Wind profiles in and above a forest canopy

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(Manuscript received 15 March 1971)

SUMMARY

Using an on-line computer, measurements were made of wind speeds in and above a pine forest together with accurate potential temperature profiles over a wide range of stability conditions. It was found that between values of Richardson number of approximately $-0.05$ and $+0.10$ the wind profile above the canopy followed a pure log form with the measured, roughness length increasing linearly from 0.75 to 1.23 m, respectively. Outside this stability range a log-linear profile could be fitted. The shape of the wind profile within the canopy was determined, and an increase of wind speed within the trunk space was noted.

A preliminary experiment to determine the effect of the anemometer tower structure upon wind speed readings is also described.

1. INTRODUCTION

All the measurements described in this paper were obtained at the Institute of Hydrology's site in Thetford Forest, Norfolk, where a large-scale experiment to measure meteorological and biological factors affecting evaporation is being carried out. The trees are a mixture of Scots and Corsican Pine with a mean height of 15-5 m and a spacing of one per 10 m$^2$. The forest is flat and uniform with a fetch of over two kilometres in most directions. The primary objective of the 1970 wind measurements was to determine the form of the velocity profile in and above the canopy under all types of conditions, and also to prove the validity of a computer method for taking wind speed readings.

Measurements of wind and temperature profiles were made by means of anemometers and thermometers mounted on separate towers some 30 m high. Electrical signals from the instruments were fed to a caravan housing the data-acquisition system which simplified the crude data before listing the results on a teleprinter for further analysis.

2. APPARATUS AND DATA ACQUISITION

Booms mounted horizontally from the sides of the tower were used to support anemometers at 10 levels (Fig. 1), five levels above and five below the top of the canopy. The anemometers were Casella photoelectric models, with their electronics specially built at the Institute to give a computer-compatible output. The anemometers were fitted with eight-cup rotors made of expanded polystyrene which have been shown to give a more accurate value of mean wind speed than the standard three-cup metal rotors (Jones 1965). The anemometers were calibrated in a wind tunnel using a pulse totalizing system made at the Institute. For the experiment in the forest the pulses from all the anemometers were fed directly into the computer via a single sixteen bit interface (Oliver and Oliver 1971).

Temperature profiles were obtained from aspirated quartz crystal thermometers mounted inside radiation shields at six levels above the canopy between 16-8 and 30-2 m and also at 12-8 m inside the canopy. The temperature readings were fed directly into the computer once a minute and twenty-minute average potential temperatures were listed on the teleprinter. The temperatures above the canopy were measured with two sets of instruments facing in opposite directions and on each occasion the readings for the more upwind side were selected for analysis. The thermometers had been intercalibrated to an accuracy of a few thousandths of a degree.

3. DETERMINATION OF ACCURATE MEAN WIND SPEEDS

Before accurate values of mean wind speed could be obtained for analysis the effect of the tower structure on wind speed measurements made from it had to be determined so that corrections
could be applied. If these corrections are not applied, values of Richardson number which involve the square of the wind speed gradient can be considerably in error. For this preliminary experiment anemometers were mounted on long horizontal booms at distances of 3, 4.5, 8 and 13 m from two opposite sides of the tower at a height of 20 m. The more upwind of the two outer anemometers was assumed to read "true" wind speed, i.e. unaffected by the tower, and the values from the six inner anemometers were compared with this. This procedure was repeated for different wind directions until calibration graphs for each anemometer distance were built up.

The graph of wind speed correction for an anemometer at a distance of 4.5 m—the distance used in the main experiment—is shown in Fig. 2. Similar results for other designs of tower have previously been published (Gill 1967; Moses and Daubek 1961). The graph is shown only for a 300 degree range of directions as values in the lee of the tower tend to be rather variable. Measurements of wind speed used for profile analysis were not made within 4 m of the top of the tower and it was assumed that the same correction could be applied at all the levels.

The computer was programmed to totalize pulses over periods of twenty minutes and, by applying the calibration factors, to calculate the mean twenty-minute wind speeds. These values were listed on the teleprinter and the tower effect correction was then applied using the mean wind direction as determined for the same period from anemograph trace.
4. **Analysis**

(a) **Profiles above the canopy**

The twenty-minute average values of the corrected wind speeds for anemometer levels 6 to 10 were plotted together with the average potential temperature profiles. From the gradients of these profiles at a height of 20.5 m the value of the Richardson number was calculated for this level, which is 5 m above the top of the canopy. The first stage of the analysis was to determine the value of the zero plane displacement, $D$. The equation for a neutral velocity profile above an extensive uniform surface is

$$ U = \frac{U^*}{k} \ln \frac{Z - D}{Z_o} $$

where $U$ is the velocity, $Z$ the height above ground level, $U^*$ is the friction velocity, $k$ is the von Kármán constant, $D$ is the zero plane displacement and $Z_o$ is the roughness length. Wind profile data were selected for very near neutral conditions ([$Ri| < 0.003$) where the logarithmic relationship given above would certainly be expected to apply. Plots were then made of wind speed against $\ln(Z - D)$ for different values of $D$ until a value of $D$ was found for which the relationship was seen to be approximately linear. The average of $D$ so obtained was $11.8 \pm 0.2$ metres and this value was found to apply equally well for all wind speeds. A straight line using $D = 11.8$ m was then fitted by eye for all the remaining profile data, examples of the results obtained being shown in Fig. 3.

