# Comments on Measuring Turbulent Exchange Within and Above Forest Canopy[1]

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## Abstract

*Actual problems of measuring the turbulent exchange in and above forests* (e.g., site requirements of micrometeorological observations, aerodynamic characteristics of forests, observations of the crown-produced mixing layer, flux-profile relationships above forests, and some experimental difficulties) are discussed. The present state of knowledge regarding the micrometeorology of forests is poor, and there are good opportunities for experimental and theoretical research. A wider participation of universities and research institutes (in forest meteorological research) and their international coordination is needed.

## 1. Introduction

Turbulent exchange in the surface boundary layer of the atmosphere has been a subject of intensive study for more than 40 years; because of its importance, it holds a distinguished position in atmospheric science. The initial studies were focused on Prandtl's theory, and on investigations by Rossby and Montgomery, Sverdrup, and others. Post-war developments were characterized by rapid progress in measurement techniques and basic theory. Analyses based on the similarity theory of Monin and Obukhov, and on the relationship given by the KEYPS formula, in conjunction with direct flux measurement, played an important role in more recent research. Results of that research are still a subject of discussion, and have been reviewed recently by Yaglom (1977). With regard to the existing problems and disagreements, Yaglom's analysis suggests that experimental errors may be one of the sources of differences among authors. In my opinion, that conclusion is also applicable in micrometeorological research in forests.

Most micrometeorological research has been carried out above "ideal" land surfaces with small roughness. Turbulent exchange above forests has been studied less intensively, for various reasons. Micrometeorological studies above forests are more laborious than, e.g., those above low crops. In addition, the forest–atmosphere interaction creates phenomena (e.g., the most intensive production of dynamic and thermal turbulence in the upper crown space) that make the study of turbulent exchange above forests more difficult.

Forests cover about 30% of the continental earth's surface, and they appear as an important factor in the earth–atmosphere interaction, in the bioproductivity of the earth, and its $CO_2$ balance. In this connection, knowledge of the turbulent exchange between forests and the atmosphere is important. Some actual problems of measuring the turbulent exchange above forests will be discussed.

## 2. Site requirements

Micrometeorological experiments ideally are conducted at sites where turbulent fluxes in the surface boundary layer are constant both in time and space. Such an assumption can be justified under strictly-defined site conditions. The experimental site should be an extensive, horizontal, uniform area. In addition, the distance (fetch) between the experimental station and the edge of the site, and the height of the instruments above tree tops, should satisfy the relationship given by "height/fetch ratio."

The recommended height/fetch ratios for smooth surfaces or low vegetation are in the range from 1/100 to 1/500 (Fritschen *et al.*, 1973). They have been derived on the basis of turbulent boundary layer theory at a rigid wall. Solutions for media such as forest, characterized by complex structure in both vertical and horizontal directions, have not yet been developed. Laykhtman (1955) discussed transformations of the vertical wind profiles, and of the vertical profile of the coefficient of turbulent diffusion, when air passes from an open area to a forest. His relationships contain such parameters as the mean distance between trees and the size of forest openings, but a numerical solution is not given. Experimental studies in pine forests by Reifsnyder (1955) and Raynor (1971) have shown that "representative" air flow was established in forests at distances equivalent to about five or six tree heights from the forest edge (i.e., 96 and 60 m, respectively).

The problem of advective mass and energy exchanges between forests and surrounding areas has not been studied extensively. Under average summer weather conditions, forests are usually cooler than their surroundings, unless evapotranspiration is reduced substantially by a limited water supply from the soil. The heat transferred to the forest by advection contributes to its energy balance. "Excessive" evapotranspiration can be observed especially at the leading

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[1] Published with the approval of the Director of the West Virginia Agricultural and Forestry Experiment Station as Scientific Article #1706.

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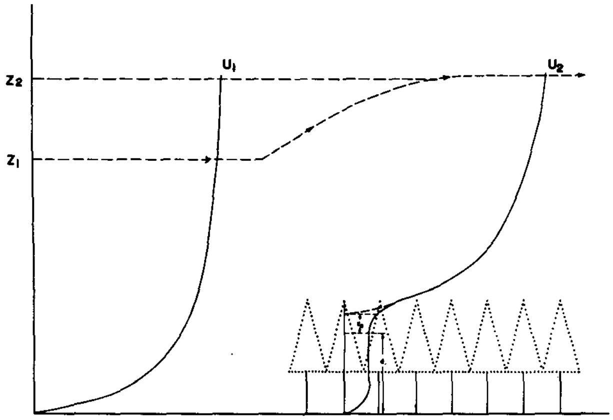

FIG. 1. Modification of the vertical wind profile by forest cover. Adopted from Marunich (1971).

edge of the forest, but this effect decreases with increasing distance from the edge. Rauner (1963) has shown that the edge effect can easily be observed at distances of one to 1.5 km from forest edge; it was negligibly small at about 3 km. Hicks *et al.* (1975) found advective effects to be important when the fetch across the forest canopy was less than about 0.8 km. It can be suggested on the basis of these examples that the distance between the micrometeorological station and the forest edge should be at least 1 km.

## 3. Aerodynamic characteristics of forests

When air passes from an open area to a forest, the vertical profile of the horizontal component of wind speed is modified, as shown in Fig. 1. At a certain distance from the forest edge, a new wind characteristic of the forest is established; if thermal stability of the air is neutral, the vertical wind profile above the forest can be described by the logarithmic law

$$u(z) = \frac{u_*}{k} \ln \frac{z-d}{z_0} \tag{1}$$

where $u(z)$ is wind speed at height $z$ above the ground, $u_*$ is friction velocity, $k$ is von Karman's constant (equal to 0.4), $d$ is zero plane displacement, and $z_0$ is the roughness length of the forest.

The parameters $d$ and $z_0$ commonly are regarded as aerodynamic characteristics of forests. These parameters can be calculated, or estimated graphically, using semi-logarithmic paper (as shown in Fig. 2) and wind profile data obtained under conditions of neutral stability.

