Evaporation Sources and Apparent Diffusivities in a Forest Canopy

O. T. DENMEAD

Division of Plant Industry, C.S.I.R.O., Canberra, Australia

(Manuscript received 24 October 1963, in revised form 22 January 1964)

ABSTRACT

An energy balance technique for computing fluxes and diffusivities within crop canopies is described. The technique was used in an investigation of the vertical variation of evaporation sources and diffusivities in the canopy of a pine forest. Evaporation sources were found to be fairly evenly distributed over the depth of the canopy, their vertical distribution and relative strengths corresponding roughly to the foliage distribution. Diffusivities decreased rapidly within the canopy, with the sharpest decline occurring at the top of the foliage. The results suggested that even with light winds, transfer processes within the canopy are turbulent in nature and that the level of turbulence is probably associated with momentum transfer.

1. Introduction

One of the more fruitful applications of micrometeorology is to problems associated with agronomic research. Of particular interest to agronomists concerned with the response of crop plants to their physical environment are the exchanges of carbon dioxide and water vapor between atmosphere and crop resulting from the physiological processes of photosynthesis and transpiration. Not only are the magnitudes and diurnal variations of these fluxes at the crop surface of interest, but also the spatial distribution of sources and sinks of these entities within the crop canopy.

These source-sink distributions can be specified by consideration of the vertical flux profiles. In the absence of direct measurement of the eddy fluxes, the vertical flux profiles can be established if we know the vertical gradients of the entities of interest and the corresponding, height-dependent, turbulent diffusivities. The measurement of the vertical gradients of carbon dioxide and water vapor can be accomplished with more or less standard micrometeorological techniques; the problem here is primarily one of sampling. The measurement of the diffusivities as functions of height is not so straightforward. Within the canopy of the crop, the fluxes are not constant with height and the exact form of the wind profile is uncertain, so that the diffusivities can not be easily deduced from similarity considerations of the wind profile.

Penman and Long (1960) have estimated diffusivities within a wheat crop by first estimating the horizontal flux of water vapor in the transpiration stream from leaf to air at a number of points in the canopy, building up the vertical flux profile by integrating the horizontal flux with respect to height, and then calculating diffusivities from the vertical humidity gradient. This pro-

cedure involves a number of assumptions, estimates and difficult measurements and was not attempted in the present work.

Uchijima (1962) has made some estimates of the variations of diffusivity with position in the canopy of a paddy field and a fir forest based on an assumed empirical vertical distribution of net radiation and published measurements of temperature and humidity gradients. A somewhat more direct approach, based on (i) actual measurements of the available energy at a number of heights in the canopy, (ii) simultaneous measurements of the profiles of temperature and humidity, (iii) the partitioning of the available energy into its component fluxes of sensible and latent heat, and (iv) calculation of diffusivities from the vertical flux estimate and the vertical gradient measurements, has been used in the present work. The results described herein were obtained in an investigation of the vertical variation of evaporation sources and diffusivities in the canopy of a pine forest. The study forms part of a larger project which is examining the whole question of gas and energy exchange in the canopies of crop communities in relation to their growth.

2. Energy balance

Assuming that there is horizontal uniformity, that steady state conditions prevail, and that the smaller components of the energy balance, such as the energy of photosynthesis and the change in heat storage of the crop-air layer, can be neglected, the energy balance expressed in terms of R , H , and LE at height z in the canopy may be represented by the equation

$$R(z) = H(z) + LE(z) + G, \quad (1)$$

where R is the net radiation, H is the flux density of

sensible heat to the atmosphere, LE is the flux density of latent heat to the atmosphere, and G is the flux density of heat to the ground. The flux density of sensible heat is given by the relationship

$$H(z) = -\rho c_p K_H(z) (\partial T / \partial z + \Gamma), \quad (2)$$

where ρ is the density of air, c_p is the specific heat of air at constant pressure, K_H is the diffusivity for heat, $\partial T / \partial z$ is the gradient of temperature, T , with height, z , and Γ is the adiabatic lapse rate. The flux density of latent heat is given by

$$LE(z) = -\rho L K_V(z) \partial q / \partial z, \quad (3)$$

where ρ and z have the same meaning as before, L is the latent heat of evaporation of water, K_V is the diffusivity for water vapor, and $\partial q / \partial z$ is the vertical gradient of specific humidity, q .