The general result so obtained was that for a wide range of stability conditions the wind profile followed a pure log form. For values of $|Ri|$ less than about 0.08 a plot of $\ln(Z - 11.8)$ against wind speed gave a good straight line – the deviation of any point from the line not exceeding about one per cent – for speeds measured at levels 6 to 9. The wind speed measured at level 10 also lay on the line for $|Ri| < 0.05$ but outside this range began to deviate from it. For values of $|Ri|$ in excess of 0.08 a fairly good straight line was usually followed by speeds measured at only the lowest three or four levels above the canopy, by far the better fits being obtained in very stable rather than very unstable conditions, very stable conditions being associated with very large values of $Z_o$. The trends of the deviations from a pure log plot were the same as those which would be expected theoretically: under unstable conditions the turbulence increases, producing better mixing and smaller wind gradients; under stable conditions the reverse is the case with weak
turbulence, less mixing and consequently larger wind gradients.

Each straight line produced on the log plot was extrapolated back to the $U = 0$ axis to yield the apparent value of $Z_o$ for that profile. A plot was then made of roughness length against Richardson number, different symbols being used for various wind speed ranges. The graph of the data obtained for Richardson numbers between $-0.08$ and $+0.10$ is reproduced in Fig. 4. It can be seen that there is a definite trend in the values of $Z_o$ with $Ri$ but that no significant dependence upon mean wind speed is demonstrated. The trend in $Z_o$ can be well approximated by the straight line

$$Z_o = (0.91 + 3.2Ri) \text{ m}$$

(2)

the value of $Z_o$ under neutral conditions being $0.91 \text{ m}$.

Because of the expected failure to get a good fit to a pure log plot for the wind profile for more extreme stability conditions the log-linear equation was tried for the stability ranges for which a
The pure log profile did not fit. The log-linear equation is written in the form

\[ U = \frac{U^*}{k} \left[ \ln \frac{Z - D}{Z_0} + a \left( \frac{Z - D - Z_0}{L} \right) \right] \]  

(3)

in which \( L \) is the Obukov scale length, and \( a \) is a numerical 'constant'; the stability correction is \( a (Z - D - Z_0)/L \). Each value of \( Z_0 \) and \( D \) is assumed to be that found for neutral conditions.

The method of Webb (1970) was used to derive values of \( a \) for the more extreme of the observed stability conditions. For \( -0.05 < \text{Ri} < 0.15 \), the value \( a = 8.5 \pm 2.5 \) was determined. However, in the range \( 0.1 < \text{Ri} < 0.3 \) a closer approximation to a pure log profile was found to apply, with \( a \) having an average value just below unity.

(b) Profiles in and below the canopy

Wind speeds were only measured at one position at each level in and below the canopy, and to eliminate possible sampling errors a wind profile was obtained by averaging some forty different sets of data over several days and wind directions. The profile thus obtained is shown in Fig. 1, the profile being normalized to give unit velocity at level 6—the first level above the canopy. The general shape of the profile is similar to that found by other workers for trees (Geiger 1965) with a definite increase in mean scalar wind speed in the region below the base of the canopy, the maximum value being a little over twenty per cent of that at level 6. A minimum wind speed occurred at approximately the level of the base of the canopy. Little significant variation of the shape of the profile was found for different mean wind speeds.

5. Conclusions

Over the range of Richardson numbers for which data are presented (\(-0.15 < \text{Ri} < 0.3\)), the wind profile can be well described by the pure log equation with a suitable value of \( Z_0 \) or the log-linear equation with a suitable value of \( a \).

The temperature gradients above a forest are very small because the aerodynamic transfer of heat and momentum is very efficient; the range of Richardson numbers is therefore smaller than that found over grassland.

The apparent change of \( Z_0 \) with \( \text{Ri} \) may well be only an artefact of describing non-neutral wind profiles with an equation of neutral form (Eq. (1) with \( Z_0 \) from Eq. (2)). However, empirical equations of the form of Eq. (2) are expected to be of practical use in further studies of wind profiles over forests. The fact that \( Z_0 \) and \( D \) do not vary with wind speed to a measurable degree is perhaps accounted for by the relative strength of the trees. A value of 75 per cent of the mean tree height for \( D \) is not inconsistent with other data (Stanhill 1969).
Acknowledgments

Thanks are due to my colleagues at the Institute, especially to Mrs. S. A. Oliver who devised the computer method of obtaining wind speed readings and wrote the data acquisition programme, and to Mr. G. P. Brunsdon who designed and built the anemometry electronics.

I also wish to thank the Meteorological Research Unit Porton Down for the construction of the anemometer cups and the use of their wind-tunnel for calibrations.

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