Marunich (1971) defined $d$ as the displacement of a trajectory from level $z_1$ to level $z_2$ as illustrated diagrammatically in Fig. 1. Assuming that the rate of mass flow between ground level and $z_1$ in the open is equal to that between ground level and $z_2$ in and above the forest, the following relationship applies

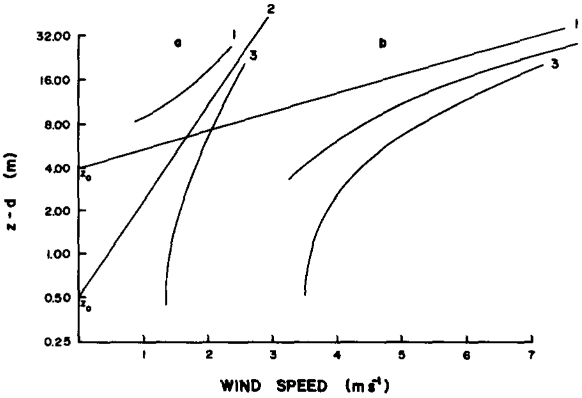

FIG. 2. Estimating $d$ and $z_0$ on a semi-log plot of $(z - d)$ over wind speed at a) low wind speeds, and b) high wind speeds. (1: $d = 5$ m; 2: $d = 12$ m; 3: $d = 16$ m; mixed deciduous forest, $\overline{H} = 16.5$ m). Adopted from Rauner (1972).

$$\int_0^{z_1} u_1(z)\, dz = \int_0^{z_2} u_2(z)\, dz. \tag{2}$$

If levels $z_1$ and $z_2$ are high enough, the air stream velocity, $U$, between $z_1$ and $z_2$ is almost constant, and the following relationship can be obtained from Eq. (2)

$$z_2 - z_1 = \int_0^{z_2} \left( \frac{u_1(z)}{U} - \frac{u_2(z)}{U} \right) dz. \tag{3}$$

The vertical wind profile in and above the forest, $u_2(z)$, must be obtained from measurements. The vertical wind profile in the open, $u_1(z)$, can be obtained with sufficient accuracy from the formula:

$$u_1(z) = U \ln\left(\frac{z}{z_0}\right) \Big/ \ln\left(\frac{z_2}{z_0}\right) \tag{4}$$

where $U$ is wind speed at the level $z_2$ above the forest, and $z_0$ is the roughness length of the forest floor. The value of $d$ can be obtained from Eq. (3) by numerical integration; the roughness length of the forest can then be obtained by least squares, or with the help of semi-logarithmic graph paper. The study reported by Marunich was carried out in a spruce forest where the average height of trees was 26 m. The wind speed at 42 m height was used for $U$ in Eq. (4).

Values of $d$ and $z_0$ are used in the analysis of vertical profiles of meteorological parameters above forests. It is, however, questionable if the available values of $d$ and $z_0$ are suitable for such analyses. Tajchman (1967), e.g., stated that $d$ obtained from the wind profile cannot be used for temperature and humidity profiles in the logarithmic law. Hicks *et al.* (1975) found that the zero plane displacement for heat is not significantly different from that for momentum, but the roughness length for heat was only one-third of that for momentum. Raupach's (1979) analysis based on the flux-gradient relationships suggested that the zero plane displacement for heat was 0.39 of that for momentum. It is possible that inaccuracy in measurements used to define neutral stability and associated wind profiles above forests may be responsible for substantial errors in $d$ and $z_0$.

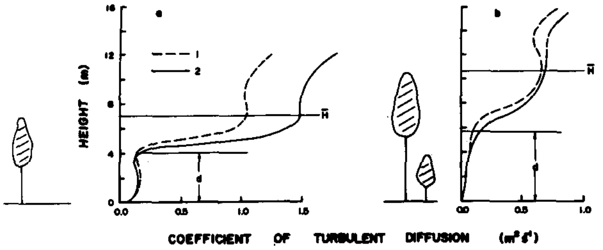

FIG. 3. Vertical profiles of the coefficient of turbulent diffusion in and above a) pine forest, and b) aspen forest (1: solar elevation >30°; 2: solar elevation >45°). Adopted from Rauner (1972).

Data on $d$ and $z_0$ for different forest sites have been recently analyzed by Jarvis *et al.* (1976). In relation to mean forest height, $\overline{H}$, they fall within the following ranges:

$$0.61 \le d / \overline{H} \le 0.90$$

$$0.02 \le z_0 / \overline{H} \le 0.26$$

The analysis by Jarvis *et al.* (1976) would be more comprehensive if it included results obtained by Konstantinov and Fedorov (1960), Marunich (1971), Rauner and Ananev (1971), and by Rauner (1972). Results and discussions in those reports present an interesting view in regard to the physical interpretation of $d$ and $z_0$. Konstantinov and Fedorov (1960) found that both $d$ and $z_0$ of a 26 m tall spruce forest were dependent on wind speed above the forest, and that when wind speed increases, $d$ decreases and $z_0$ increases. At the same time, they called the vegetation layer of height $d + z_0$ the "active layer." According to their data, the height of the active layer decreases slightly as wind speed increases. This finding seems to be supported by Allen (1968), who reported deeper penetration of larger eddies into the forest during high winds. Meroney (1968) expressed the view that the streamlining of trees at high velocities can reduce the effective cross-sectional area of more flexible species, and Marunich (1971) concluded that the aerodynamic behavior of a spruce forest may be different from that of a deciduous one. The relationship between the aerodynamic parameters and wind speed obtained by Marunich (1971) is similar to that obtained by Konstantinov and Fedorov (1960).