On the assumption that the finite difference ratios $\Delta T / \Delta z$ and $\Delta q / \Delta z$ approximate the average temperature and specific humidity gradients for a crop layer between two planes, a vertical distance Δz apart, then, for the layer,

$$\bar{H} + L\bar{E} = -\rho c_p \bar{K}_H (\Delta T / \Delta z + \Gamma) - \rho L \bar{K}_V \Delta q / \Delta z, \quad (4)$$

where the bar denotes an average quantity for the layer. Setting $\bar{K}_H = \bar{K}_V = K$, the average apparent diffusivity for the layer, Eq (4) becomes

$$\bar{H} + L\bar{E} = -\rho K \{c_p (\Delta T / \Delta z + \Gamma) + L \Delta q / \Delta z\}. \quad (5)$$

Writing Eq (1) in terms of average quantities for the layer Δz , substituting for the average flux densities of sensible and latent heat from (5), and approximating the average net radiation for the layer by the arithmetic mean of the net radiation measurements R_1 and R_2 at the top and bottom of the layer, we obtain

$$\bar{R} = \frac{1}{2}(R_1 + R_2) = \rho K \{c_p (\Delta T / \Delta z + \Gamma) + L \Delta q / \Delta z\} + G, \quad (6)$$

whence,

$$K = -\frac{\Delta z \{ \frac{1}{2}(R_1 + R_2) - G \}}{\rho \{ c_p (\Delta T + \Gamma \Delta z) + L \Delta q \}}. \quad (7)$$

Eq (7) can be further simplified by making use of the relationships

$$q = \frac{0.622e}{p - 0.378e} \approx \frac{0.622e}{p}, \quad (8)$$

and

$$\frac{T - T_w}{e_w - e} \approx \frac{0.622L}{c_p p} = \gamma^{-1}, \quad (9)$$

where e is vapor pressure, p is atmospheric pressure, T_w is the wet-bulb temperature, e_w is the saturated vapor pressure at the wet-bulb temperature, and γ is the psychrometric constant.

On substituting the value for e from (9) into (8), and then further substituting for Δq in (7), it can be shown that

$$K = -\frac{\Delta z \{ \frac{1}{2}(R_1 + R_2) - G \}}{\rho c_p \left\{ \Gamma \Delta z + \Delta T_u \left(1 + \frac{S}{\gamma} \right) \right\}}, \quad (10)$$

where S is the slope of the curve of saturation vapor pressure versus temperature at the wet-bulb temperature.

This layer technique has been used in the present work to study the vertical variation of the apparent diffusivity in the forest canopy.

It is apparent that many simplifying assumptions have been made in arriving at Eq (10) and it is well to examine them. The assumption of horizontal uniformity on the large scale has not been examined rigorously in the present work. Preliminary estimates of the fluxes of heat and water vapor at the surface of the forest obtained from energy balance measurements and measurements based on the wind profile in near neutral conditions were in good agreement. In the absence of more measurements designed to establish the magnitude of any advective effect, the assumption has been adopted as a first approximation. In order to minimize possible advective effects, the measurements have been made at a site within the forest situated some 400–500 m from the leading edge.

On the smaller scale, between neighboring trees, there is certainly some horizontal heterogeneity. The forest is a ten year old stand of *Pinus radiata*, unthinned and unpruned; the trees are planted on an approximate 8-foot square grid. The branches of neighboring trees touch and completely cover the ground at some spots but there are gaps in the foliage cover at others. No detailed examination of this heterogeneity has yet been undertaken so that the magnitude of the error arising from it is not known.

In order to satisfy the requirement for steady-state conditions, the measurements reported in this paper were obtained over periods of 40 or 60 minutes between the hours of 1000 and 1600 Australian Eastern Standard Time under conditions of clear skies and reasonably steady winds, when gradients appeared to be changing very little with time.

Regarding the magnitudes of the terms neglected in the energy balance equation (1), some recent estimates of the photosynthetic energy by Lemon (1960) indicate that under good growing conditions, this term may amount to 5 per cent of the available energy. Its neglect might then introduce an error of up to 5 per cent in the magnitude of K . Estimates of the likely maximum magnitude of the change in heat storage of the various crop-air layers using values for heat capacity suggested by de Vries (1963) indicate that neglect of this term would introduce an error of less than 1 per cent in the magnitude of K .

The assumption of equality between the diffusivities for heat and water vapor appears to be reasonable, although not strictly correct. Sutton (1953) and Priestley (1959) have concluded that under stable conditions, $K_H \approx K_V$ while under unstable conditions, $K_H > K_V$. However, the magnitudes of the differences are uncertain, and the indications are that in the lower layers of the atmosphere, the assumption of equality is acceptable (Rider and Robinson, 1951).

