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MICROCLIMATOLOGICAL INVESTIGATIONS AT SIMCOE, SOUTHERN ONTARIO

by

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This paper discusses microclimatological research in operation in southern Ontario by groups from McMaster and McGill Universities. The research embraces studies of process within the lower atmosphere, which includes a crop canopy and the soil, and also studies of relatively simple methods for predicting water loss by evapotranspiration which are potentially useful for such purposes as irrigation scheduling. McMaster University is concerned with: (1) relationships between evapotranspiration and plant and soil factors both in the short and long-term; (2) the use of the combination model in predicting actual evapotranspiration; and (3) the variation of radiation balance components over different surfaces. McGill University is studying advection induced by a surface moisture discontinuity subsequent upon localised irrigation.

The study site is a five acre corn field at the Horticultural Experiment Station near Simcoe. The use of this site and other sites in 1967 and 1968 has been made possible by the generosity of Dr. Collin, the director of the station.

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Previous Studies at Simcoe

Data gathered in 1967 were used to study certain aspects of the radiation and energy balances. An approximation of the radiation balance equation as derived by Monteith and Szeicz (1961) was used to define linear relationships between net all-wave and solar radiation for several crops. Values of the main parameters (reflection and heating coefficients) were similar to those published by Monteith and Szeicz and suggested that net radiation can be predicted from a knowledge of solar radiation (Buttimor 1968, Davies and Buttimor 1969). A second study compared estimates of hourly totals of evapotranspiration from irrigated grass using the Bowen ratio and Penman solutions (combination model) of the energy balance equation (McCaughey 1968, Davies and McCaughey 1968). The results were in excellent agreement when soil moisture was not limiting to evapotranspiration. In 1968 evapotranspiration rates for grass, wheat and a peach orchard were evaluated from soil moisture measurements by the neutron scattering method. McGill University also collected data to examine the adjustment of wind and temperature profiles downwind from the leading edge of a wheatfield. Analyses of these two sets of data are incomplete.

The present program of research is examining the environmental complex in more detail through measurement of a greater number of parameters than resources and personnel permitted in previous years. Descriptions of the programs have been prepared by each of the authors. These are presented below.

1. The Energy Balance Above and Within a Crop Canopy - J. A. Davies

The crop and the lower atmosphere above it are considered as two distinct regimes which require separate microclimatological analysis. It has been commonplace in lower atmosphere studies to make measurements above the vegetated zone. These can be used to evaluate vertical energy fluxes (non-radiative) from the surface provided these are made within the boundary layer, and an assumption of flux constancy with height is made. This assumption cannot be made within a crop because of its complex vertical heterogeneity.

From the relatively few attempts to study fluxes and transfer within crops and vegetated canopies there is sufficient evidence Begg, Bierhuizen, Lemon, Misra, Slatyer and Stern (1964), Denmead (1964), Brown and Covey (1967) and Lemon (1967) that the energy balance equation will serve as a framework for one-dimensional analysis of both regimes. The complexity of three-dimensional analysis is apparent from the Suomi and Tanner (1959) considerations of the total energy balance of a crop-air volume (Fig. 1). They showed the balance to be the sum of vertical energy fluxes, horizontal divergence and heat storage in the air and crop. From the principle of the conservation of energy, this can be written*:

Vertical fluxes + Horizontal divergence + Storage = 0

$$Rn+\lambda E+H+G+Ph \quad +\int_o^z C_p \nabla_H (\rho u T)\,\delta z+\int_o^z \frac{\lambda\omega}{R} \nabla_H \frac{(ue)}{T}\,\delta z \quad +\int_o^z C_p \frac{\partial T}{c\partial t}\delta z+\int_o^z C_p\,\rho\frac{\partial T}{\partial t}\delta z+\int_o^z \frac{\lambda\omega de\delta}{RT\partial t} z = 0$$

(1a)

* The symbols used in the equations of this article are listed as an appendix.