According to Konstantinov (1963), the boundary conditions of the interaction between vegetation cover and the atmosphere are applicable at height d. Rauner and Ananev (1971) proposed that the height of the inflection in the vertical profile of the diffusivity coefficient, $K$, inside the forest canopy can be approximately identified with $d$, which can be seen in Fig. 3. They concluded that the relationship $\partial K / \partial z = 0$ can be used as a qualitative criterion for the determination of $d$, which is then interpreted as the height of the hypothetical "rigid wall." Results for $d$ and for the vertical profile of $K$ obtained by Hager (1975) in a spruce forest, seem to support the suggestion by Rauner and Ananev. Rauner (1972) diagrammatically summarized the relationships between both $d$ and $z_0$, and wind speed, $u$, above the forest, as found at different forest sites in the USSR (maple, pine, and deciduous forest with and without foliage). He also included data from Konstantinov and Fedorov (1960). One can estimate from his diagram (reproduced in Fig. 4) that for 1 m s$^{-1}$ < $u$ < 7 m s$^{-1}$ the ratios are:

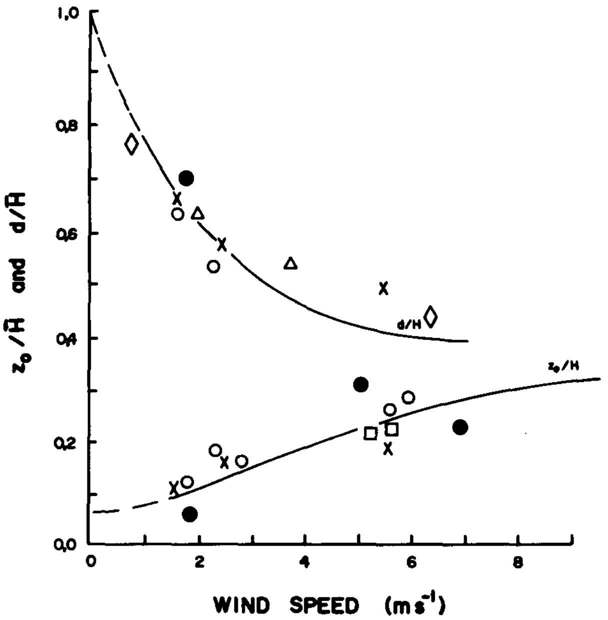

FIG. 4. The ratios $d/\overline{H}$ and $z_0/\overline{H}$ for different forest types in the U.S.S.R. as influenced by wind speed. Adopted from Rauner (1972).

$$0.30 \le d / \overline{H} \le 0.76$$

$$0.09 \le z_0 / \overline{H} \le 0.28$$

These results show that $d$ and $z_0$ assume a wide range of values for the same forest height. These values seem to be dependent on the structural characteristics of forests. The dependence of the two parameters on wind speed above the forest has not yet been generally confirmed. Landsberg and Jarvis (1973) did not find any consistent relationship between $d$ (and $z_0$) and wind speed above the forest. Further progress in the physical interpretation of $d$ and $z_0$, and in defining the aerodynamic behavior of forests, will require more precise measurements of wind and temperature profiles above forests, and a better knowledge of forest structural characteristics.

## 4. Micrometeorological observations in the upper crown space

The role of vegetative cover in earth-atmosphere interactions was recognized long ago, but most studies have been conducted during the last 20 years or so (Baumgartner, 1956; Dzerdzeevskiy and Rauner, 1960; Konstantinov and Fedorov, 1960). A. I. Voejkof discussed the "outer effective surface" that can be identified as the upper vegetation surface, and that plays a role similar to that of the ground surface (Geiger, 1965). Recent studies indicate that it is more appropriate to identify an "active layer" in the upper crown space. In forests, the leaf area can be as much as 10 times greater than the ground area below, and the distribution of foliage, branches, and stems represents a complex system that has dominant influence on forest microclimate, particularly on the microclimate of the crown space.

Baumgartner (1956) measured the vertical profile of net radiation in a young spruce forest (average height of trees $\bar{H} = 5.55$ m) in Bavaria. On a sunny day, the greatest rates of decrease of net radiation appeared in the upper crown space between approximately 0.9$\bar{H}$ and 0.6$\bar{H}$; below 0.6$\bar{H}$ the net radiation was nearly constant with height. In Baumgartner's opinion, the structure of crowns should be responsible for large spacial differences in radiant flux density and temperature, and for the development of microconvection.

In an Australian pine forest (*Pinus radiata*) 5.5 m tall, Denmead (1964) observed the greatest absorption of the incoming radiation between 0.73$\bar{H}$ and 0.55$\bar{H}$ at 11:45 on a clear day. At the same time, the rate of decrease of net radiation increased from the top of the forest downward, reaching its maximum at approximately 0.64$\bar{H}$. It further decreased downward from this level, whereas the maximum value of air temperature was observed at 0.55$\bar{H}$.

The vertical profiles of net radiation in an 18 m tall deciduous forest in New York state are shown in Fig. 5 as observed by Droppo and Hamilton (1973). At noon, under a cloudless sky, the greatest vertical gradients of net radiation appeared between $\bar{H}$ and 0.67$\bar{H}$. The greatest variability of radiation fluxes was observed between 0.78$\bar{H}$ and 0.60$\bar{H}$. In the afternoon, net radiation had higher values deeper in the forest canopy, and its vertical gradients decreased. Maximum air temperature also was observed deeper in the canopy in the afternoon.

Droppo and Hamilton (1973) observed a maximum value of net radiation in the canopy at a height approximately equal to $\bar{H}$ at noon. It was their opinion that this was a result of the vertical variation of reflected solar radiation. Also, Rauner and Rudnev (1965) observed a similar maximum of flux densities of shortwave incoming radiation and net radiation at the tops of a mixed deciduous forest and an oak forest near Kursk, U.S.S.R. According to Rauner and Rudnev, radiation reflected from branches was responsible for the increase of the incoming radiation. The vertical variation of reflected solar radiation and, to a lesser extent, the vertical variation of the longwave radiation balance (longwave emission from a relatively warmer surface of the biomass surrounding the radiation instrument) were responsible for the maximum in net radiation.