3. Instrumentation

Profiles of temperature were obtained with shielded, aspirated platinum resistance thermometers. The thermometers were connected in a dc bridge circuit in which the out-of-balance emf was proportional to the temperature difference between two thermometers which formed one arm of the bridge. Six thermometers, mounted at different heights, were used in this way and the temperature differences between one of these thermometers and the remaining five were recorded with a multi-channel potentiometric recorder.

A similar system in which the resistance thermometers were fitted with a wick, and water supply was used to record profiles of wet-bulb temperature differences. The wet-bulb thermometers were mounted adjacent to the dry-bulb units.

Although the thermometers are accurate to 0.02°C, our method of securing temperature measurements truly representative of the various horizontal planes was somewhat subjective. The thermometers were mounted on an instrument mast located at the center of one of the grid squares formed by the trees. All thermometers were in roughly the same vertical plane. Those in the canopy were positioned near one of the trees in such a way that the air-space sampled by each appeared by visual examination to contain a foliage density representative of its particular height. More objective methods are in the course of development and will be used in later work.

Net radiation intensity above the forest was measured continuously with a net radiometer of a type described by Funk (1959). Soil heat flux plates similar to those described by Deacon (1950) were installed in the forest floor. Within the forest canopy the average net radiation intensity in the same planes as those in which temperature measurements were made were measured with a miniature net radiometer of a type described by Funk (1962). The average net radiation intensity was taken to be the mean of three readings in each plane.

Wind profile measurements above the forest were made with small, sensitive, contacting anemometers.

The mean height of trees in the forest was 550 cm. The top of the forest canopy for about 100–150 cm, was composed mainly of spikelike extensions of the tree trunks with little lateral branch development. Lateral branch development and foliage density increased below these heights and dense foliage continued almost to

ground level. As mentioned previously, the branches of neighboring trees touched and completely covered the ground in some places but the foliage cover was incomplete at others. The canopy extended to about 50 cm above the ground. The understory at the time when measurements were taken consisted of a sparse cover of dead grass.

The measurements were at heights of 843, 583, 429, 291, 157 and 36 cm. The two top measurement heights were in the unobstructed air layer above the trees; the 429-cm height coincided with the bottom of the spikes; the next two measurement heights were spaced at approximately equal distances within the dense foliage, while the bottom height of 36 cm was below the bottom branches.

4. Flux measurements

Although the prime purpose of the investigation was to examine the variation of the apparent diffusivity with position in the canopy, interesting information on the vertical flux profiles of heat and water vapor was also obtained. Two representative situations are depicted in Figs. 1 to 6.

Fig. 1 shows the mean profiles of temperature and specific humidity observed over a 40-min period about noon on a clear day under slight lapse conditions with moderate insolation and moderate wind. Fig. 2 shows the corresponding net radiation distribution and the computed vertical flux profiles of heat and water vapor, the latter being expressed as latent heat. Not shown in Fig. 2 is the soil heat flux which was 0.25×10^{-3} cal cm⁻² sec⁻¹, into the ground. Fig. 3 shows the source-sink distributions in the canopy, obtained by approximate differentiation of the vertical flux profiles with respect to height.

* In differentiating the vertical flux profiles with respect to height, it was desirable to adopt a procedure which would be as objective as possible. In order to obtain the profiles of dR/dz , LdE/dz and dH/dz shown in Fig. 3, the procedure adopted was to fit to the vertical profiles of LE and R , cumulative incomplete Beta functions $I_x(p, q)$, where

$$I_x(p, q) = B_x(p, q) / B(p, q) \quad (11)$$

$$= \frac{\int_0^x x^{p-1}(1-x)^{q-1}dx}{\int_0^1 x^{p-1}(1-x)^{q-1}dx}, \quad 0 \leq x \leq 1, \quad p, q > 0. \quad (12)$$

For the canopy, the argument x was made equivalent to the reduced vertical distance z/h , where h is the canopy height, viz., 550 cm. The source strength y could then be represented by the functional form

$$y = y_0 x^{p-1} (1-x)^{q-1}. \quad (13)$$

FIG. 1. Vertical gradients of temperature and humidity in and above the forest canopy at 1145 AEST on 20 May 1963.

FIG. 2. Vertical profiles of net radiation, latent heat flux, and sensible heat flux in the forest canopy at 1145 AEST on 20 May 1963.

FIG. 3. Source-sink distributions of radiant energy, latent heat and sensible heat in the forest canopy at 1145 AEST on 20 May 1963.

FIG. 4. Vertical gradients of temperature and humidity in and above the forest canopy at 1540 AEST on 20 May 1963.

