum, and a morning minimum two hours after sunrise.

4) Winds under the canopy are from 1 to 5 per cent of those measured 50 ft above the canopy.

5) Above the canopy a uniform flow of air exists as evidenced by high correlations between directions on the two towers at 200 and 146 ft. Below the canopy the flow is less organized as evidenced by the low correlations found at 74, 56 and 6.5 ft.

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