Konstantinov and Fedorov (1960) reported results of micrometeorological observations in a spruce forest (average height of trees $\bar{H} = 26$ m) near Valday, U.S.S.R. The height of maximum temperature in the crown space varied during the day. In the morning, the maximum temperature was observed between $\bar{H}$ and 0.96$\bar{H}$; it appeared between 0.81$\bar{H}$ and 0.77$\bar{H}$ between 10:00 a.m. and 5:00 p.m., and then between $\bar{H}$ and 0.96$\bar{H}$ again. During hot days, the layer of maximum temperature extended downward to between 0.6$\bar{H}$ and 0.58$\bar{H}$ from 3:00 to 4:00 p.m.

Maximum wind gustiness was observed by Konstantinov and Fedorov between the level $d + z_0$ and the tops of trees, with the level $d + z_0$ appearing between 0.66$\bar{H}$ (high wind speed) and 0.85$\bar{H}$ (low wind speed). Turbulence intensity in the upper crown space was higher than over open land at the same height, in agreement with results obtained by McBean (1968). The ratio of the vertical fluctuations of wind speed to the mean horizontal wind speed, and the ratio of the vertical fluctuations to the horizontal fluctuations of wind speed, reached maxima at the height equivalent to 0.88$\bar{H}$. In a pine forest 10.5 m tall at the Brookhaven National Laboratory, Long Island, Raynor (1971) observed maximum wind gustiness at approximately 0.86$\bar{H}$ during the daytime; minimum wind gustiness was observed at night. Raynor concluded that the dynamic turbulence generated by the roughness elements in the forest crown, and the convective turbulence caused by unequal heating of the canopy, penetrated into the trunk space under unstable conditions, causing enough mixing so that wind speed varied little with height or location below the canopy. Data from different forest sites summarized by Cionco (1972), and his own measurements in a black spruce forest 20 m tall, support the above findings. Figure 3, adapted from Rauner (1972), shows the vertical profiles of the coefficient of turbulent diffusion, $K$, in and above a pine forest and an aspen forest. Using the energy balance approach, calculations of $K$ were derived from vertical profiles of air temperature, humidity, and net radiation. The values of $K$ at the average forest height, or just below this level, were greater than the appropriate values above the top of the canopy.

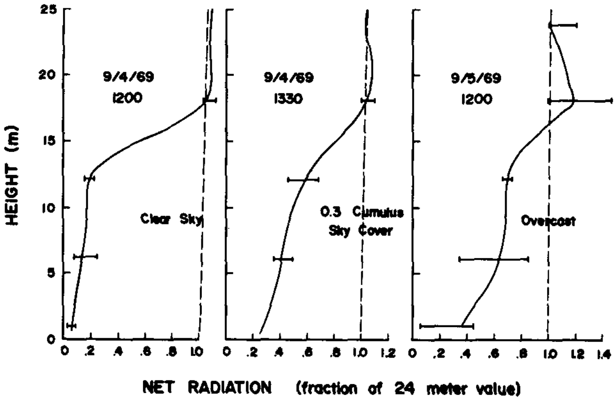

FIG. 5. Vertical profiles of net radiation in and above a deciduous forest under different sky conditions. Adopted from Droppo and Hamilton (1973).

Observations by McBean (1968) indicated that the shape of the cospectra in the forest may be different from that over open ground. Vertical velocity spectra above a pine forest obtained by Shaw *et al.* (1974) were more peaked than the universal curve, and the authors concluded that the additional variance resulted from mixing, caused by the individual roughness elements. Theoretical studies by Dubov and Bykova (1973, 1974), and experimental studies by Marunich (1971) and Lesnik (1974) show maximum turbulent energy that is transferred upward and downward from the upper crown space.

Changes in the vertical temperature profile during 12 s periods in the upper crown space of a 27 m tall spruce forest and in the adjacent air layer above, were observed by

Tajchman (1967). He reported that during periods of several minutes, typical lapse conditions alternated with chaotic temperature distributions during sunny days, and that the level of maximum temperature fluctuated within the upper crown space. Measurements by Lorenz and Baumgartner (1969) carried out at the same forest site, indicated surface temperature differences from about 2.5 to 3.0°C between shaded parts of crowns, and those exposed to the sun during sunny weather. The air temperature was approximately 1 to 3°C lower than the mean surface temperature of the biomass. McBean (1968) observed rapid temperature oscillations in a 4.6 m tall lodgepole pine forest at low wind speed, and attributed them to the advection of air of different mean temperature and humidity, which was caused by the inhomogeneity of the forest and turbulence flutuations.

Rauner and Ananev (1971) found surface temperatures of biomass from 3 to 4°C higher than air temperatures in the crown space of a mixed deciduous forest 12 m tall. They reported the existence of a thermodynamically active layer in the upper crown space in which heat is transferred from the biomass to the surrounding air, with resultant heating of the air during the day. In addition, longwave radiation exchange between biomass and surrounding air contributes to increasing air temperatures. Figure 6, adapted from Rauner (1972), presents vertical profiles of downward and upward fluxes of longwave radiation, air temperature, and surface temperature of the foliage in a mixed deciduous forest on a clear day.

Hanna (1971) used smoke puffs to investigate air flow in a forest. He found little correlation between wind directions above and below the crown at low wind speeds. The direction of flow in the forest was sometimes opposite to that of the wind above it. Air movements in the forest were highly variable. Hanna concluded that spurious local pressure gradients occurred, modifying the synoptic pressure gradients. Similar investigations were carried out by Oliver (1973) who observed convective plumes above the forest. Raynor (1971) observed smoke plumes released in the forest at several levels between the ground and treetops. His observations indicate that most downward flow occurs through openings in the canopy, and that compensating upward motions occur in the denser portions of the trees. In Raynor's opinion, both aerodynamic and thermal forces contribute to the observed pattern.