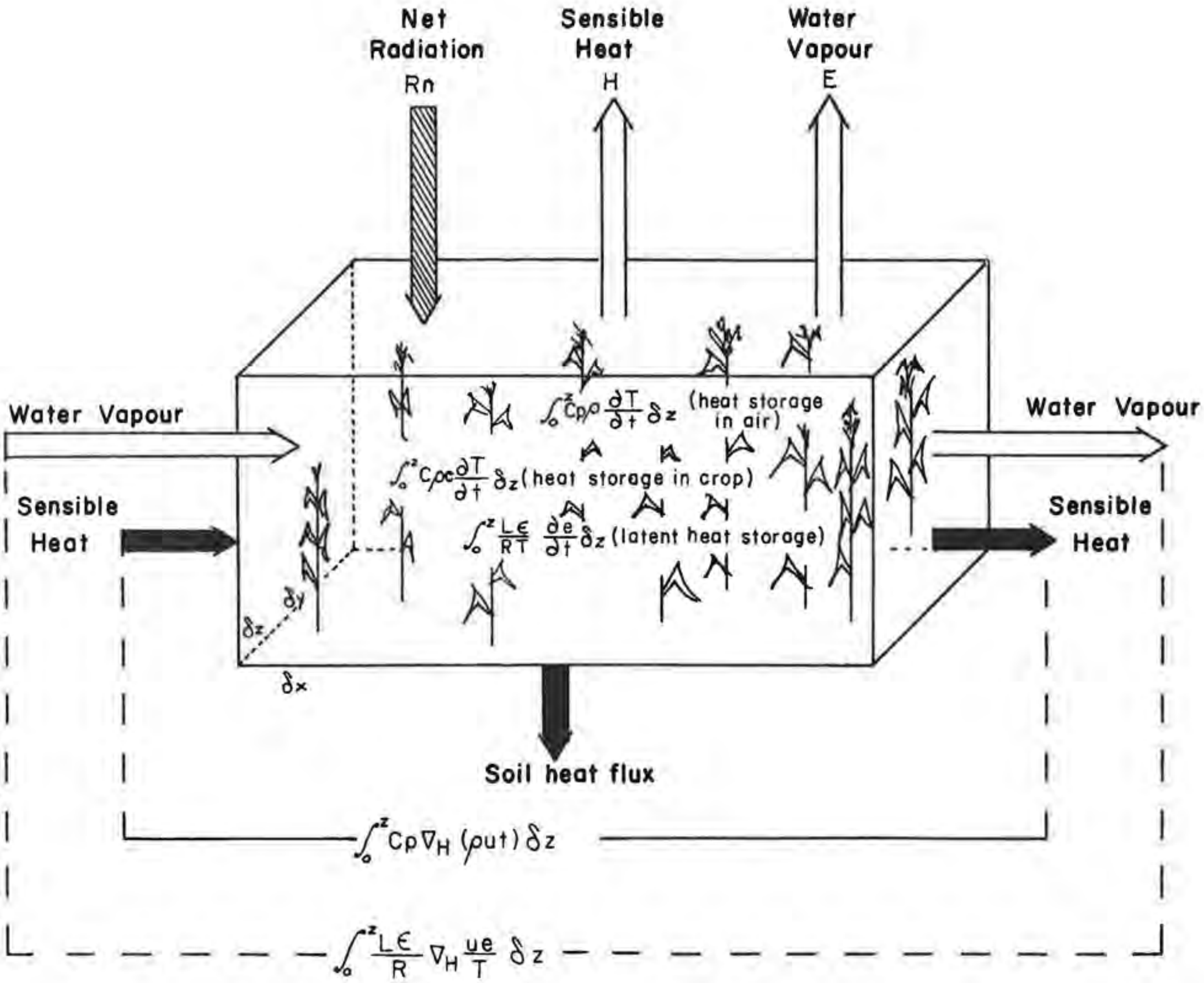

Fig. 1 Total Energy Balance of Crop-Air Volume
(after Suomi and Tanner, 1958)

Horizontal divergence and storage terms disappear for non-vegetated surfaces since $\delta z \simeq 0$. In the case of vegetated surfaces $\delta z > 0$ but if an homogeneous experimental site with adequate fetch is selected divergence and storage terms are small compared with the vertical fluxes and it is common practice to omit them. Divergence, storage and photosynthesis usually amount to less than 10% of the net radiation in such conditions. Equation (1a) then simplifies to its usual form:

$$Rn + \lambda E + H + G = 0. \tag{1b}$$

A solution for evapotranspiration is obtained through the Bowen ratio $H/\lambda E$. The ratio is evaluated using finite difference forms of one-dimensional mass transfer equations for the two turbulent heat fluxes and making an assumption about the value of the ratio of the eddy diffusivities for sensible and latent heat. A value of unity is usually assumed and has been confirmed by recent results of Dyer (1967) and Swinbank and Dyer (1967). From this method:

$$\lambda E = - \frac{(Rn - G)}{1 + \frac{C_p p}{\lambda \omega} \frac{\Delta T}{\Delta e}} . \tag{2}$$