FIG. 5. Vertical profiles of net radiation, latent heat flux and sensible heat flux in the forest canopy at 1540 AEST on 20 May 1963.

The parameters y_0 , p and q were determined from use of tables of the incomplete Beta function (Pearson, 1934) and from the known integral properties of the complete Beta function, viz.,

$$B(p, q) = \frac{\Gamma(p)\Gamma(q)}{\Gamma(p+q)}. \quad (14)$$

The values of the Gamma functions for p and q were obtained from tabulated values.

The source-sink distribution of sensible heat was then determined from the relationship

$$dH/dz = dR/dz - LdE/dz. \quad (15)$$

A notable feature of the flux profiles is the fact that while most of the absorption of incoming energy appears to occur in the foliage layer between 300 and 400 cm, at the top of the dense foliage, the evaporation sources are more evenly distributed over the depth of the canopy, roughly in proportion to the foliage density. Sensible heat diffuses away from the absorption region and this movement is associated with the development of large temperature gradients, particularly in the lower parts of the canopy where, e.g., the temperature at 157 cm is 1.49°C less than at 291 cm. In the lower layers, the influx of sensible heat serves to maintain the transpiration rate in excess of the available radiant energy supply.

FIG. 6. Source-sink distributions of radiant energy, latent heat and sensible heat in the forest canopy at 1540 AEST on 20 May 1963.

Fig. 4 shows the mean profiles of temperature and specific humidity observed over a 40-min period late in the afternoon of the same day, when slight inversion conditions prevailed. The corresponding net radiation distribution and computed flux profiles are shown in Fig. 5. The soil heat flux was $-0.3 \times 10^{-3} \text{ cal cm}^{-2} \text{ sec}^{-1}$, away from the ground. On this occasion the evaporative flux of the whole forest canopy exceeded the available energy and there was a net gain of sensible heat from the atmosphere. The source sink distributions of net radiation, latent and sensible heats are shown in Fig. 6. In obtaining the profiles of dR/dz , LdE/dz and dH/dz shown in Fig. 6, a differentiation procedure similar to that already described was again adopted. In this case, cumulative incomplete Beta functions were fitted to the vertical profiles of LE and H and dR/dz was obtained by summing LdE/dz and dH/dz .

A distribution of evaporation sources similar to the mid-day distribution was again observed. On this occasion, the strength of the sources was less. The transpiration rate was maintained by diffusion of sensible heat away from the absorption region, by a net gain of sensible heat from the atmosphere and by an upward flux of heat from the ground.

5. Apparent diffusivities

The ratios of the computed values of K for the various canopy layers to that computed for the unobstructed air layer above the top of the foliage, K_0 , are shown in Fig. 7. The figure combines the results of 8 runs, each of 40 or 60 minutes duration, made under clear skies but under varying conditions of insolation, lapse rate and wind strength. The pertinent data for the 8 runs are shown in Table 1. Also shown in Fig. 7 is the ratio of the eddy diffusivity for momentum, K_M , calculated from simultaneous wind profile observations in the air layer above the forest, to K_0 . The calculations of K_M were made on the assumptions of a logarithmic variation of wind velocity with height, constant roughness height and constant zero-plane displacement. No stability corrections were applied.

The lines drawn in Fig. 7 represent the variation of the mean ratios with height. The broken line pertains to K , the unbroken line to K_M . As is to be expected, the diffusivity decreases rapidly with height inside the canopy, the sharpest decline occurring at the top of the canopy. The spread in the computed ratios for the various canopy layers is within reasonable limits. Considering the possible sources of error, discussed in an earlier section of the paper, and the variety of climatic conditions encountered in the 8 runs, the agreement both between runs and between heights is quite en-

couraging. It is interesting to record that the lowest value of the apparent diffusivity computed in the canopy was of the order of $100 \text{ cm}^2 \text{ sec}^{-1}$, a value considerably in excess of molecular diffusivities.

The ratio K_M/K_0 shows a much larger variation than K/K_0 and an examination of the Richardson numbers and wind velocities in Table 1, indicates a trend towards a dependence of the ratio on stability.

Although the departures from neutral stability in the various runs were not large, the general trend was for

TABLE 1. Meteorological conditions pertaining during experimental runs.