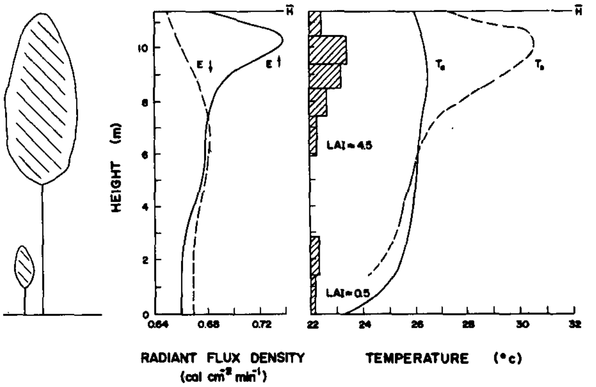

FIG. 6. Vertical profiles of leaf area (LAI), longwave radiation ($E$), air temperature ($T_a$), and foliage temperature ($T_s$) in a deciduous forest during daytime in July under mostly clear skies. Adopted from Rauner (1972).

The above results show that forests create a layer of intensive turbulent mixing in the upper crown space. The existence of that layer is caused by the increased dynamic turbulence produced by the roughness elements of crowns, and by thermally-induced mixing, originating from the inhomogenous distribution of solar energy absorption in the crown spaces. It appears that this mixing layer interacts with the meteorological regimes above and below the crowns. Short-term changes in the vertical temperature distribution in the upper crown space on sunny days, as observed by Tajchman (1967), may have been connected with the periodic character of this interaction. During periods when the exponential temperature profile extends down into the crown space, the regime of the external boundary layer penetrates downward into the canopy—whereas during periods of chaotic thermal structure, the thermal regime of the crown-produced mixing layer dominates the crown space and the adjacent air layers. Knowledge of the vertical extension of the crown-produced mixing layer and its daily fluctuations are of scientific and practical importance, e.g., for the determination of the height for micrometeorological observations above forests; the study of the turbulent energy transfer between the forest and the atmosphere; and the study of the structure of the boundary layer of the atmosphere above forests. The appropriate quantitative theory that would integrate both thermal and dynamic regimes has not been developed for forests.

## 5. Vertical turbulent fluxes above forests

The energy balance (Sverdrup's method, Bowen ratio method) and the aerodynamic method are used for routine measurement of vertical turbulent fluxes in the surface boundary layer. Knowledge of the vertical profiles of meteorological parameters is important in both methods, and the determination of the stability correction represents a special problem in the aerodynamic method. Application of the eddy correlation method is becoming more frequent, but experiments with fluxmeters show that there are still limitations in using them for routine and continuous measurements.

It generally has been assumed that, when using the aerodynamic method, vertical turbulent fluxes above natural surfaces can be obtained accurately. This has been confirmed by comparative flux estimates, but only for surfaces with relatively small roughness (Budyko *et al.*, 1953; Rusin, 1955; Tajchman, 1967, 1971). Most of the energy balance data for forests have been obtained by the energy balance method, but in earlier studies (Baumgartner, 1956; Konstantinov and Fedorov, 1960) the aerodynamic method also was applied to forests.

Tajchman (1967, 1971) reported the unsuccessful comparison of aerodynamic and energy budget estimates of fluxes over a 27 m tall spruce forest. In that comparison, the aerodynamic method appeared inapplicable to the forest when the logarithmic law was used for the analysis of the vertical profiles of meteorological parameters. Tajchman suggested that measurements of dry- and wet-bulb temperature should be taken at more than three heights above the forests, and that the zero plane displacement for wind should not be applied to temperature and humidity in the logarithmic law.

Another study by Tajchman (1973) presents a successful comparison of aerodynamic and energy balance estimates of sensible and latent heat fluxes above a pine forest 2.8 m tall. The instrumentation is shown in Fig. 7. Virtual temperature $T$ and wind speed $u$ from five levels, and specific humidity $q$ from four levels above the forest, were used in the analysis of vertical profiles of these parameters with help of the Monin-Obukhov equations:

$$u(h) = \frac{u_*}{k}\left(\ln\frac{h}{z_0} + \alpha\frac{h-z_0}{L}\right) \tag{5}$$

$$T(h) = T_0 + T_*\left(\ln\frac{h}{z_0} + \alpha\frac{h-z_0}{L}\right) \tag{6}$$

$$q(h) = q_0 + q_* \ln\left(\frac{h}{z_0} + \alpha\frac{h-z_0}{L}\right) \tag{7}$$

where the reduced height $h = z - d$, symbols $z$, $z_0$, $d$, $u_*$, and $k$ have the same meaning as in Eq. (1); $\alpha$ is the Monin-Obukhov coefficient, $L$ is the stability length, $T_*$ is temperature scale, and $q_*$ is humidity scale (Monin and Obukhov, 1954). The values of $T_0$ and $q_0$ can be obtained by extrapolating the vertical temperature and humidity profiles observed above the forest downward to the level $d + z_0$. These are usually different than the respective real values of these parameters at the same height.

The roughness length ($z_0 = 26$ cm) and the zero plane displacement ($d = 160$ cm) of the forest were estimated graphically and accepted as constants. The values of $u_*/k$ and $\alpha/L$ were calculated from Eq. (5) by least squares, and hence $T_0$, $T_*$, $q_0$, and $q_*$ were obtained from Eqs. (6) and (7) by least squares. The coefficient $\alpha$ and $L$ were calculated using the relationships given by Webb (1970).