Excellent agreement between results from this equation and direct lysimeter measurements has been demonstrated consistently to support the method and its assumptions. At Simcoe short (half-hourly) and long-term (weekly) evapotranspiration rates obtained by the Bowen ratio method will serve as standards against which results from other methods will be compared.

Further probings into physical process, however, requires an analysis which indicates the pattern of energy exchange and transfer rates (at least the variation in the vertical) within the plant zone. In this way it may be possible to demonstrate plant involvement in energy exchange which cannot be shown adequately from measurements made over a crop. The energy balance approach provides a fairly simple means for calculating diffusivity, fluxes, and the sinks and sources of energy.

The energy balance for a level z within a crop may be written in the form:

$$Rn(z) + G - \frac{\lambda\omega\rho}{p} K_W(z) \frac{\partial e}{\partial z} - C_p \rho K_H(z) \frac{\partial T}{\partial z} = 0 \tag{3}$$

where the negative signs indicate transfer away from level z. The diffusivity at level z is defined by re-arranging equation (3):

$$K(z) = \frac{Rn(z) + G}{\frac{\lambda\omega\rho}{p} \frac{\partial e}{\partial z} + C_p \rho \frac{\partial T}{\partial z}} . \tag{4}$$

Given profile measurements of radiation, temperature and humidity, values of K for different heights can be obtained from equation (4) to give the necessary terms for the evaluation of the turbulent heat fluxes from the basic definitions:

$$H(z) = - \rho C_p K(z) \frac{\partial T}{\partial z} \tag{5}$$

$$\lambda E(z) = - \frac{\lambda\omega\rho}{p} K(z) \frac{\partial e}{\partial z} . \tag{6}$$

Sink and source distributions (vertical divergence) of Rn, H and λE can be calculated by approximate differentiation (graphically or numerically) of two vertical fluxes with height (i.e. $\partial Rn/\partial z$, $\partial H/\partial z$). Since the principle of the conservation of energy applies, the third flux divergence follows from:

$$\frac{\partial \lambda E}{\partial z} = \frac{\partial}{\partial z}\left(\frac{\lambda \omega \rho}{p} K \frac{\partial e}{\partial z}\right) = \frac{\partial Rn}{\partial z} - \frac{\partial H}{\partial z} . \tag{7}$$

Vertical variation of the fluxes and diffusivity will depend on several factors but the variation of foliage density with height has been previously shown to be of major importance. Foliage density can be parameterized by leaf area density F (the total area of foliage per unit volume of space). The significance of leaf area density is most obvious with respect to radiation fluxes. Brown and Covey (1967) have shown that net radiation at any height z depends upon F cumulated from level h, the top of the crop, downwards to level z. The dependence was shown using Beer's law:

$$Rn(z) = Rn(h)\ \exp(-\eta \int_z^h F dz) \tag{8}$$

where η is an extinction coefficient. This type of energy-crop relationship can be extensively examined with the data collected at Simcoe.

Alongside detailed studies of canopy exchange processes and evapotranspiration by the Bowen ratio method, further study of the combination model is planned. Although the Bowen ratio method gives