Day	Hour*	$R_{\uparrow}$	Ri^{**}	$u_{\uparrow\uparrow}$	K_0^{***}	Symbol
15 May 1963	1110-1150	10.0	-0.06	551	18,690	.
15 May 1963	1430-1510	2.8	+0.02	526	7,180	+
16 May 1963	1025-1125	5.9	-0.06	609	17,140	×
20 May 1963	1125-1205	8.3	-0.018	393	20,090	Δ
20 May 1963	1435-1515	5.4	-0.03	470	10,690	Φ
20 May 1963	1520-1600	1.3	+0.02	351	9,280	Θ
23 May 1963	1420-1500	4.2	-0.08	213	9,390	▽
23 May 1963	1530-1610	1.3	+ --	—	4,730	*

* In Australian Eastern Standard Time.

† R = net radiation measured above forest canopy ($\text{cal cm}^{-2} \text{ sec}^{-1} \times 10^{-3}$).

** Ri = Richardson number for layer 583 cm to 843 cm.

†† u = mean wind velocity at 700 cm (cm sec^{-1}).

*** K_0 = average apparent diffusivity for layer 583 cm to 843 cm ($\text{cm}^2 \text{ sec}^{-1}$).

FIG. 7. Vertical variation of apparent diffusivity and diffusivity for momentum in and above the forest canopy for 8 observation periods. See Table 1 for meteorological conditions prevailing during each period.

the ratio to increase with increasing stability and to decrease with increasing instability. Insufficient observations were made to indicate the true nature of this dependence.

The variation of the mean values of K_M/K_0 with height above the canopy and the variation of the mean values of K/K_0 appear to be reasonably consistent with one another. It is probably reasonable to assume that turbulence levels in the canopy are associated with the transfer of momentum and that even with light winds, transfer processes within the canopy are turbulent in nature.

6. Summary

The magnitude and variation of the apparent diffusivity, K , for heat and water vapor within the canopy of a pine forest have been examined by an energy balance technique under conditions of varying insolation, lapse rate and wind strength. Although the absolute values of K varied from run to run, the ratios of K computed for given layers in the canopy, to K computed for the air layer above the forest showed reasonably good agreement both between runs and between heights. There was a sharp decline in K within the crop canopy, the sharpest decline occurring at the top of the foliage. The measurements of K and those of K for momentum suggest that even with light winds, transfer processes within the canopy are turbulent in nature and that the level of turbulence is probably associated with momentum transfer.

Interesting source-sink patterns for heat and water vapor were found. The evaporation sources appeared to be fairly evenly distributed through the canopy, in a manner roughly proportional to the distribution of the foliage. On the other hand, most of the absorption of incoming radiation occurred in a shallow foliage layer near

the top of the canopy. Sensible heat moved away from the absorption region, the supply of sensible heat to the lower canopy serving to maintain transpiration there at a rate in excess of the available radiant energy supply.

Acknowledgments. The author is indebted to Mr. F. J. Moore for his assistance both in construction of the necessary measurement equipment and in performance of the field measurement program. Our thanks are due to the Director-General of the Commonwealth Forestry and Timber Bureau for making the site available.

REFERENCES

- Deacon, E. L., 1950: The measurement and recording of the heat flux into the soil. *Quart. J. R. meteor. Soc.*, **76**, 479-483.
- Funk, J. P., 1959: Improved polythene-shielded net radiometer. *J. sci. Instr.*, **36**, 267-270.
- , 1962: A net radiometer designed for optimum sensitivity and a ribbon thermopile used in a miniaturized version. *J. geophys. Res.*, **67**, 2753-2760.
- Lemon, E. R., 1960: Photosynthesis under field conditions. II. An aerodynamic method for determining the turbulent carbon dioxide exchange between the atmosphere and a corn field. *Agron. J.*, **52**, 697-703.
- Pearson, K., 1934: *Tables of the incomplete Beta-function*, Cambridge, Cambridge University Press, 494 pp.
- Penman, H. L., and I. F. Long, 1960: Weather in wheat: an essay in micro-meteorology. *Quart. J. R. meteor. Soc.*, **86**, 16-50.
- Priestley, C. H. B., 1959: *Turbulent transfer in the lower atmosphere*. Chicago, Univ. Chicago Press, 5-12.
- Rider, N. E., and G. D. Robinson, 1951: A study of the transfer of heat and water vapour above a surface of short grass. *Quart. J. R. meteor. Soc.*, **77**, 375-401.
- Sutton, O. G., 1953: *Micrometeorology*. New York, McGraw-Hill, 318-319.
- Uchijima, Z., 1962: Studies on the micro-climate within the plant communities (1) On the turbulent transfer coefficient within plant layer. *J. agric. Meteor., Japan*, **18**, 1-10.
- Vries, D. A. de, 1963: The physics of plant environments. *Environmental control of plant growth*, New York, Academic Press, 18-20.