The turbulent exchange between the forest and the atmosphere was calculated as follows: Using the aerodynamic approach, the coefficient of turbulent diffusion for momentum, $K_M(h_0)$, at the reduced height $h_0$ can be calculated from

$$K_M(h_0) = u_* k h_0 / \phi_M \tag{8}$$

where $$\phi_M = (kh_0/u_*)\,(du/dh)_{h=h_0}. \tag{9}$$

Another relationship for $\phi M$ that may have practical applications is given by the modified KEYPS formula (Businger *et al.*, 1971)

$$\phi_M = (1 - \gamma h_0/L)^{-1/4} \tag{10}$$

where $\gamma$ is a coefficient that can be estimated empirically. As stated by Kraus (1970), $\gamma$ does not seem to be a constant, since its values obtained by different authors appeared in the range from 4 to 14.

The coefficient of turbulent diffusion for heat transfer, $K_H(h_0)$, can be obtained from

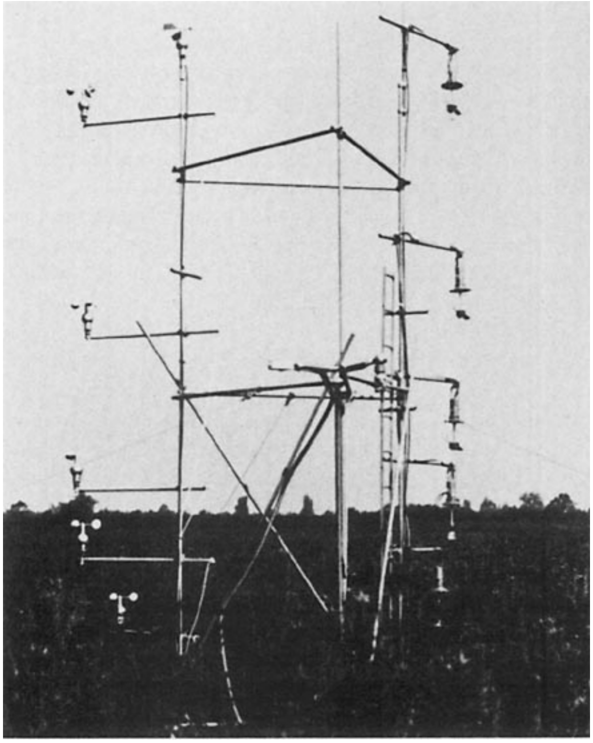

FIG. 7. Micrometeorological instrumentation above a forest canopy used by Tajchman (1973).

$$K_H(h_0) = K u_* z/\phi \tag{11}$$

where $\phi$ is the dimensionless temperature gradient. The value of $\phi$ is often taken to be the same for water vapor and for heat, with $\phi = \phi_M^2$ (Businger *et al.*, 1967; Dyer, 1967).

The coefficient of turbulent diffusion for sensible and latent heat, $K(h_0)$, also can be obtained from a combination of the aerodynamic and energy balance equations

$$K(h_0) = -\frac{R_n + B_\Sigma}{\rho\left[c_p\left(\frac{dT}{dh}\right)_{h=h_0} + \lambda\left(\frac{dq}{dh}\right)_{h=h_0}\right]} \tag{12}$$

where $R_n$ is net radiation measured above the forest, $B_\Sigma$ represents the sum of energy fluxes in soil, in biomass, and in photosynthesis, $\rho$ is air density, $c_p$ is the specific heat of air at constant pressure, and $\lambda$ is the latent heat of vaporization of water.

Calculations of the turbulent exchange based on hourly average values of meteorological parameters were carried out for four days (0800–1600) for the reduced height $h_0 = 2$ m. Values of $\phi$ were obtained from Eq. (9), the appropriate values of $h_0/L$ were substituted in Eq. (10), and the coefficient $\gamma$ was calculated; its average value was 55. The coefficients of turbulent diffusion were calculated from Eqs. (8) and (12). The relationship between values of $K(h_0)$ and $K_M(h_0)$ yields $\phi = \phi_M^2$. The difference between the daily sums of aerodynamic and energy-balance estimates of sensible heat exchange was between 0.4% and 4.1% for three days (steady weather conditions, moderate wind) and was 19% for one day (low wind speed, variable wind direction).

Results of this study suggest that the Monin–Obukhov equations describe satisfactorily the vertical profiles of meteorological parameters above a rough vegetation, and that fluxes of sensible and latent heat above a forest can be obtained from profile measurements only. It is worth mentioning that the value of 1.24 was obtained for the dimensionless heat flux, which is in good agreement with values above surfaces with small roughness obtained by others (Crawford, 1965; Dyer, 1967).

Some other relevant studies were carried out in a pine forest 15.8 m tall near Thetford, England. Stewart and Thom (1973) and Thom *et al.* (1975) reported discrepancies between aerodynamic and energy balance flux estimates. Gradients of meteorological parameters above the forest were estimated from slopes of semi-logarithmic curves hand-fitted to six experimental points. The flux-profile relationships based on the logarithmic law, and the stability correction of Dyer and Hicks, were applied in the aerodynamic method. The authors came to a conclusion that the aerodynamic method ought not to be used for independent flux estimates above forests. Another reason that precludes the application of the aerodynamic method above forests is, accoring to Thom *et al.*, the prohibitive amount of equipment required. Results by McNeil and Shuttleworth (1975) obtained at the same site do not seem to support these conclusions. They found a systematic relationship between the sensible flux magnitudes obtained by the Bowen ratio method and by the eddy correlation apparatus at 4 m above the average canopy height. The relationship between fluxes obtained by the aerodynamic and eddy correlation techniques was poor. The authors were unable to explain how the successful application of the eddy correlation techniques was related to the "anomalous aerodynamic behavior observed near the forest-atmosphere interface," as reported by Thom *et al.* (1975).

McNeil and Shuttleworth (1975) reported data that seem compatible with those obtained by Marunich (1971), who stated that the turbulence intensity above the forest was nearly constant above the level of $1.3\overline{H}$ and that above the levels of $1.3\overline{H}$ to $1.5\overline{H}$, the similarity theory of Monin and Obukhov should be applicable.