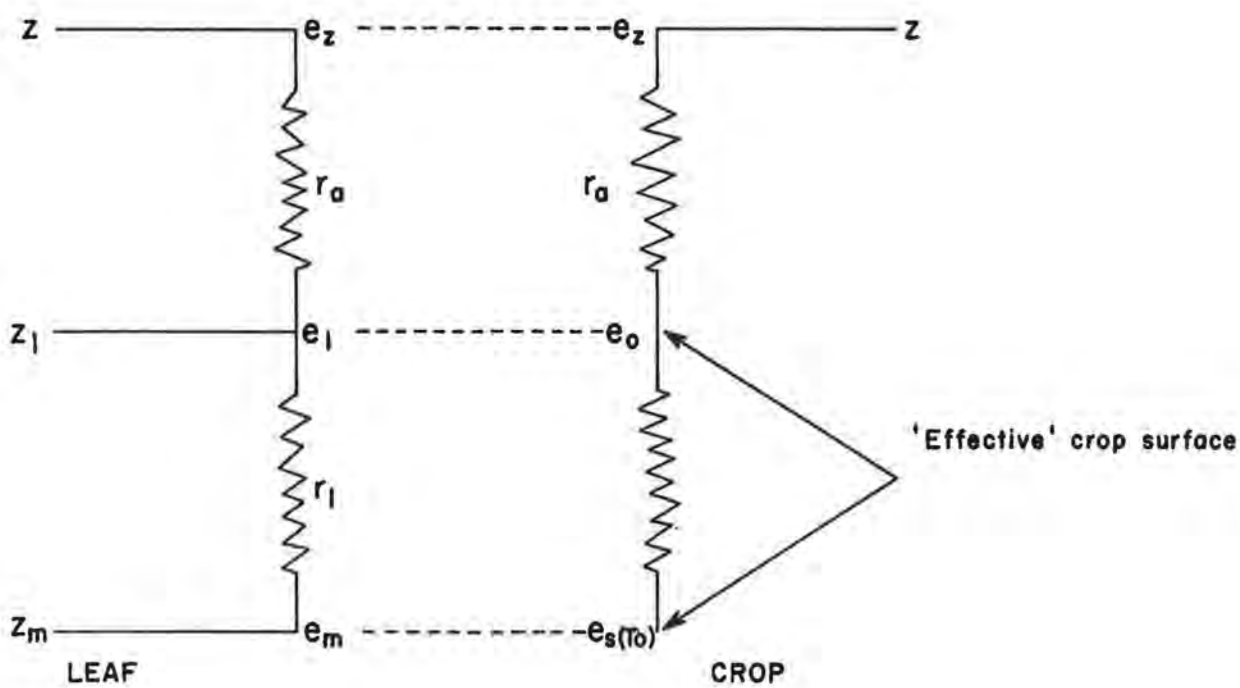

Fig. 2 Leaf and Canopy Resistance Network for Vapour Flux

excellent results its measurement requirements are too stringent for widespread use over long time periods. The combination model of Penman (1948) offers a promising alternative.

The combination model can be derived for actual as opposed to potential evapotranspiration. It may be expressed in several forms (Penman (1961) Slatyer and McIlroy (1961); Monteith (1965), and Tanner and Fuchs (1968)); of these Monteith's derivation is the most relevant for vegetated surfaces. It is written:

$$\lambda E = \frac{S(Rn - G) + \rho C_p \, [e_s(T) - e]/r_a}{S + \gamma(1 + r_s/r_a)} \tag{9}$$

The application of this equation is not a simple matter because of the difficulty in obtaining values of the two resistances r_s and r_a.

Crop resistances are obtained by analogy with leaf resistances (Fig. 2). If we consider vapour pressures within the mesophyll, at the leaf surface and in the atmosphere, two potentials e_m-e_ℓ and $e_\ell-e_z$ across diffusive resistances paths r_ℓ and r_a can be formulated. Vapour flux can be defined by analogy with Ohm's law as:

$$E\left(\frac{p}{\lambda\omega\rho}\right) = \frac{e_m - e_\ell}{r_\ell} = \frac{e_\ell - e_z}{r_a} = \frac{e_m - e_z}{r_\ell + r_a} \tag{10a}$$

A crop surface can be treated analogously if e_m and e_ℓ are replaced by $e_s(T_o)$ and e_o and r_ℓ is replaced by r_s. Here $e_s(T_o)-e_o$ is the saturation deficit at the crop 'surface'. Hence:

$$E\left(\frac{p}{\lambda\omega\rho}\right) = \frac{e_s(T_o) - e_o}{r_s} = \frac{e_o - e_z}{r_a} = \frac{e_s(T_o) - e_z}{r_s + r_a} \tag{10b}$$