The problem of proximity of micrometeorological measurements above rough surfaces has been considered in the past, but a general quantitative solution is still lacking. Monin (1953) suggested that, because of the influence of microrelief of the steppe, profile measurements should not be taken below 0.5 m height. Lettau's rule of thumb (in Fritschen *et al.*, 1973), suggests that sensors should be at least five times the average roughness length above the surface. Assuming that the roughness length of the forest is equal to about $0.1\overline{H}$, Lettau's suggestion seems to be supported by the findings of Marunich (1971) mentioned above. Fritchen *et al.* (1973) suggested limits for sensor heights, and presented a diagram showing the suggested minimum height for successful application of different energy exchange models above vegetation covers. Garratt's (1978) estimates of the minimum height of validity of the neutral logarithmic law, equal to approximately $4.5\overline{H}$ for momentum transfer and $3\overline{H}$ for heat transfer, appear to be anomalous when compared to the above values.

It was suggested above that at least 1 km fetch for micrometeorological studies in forests is required. This is due mainly to the influence of advection on the energy balance. Since the surface boundary layer grows faster when the roughness of the underlying medium is greater, it seems that the required height/fetch ratios for forests may appear higher than for sites with smaller roughness.

## 6. Errors and experimental problems

An important part of the analysis of experimental data is the identification of sources of errors and the determination of their magnitude. Some basic information on meteorological measurements is given by Hofmann (in Geiger, 1965). Although these problems are included in basic applied meteorology courses, they are often overlooked in the field work. In the following section, some experimental problems and errors that often appear in measuring the vertical turbulent fluxes of sensible heat ($H$) and latent heat ($V_L$) above tall vegetation by the Bowen ratio method, and by the aerodynamic method, will be discussed. Both methods and their combination are still widely used.

### *a. The Bowen ratio method*

To obtain $H$ and $V_L$ by the Bowen ratio method, the following parameters are needed: Net radiation ($R_n$), energy storage in the soil ($B$) and in the biomass ($M$), energy used in photosynthesis ($P$), and the vertical gradients of air temperature and humidity.

### 1) NET RADIATION

In selecting the exact position of an experimental site, an attempt should be made to choose a location for the tower and instruments that is representative of a more extensive forest area. Net radiation measurements above forests show that such a requirement is not often fulfilled. Droppo and Hamilton (1973) reported differences as high as 13% between $R_n$ values measured at three points 15 m apart at 6 m above the canopy, whereas Stewart and Thom (1973) found 4% differences between values measured at two points 10 m apart, at 4.7 m above the canopy. With increasing height of the net radiometer above the forest, the forest area "seen" by the net radiometer increases and becomes more "representative." Munn (1966) calculated that when the sensor is $z$ meters above a surface, it receives 90 and 99% of the upward flux from a surface area of radius $3z$ and $10z$, respectively (flux divergence is not taken into account). This result can be used as a guide for estimating the required minimum height of a net radiometer above a forest, as related to its structure.

### 2) ENERGY STORAGE IN THE SOIL AND BIOMASS

If the volume heat capacity of the soil is known, $B$ can be calculated from measurements of soil temperature profiles. The parameter $M$ can be obtained from measurements of the temperature of the biomass and its specific heat. The sum of $B$ and $M$ usually does not exceed 10% of $R_n$ during the daytime, and over a long period of time, it amounts to from 1 to 2% of $R_n$, e.g., during the growing season. Values of $B$ and $M$ obtained at a point may not be representative for a large forest area because of variability in the forest structure and its influence on radiation exchange. Because of the relatively small magnitude of both parameters, errors are small in comparison to $R_n$, and are not of significant importance in the energy balance.

#### 3) ENERGY USED IN PHOTOSYNTHESIS

The component $P$ is usually not measured in energy balance studies of forests. It is, like $B$ and $M$, a relatively small component. Daily sums of $P$ may be as much as 3% of $R_n$ (Denmead, 1968) and yearly sums 1.2% of $R_n$ (Hager, 1975). Appropriate corrections can be introduced in the energy balance equation. Generally speaking, daily sums of $B$, $M$, and $P$ should not exceed 10% of $R_n$, and during the growing season, will equal about 2–3% of $R_n$.

#### 4) VERTICAL GRADIENTS OF AIR TEMPERATURE AND HUMIDITY

The vertical temperature and humidity gradients can be obtained from temperature and humidity measurements at several levels. In practice, unfortunately, measurements are usually taken at two levels only.

According to the requirement based on calculations by Kachurin and Patriki (1965), in measuring the vertical humidity gradients in the surface boundary layer, the maximum error of temperature differences should not exceed 0.01–0.02°C. Some authors have reported air temperature measurements with an accuracy of 0.01°C, but such accuracies may only be possible in laboratory calibration. As an example of difficulties encountered in field experiments, it is of interest to consider an experiment partly described by Tajchman (1967) in which dry and wet bulb temperatures were measured by electrically ventilated resistance psychrometers (Frankenberger type). During the summer daytime, the sampling error of one measurement was 0.4°C, and the error of the arithmetic mean obtained from 75 measurements during one hour was 0.05°C; 1600 measurements would be needed to diminish this error to 0.01°C. During this experiment, two ventilated psychrometers, one shaded and another exposed to solar radiation, were used to detect radiation errors. Both psychrometers indicated the same bulb temperature when they were shaded. The temperature difference reached 0.07°C when one psychrometer was exposed to solar radiation under low wind speeds ($\simeq$0.6 $\mathrm{ms^{-1}}$). The temperature difference was negligibly small when the wind speed was greater than 1.5 $\mathrm{m\ s^{-1}}$. Changing the orientation (azimuth) of the psychrometer (with thermometers usually directed to the north) was found to cause changes in the magnitude of the radiation error.