The fundamental definitions of r_s and r_a follow as:

$$r_s = \frac{\lambda\omega\rho}{P} \frac{e_s(T_o) - e_o}{E} \tag{11a}$$

$$r_a = \frac{\lambda\omega\rho}{P} \frac{e_o - e_z}{E} \tag{11b}$$

$$r_s + r_a = \frac{\lambda\omega\rho}{P} \frac{e_s(T_o) - e_z}{E} \tag{11c}$$

The surface resistance r_s may be thought of as the stomatal resistance r_ℓ of all leaves in parallel. It is proposed to obtain it by making the necessary measurements to solve equation (11a). E will be obtained from the Bowen ratio. Following Monteith, an effective surface vapour pressure and temperature can be obtained by plotting T and e profile values measured above the crop against wind values. In neutral stability conditions the plots will be linear and extrapolation allows T_o and e_o to be taken as intercept values where u = 0. These will be working values which are not to be identified with actual values at a specific level in the crop. It is also hoped to measure r_ℓ with a porometer to establish mean values for several layers in the crop. Then

$$r_s = \frac{1}{r_{\ell_1}} + \frac{1}{r_{\ell_2}} + \frac{1}{r_{\ell_3}} + \dots + \frac{1}{r_{\ell_n}} \tag{12}$$

where r_{ℓ_n} is the mean stomatal resistance of the nth layer.

The aerodynamic resistance, r_a, can be derived from the assumed model of the wind profile above a crop. The logarithmic profile has been used frequently. The aerodynamic equation for evapotranspiration written with a lower level of vapour pressure (obtained by the extrapolation procedure described above) as

$$E = \frac{\lambda\omega\rho}{p} \frac{k^2(e_o - e)\,u}{[l_n(z-d)/z_o]^2}, \tag{13}$$

and combined with equation (11b) defines aerodynamic resistance:

$$r_a = \frac{[l_n\,(z-d)/z_o]^2}{k^2 u}. \tag{14}$$

This definition will apply over moist surfaces in near neutral stability but a correction factor is needed for non-neutral stability. Fuchs, Tanner, Thurtell and Black (1969) have reported considerable success with a correction factor Φ in their work over bare soil. With this correction:

$$r_a = \frac{[\Phi + l_n(z-d)/z_o]^2}{k^2 u} \tag{15}$$

where

$$\Phi = \int_o^z \left[\frac{(1 - 18\ Ri)^{-1/4} - 1}{z - d}\right] dz. \tag{16}$$

Ri is the gradient form of the Richardson number given by:

$$Ri = \frac{g}{T} \frac{(z_2-z_1)(T_2-T_1)}{(u_2-u_1)^2}. \tag{17}$$

Once r_a and r_s have been defined by such procedures attempts must be made to operationalise them through simpler, empirical relationships which remove the need for profile measurements of temperature, humidity and wind. Recent discussion of this problem have been presented by Szeicz, Enrödi and Tajchman (1969) and Szeicz and Long (1969).

To examine evapotranspiration and the energy balance in the manner described, considerable care is required in the measurement procedures particularly those for temperature and humidity. It can be shown for example that to achieve an accuracy of 10% in evapotranspiration from the Bowen ratio method temperature gradients must be accurate to 0.01°C. Such accuracy is difficult to obtain although resolution to 0.01°C is attainable. For temperature and humidity measurements five-junction thermopiles similar to those described by Lourence (1967) have been built. These are used to measure dry-bulb temperature differences between pairs of levels and wet-bulb depressions directly. These are constructed from 36-gauge nylon-insulated copper-constantan thermocouple wire and have a uniform calibration close to $200 \mu V °C^{-1}$. The sensors are mounted within a lexan tube which is covered in styrofoam and an outer shield of aluminised tape as protection from radiation. A constant aspiration rate of about 3 m sec^{-1} is achieved for eight levels in a profile by leading plastic hose from the housings to a box which is evacuated by a standard vacuum motor. Wet-bulb sensors are kept moist with a conventional water reservoir, wick, muslin system.

Net radiation is measured continuously at a height of 1 m above the crop with a Swissteco SW-1 polyethelene-shielded radiometer (Swissteco and Pty Ltd.). Within the crop it is planned to measure net radiation at three levels with 21" linear radiometers (Swissteco) in an attempt to achieve some degree of spatial sampling.

Soil heat flux for the soil surface G_o, is needed for the energy balance equation. Since standard transducers cannot be located at or near the surface, because they interfere with moisture movement, greater accuracy can be obtained if the flux is measured at some depth in the soil and corrected for divergence in the overlying soil (Tanner and Fuchs 1968). Soil heat flux at a depth of 7.5 cm, G_z, is measured with three transducers (Middleton and Pty. Ltd.) connected in series and the surface flux is given by

$$G_o = G_z + C \frac{\Delta T}{\Delta t} \Delta z. \tag{18}$$

The heat capacity is calculated by a method given by De Vries (1963) which requires gravimetric analysis of soil samples.

Wind profile measurements above the crop are made at six levels with a Thornthwaite system (C. W. Thornthwaite's Associates).

Weekly determinations of leaf-area index for the calculation of foliage density are made in conjunction with the resident staff at the Experimental Station. Leaf stomatal resistance measurements will be made with a porometer of the type described by Van Bavel, Nakayamma and Ehrler (1965). This consists of a humidity sensor within an open-ended cylinder that can be clamped onto a leaf. Stomatal resistance is obtained from the time taken for a prescribed humidity change as shown on a portable resistance meter.

A 50-channel data logger is used for punched paper tape recording of all voltage signals and there is also sufficient strip-chart recording back-up for use when the logger is not operational.

2. Radiation Balance Components Over Contrasting Surfaces - W. R. Rouse

Whatever the scale of investigation, net radiation is the major energy source for meteorological processes at a surface. Its knowledge is, therefore, important in many studies. Direct measurements are still scarce and there is a need to be able to predict the parameter from available sets of data. Net radiation will be influenced by the radiative and non-radiative properties of a surface. It is the object of the research described in this section to study the radiative and relative non-radiative properties of natural and agricultural surfaces as revealed in the component fluxes of the radiation balance and to determine if surface characteristics are sufficiently stable to allow the development of original models or to modify existing models useful for predicting net radiation.

The radiation balance of a surface may be written in its simplest form:

$$Rn = Qi - Qo + Li - Lo \qquad (19)$$

or as:

$$Rn = Qi\ (1 - \alpha) + Ln \tag{20}$$

where α is the short-wave reflection coefficient and $Ln = Li - Li(1 - \varepsilon) - \varepsilon\sigma\ Ts^4$. The second form will be used here because it demonstrates the influence exerted by the radiative properties of the surface.

The considerable body of theory concerning radiative exchanges in the earth-atmosphere system is of only limited applicability to the problem of estimating net radiation. The incoming fluxes of short and long-wave radiation are difficult to calculate without data from radiosonde ascents which are limited to only a few points on the earth's surface. There is no method of calculating ε values for natural surfaces although empirical determinations for a number of common surfaces are available. Surface temperature for vegetated surfaces with a vertical leaf structure is difficult to define and to measure.

Generally net radiation is only measured in specialized studies. Such measurements are rarely available in climatological networks. Where they are made in national networks, such as in Canada, instruments are sited over short-grass. Extrapolation of these values to other surfaces will involve errors due to differences in reflectivity and long-wave radiation characteristics.

Empirical models for the prediction of net radiation have been developed using measurements of solar radiation for which a reasonably dense network of observing stations are available. Use has also been made of linear regression relationships between Rn and

Qi or Qi $(1 - \alpha)$. Linacre (1968) summarizes published coefficients from these latter relationships. These models are generally limited with respect to prediction for different surface types. Where reflectivity is included in the expression account is made of surface differences but there is no account of the surface variation of net long wave radiation.

Monteith and Szeicz (1961) developed a surface sensitive net radiation model. Working from Equation (20) net radiation can be expressed as a linear function of the net short-wave radiation where:

$$Rn = Qi\ (1 - \alpha)a + b \tag{21}$$

only when Ln is a linear function of Rn of the type:

$$Ln = \frac{b}{a} - Rn\left(\frac{1 - a}{a}\right). \tag{22}$$

Defining $(1 - a)/a$ as β it is apparent that β is the slope of the line relating Ln to -Rn (i.e. $\beta = -dLn/dR_n$). If Li is constant through the day, a condition which would be approached during clear sky conditions, then the fluctuation in Ln would be due entirely to fluctuations in Lo. Since Lo is closely related to surface heating Monteith and Szeicz refer to β as a "heating coefficient". Since by definition $a = 1/1 + \beta$, equation (21) can be written as:

$$Rn = \left(\frac{1 - \alpha}{1 + \beta}\right) Qi + b \tag{23}$$

where b = Rn when Qi = 0 between sunset and sunrise.