Before making the field installations, all thermometers were calibrated in the laboratory. When connectors were used in the field circuits, the temperature calibrations obtained in the laboratory were inaccurate by 0.1 to 0.2°C. After all connections were soldered, the sensors were calibrated in the field. The temperature calibrations did not change during periods of 2 to 3 months. The calibration took place in early morning or late afternoon. The sensors were placed in a copper block that was immersed in water, and the whole system was wrapped with an insulating blanket.

Taking, e.g., 0.07°C for the error of the hourly arithmetic mean of the air temperature, and 0.05°C for the radiation error, it can be shown that the error of the hourly average is 0.086°C, if systematic errors have been eliminated in the calibration procedure. At the same time, the vertical temperature differences above the forest canopy may be as small as 0.06°C $\mathrm{m^{-1}}$ (Tajchman, 1967). Assuming 0.09°C as the total error of the hourly average, it is evident that the error of the vertical temperature difference measured at two heights 1 m apart may amount to 300%. It is doubtful that vertical temperature differences above forests obtained from measurements at two levels only can be used for gradient-flux analyses, or for determining periods of neutral stability as required for obtaining zero plane displacement or roughness length.

### *b. The aerodynamic method*

In this method, data on the vertical wind profile are needed, in addition to the vertical temperature and humidity profiles. The wind data analysis must take into account the error of the wind sensor and the tower-induced measurement error. The error caused by the overspeeding of commonly-used cup anemometers amounts to about 10%, and the tower-induced error may exceed 30% of the measured wind speed (Izumi and Barad, 1970). The tower-induced error depends on the distance between the anemometer and the tower, and on the wind direction relative to the position of the anemometer and the tower. Dabberdt (1968) reported a decrease in wind speed up to 35% downwind of a triangular tower, and an increase up to 19% along the sides of a triangular tower. Experiments by Wucknitz (1977) show that distance equal to 40 mast radii between the cylindrical mast and an anemometer is needed to reduce the mast-induced error to about 1% of the measured wind speed. Taking the above numbers as the magnitudes of errors of wind speed measurement and accepting, after Wucknitz, that errors of 1% in the individual wind values can cause an error of about 10% in the gradient, it appears that obtaining accurate wind data by the commonly used methods and anemometers is difficult, and that many of the wind profile data collected above forests are probably not useful for profile-flux analyses.

Towers loaded with platforms, steps, and arms carrying instruments produce their own microclimate. Improvement that would substantially diminish the tower-induced errors could be achieved by separating the masts carrying instruments for measuring different quantities. Such an arrangement was used by Tajchman (1973) as shown in Fig. 7. Note that radiation instruments (directed towards the equator), temperature sensors (facing the opposite direction), and anemometers (oriented into the prevailing wind) are on different masts.

## 7. Outlook

World-wide activity in forest micrometeorology accelerated rapidly following the early studies conducted mainly in Europe in the '50s and early '60s. This activity was partly related to the international biological and hydrological programs. In this connection, micrometeorological studies in forests have been carried out not only by professional meteorologists but also by biologists, ecologists, and foresters. While the need for data generally has been recognized, relatively less attention has been given to basic research and to the problem of complexity of micrometeorological measurements in forests. This phenomenon explains, to some extent, the present lack of knowledge regarding the mircometeorology of forests. Some research needs in forest micrometeorology recently have been discussed by Hutchison (1979). Examination of traditional views on forest micrometeorology and for more detailed studies of forest–atmosphere interaction, including the role of structural characteristics of forests, are called for. The forest–atmosphere interaction appears important in a variety of problems including, e.g., atmospheric pollution and its effect on forest growth, and the global $CO_2$ balance and its role in the variability of climate. Also, studies of forest bioproductivity require long-term observations of evapotranspiration and $CO_2$ exchange of forests. For the solution of these problems, more coordinated studies and a wider participation of universities and research institutions in forest meteorological research are needed.

It is my opinion that sceptical views of some authors about the applicability of the aerodynamic method to tall vegetation are premature, but may be related, to a certain extent, to deficiencies in the experimental design or in data evaluation. The aerodynamic and energy balance methods, and their combination, can be used successfully for routine and long term measurement of the turbulent exchange above forests. Recent developments in optical and acoustical methods for measuring fluxes and gradients of meteorological parameters may lead to an improvement in the "representative" flux estimate. They offer promise for measuring average turbulent fluxes over extensive areas, without respect to the horizontal variability of the structure of the vegetation cover (see, e.g., Wesely, 1976; Wesely and Hicks, 1978; Coulter and Wesely, 1980; and Wyngaard *et al.*, 1978).

Results of experimental and theoretical studies as summarized in section 4 of this report give some general characteristics of the thermodynamic and turbulent regimes of the upper crown space and the adjacent air layer above. A theory that would quantitatively describe and combine both regimes has not been developed yet. The dynamic- and thermally-generated exchanges in the crown space, and their effects on the structure of the surface boundary layer in forested areas and in the air layer occupied by vegetation, remain important topics for forest meteorological research. According to some authors, e.g., Wilson and Shaw (1977), higher order closure techniques provide an alternative approach to the canopy flow problem. The authors stated correctly that it would be difficult to develop a consistent transport theory based on a flux-gradient relationship in the vegetation cover. However, the higher order closure approach requires precise closure assumptions, the basis for which is not available yet in many circumstances. Because of the spatial variability of forest structure, it seems that a solution based on the statistical relationships for the energy balance of the crown space, shearwake, and thermally generated turbulence would be most successful.

*Acknowledgment.* The original draft of this report was compiled during my summer visit, 1978, to the Atmospheric Turbulence and Diffusion Laboratory in Oak Ridge, Tenn., financed by the Oak Ridge Associated Universities and Oak Ridge National Laboratory. I would like to thank Drs. Bruce B. Hicks, Boyd A. Hutchison, Richard Lee, and K. Shankar Rao for reviewing the manuscript and for helpful discussions. I would also like to thank Ms. Gloria A. Nestor for preparing the diagrams and Ms. Geneva L. Taylor for typing the manuscript.

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