Assuming that both Lo and Li are functions of Rn

$$\beta = \frac{-dLn}{dRn} = \frac{dLo}{dRn} - \frac{dLi}{dRn} \,. \tag{24}$$

Under ideal clear sky conditions dLi/dRn = 0 and therefore β= dLi/dRn which represents the true heating coefficient. Under cloudy skies Li may still be correlated with Rn. In these latter cases β is not solely a surface characteristic. Although Monteith and Szeicz developed equation (23) for clear sky conditions it may still be valid for more normal conditions particularly if rewritten as:

$$Rn = \left(\frac{1 - \alpha}{1 + \frac{dLo}{dRn} - \frac{dLi}{dRn}} \right) Qi + b. \tag{25}$$

To obtain Rn for any given surface appropriate values of α and dLo/dRn for that surface and representative b and dLi/dRn for both the surface and sky condition can be used in equation (25) along with measured Qi. To see whether or not dLi/dRn is amenable to such treatment is one of the purposes of the study. It is proposed to directly compute β, dLo/dRn dLi/dRn and b, to assess their stability for different surfaces and variability between surfaces and to evaluate equation (23) and (25) as predictors of Rn. It is also hoped to devise and test methods of predicting dLi/dRn and b from climatological data.

The field program is designed to evaluate completely the radiation balance of a number of disimilar natural surfaces to provide some information on the behaviour of the long-wave components of this balance.

The instrument being used for measuring the fluxes is the Swissteco SW1, net radiometer. Output of the radiometer is about 40 mV ly^{-1} min^{-1} and the time constant is 40 sec. The sensor is normally fitted with polyethylene hemispheric wind-shields for the direct measurement of Rn but may also be used with double glass domes to give Qi $(1 - \alpha)$ directly. A net pyrradiometer which measures Rn and net pyranometer which measures Qi $(1 - \alpha)$ have been placed over a bare soil surface, a short-cut grass surface and a corn crop. Unidirectional adaptors are used to convert two of the instruments into a pyrradiometer and a pyranometer for measuring (Qi + Li) and Qi respectively. The measurement of the incoming fluxes of radiation permit the division of the radiation balance of each surface into its component parts.

The domes of the instruments are kept inflated and dessicated with constant nitrogen flow. This equalizes convective heat loss from each of the thermopile surfaces and prevents internal condensation. Ventilation of the exterior surfaces of the domes serves to equalize temperatures of the upper and lower domes and to prevent nightime condensation.

The long-wave and short-wave calibrations of the Swissteco SW1 differ. Reliable long-wave calibrations have been determined at the National Radiation Laboratory of the Meteorological Branch, D.O.T. Consistent short-wave calibrations have been achieved by comparison with an Eppley pyranometer using the shading technique. This inequality in calibration constants necessitates unconventional methods of data conversion.

Surface temperature, a significant variable in the long-wave balance, is being measured by several methods. Multi-junctioned thermopiles are used to obtain vertical and spatial integration of temperature at the surface of the bare soil plot and an attempt is being made to obtain a further measure by extrapolating soil temperature profiles to the surface. Cruder determinations using mercury thermometers placed in contact with the radiating surface are also made. On occasions a Barnes PRT-5 infrared thermometer can be used as a check on all of these methods.

Data analysis uses integrated hourly totals. Integration is performed numerically and the errors inherent in this method for different degrees of variability in the radiation regime are assessed.

The objectives of the study are summarised below:

1. To test the contention of Monteith (1959) of constant solar reflectivity (= 0.26) for low green agricultural crops with a complete ground cover and to assess the magnitude of error likely in using this value of α in the Monteith and Szeicz model.

2. To assess the stability of β for a given surface and to assess to what degree it may be regarded as a surface parameter.

3. To both examine the stability of dLo/dRn and test the validity of assigning values to dLi/dRn for a number of atmospheric conditions. This will show the usefulness of using equation (25) for predicting Rn during cloudy periods.

4. To devise and test methods for predicting b in equation (23) and (25) from regularly measured climatological variables.

5. To attempt a calculation of ε values for natural surfaces from the measurement of Lo and Ts.

6. To provide much-needed descriptive information on the behaviour of long-wave fluxes.

3. The Water Balance Approach to Determining Evapotranspiration - W. R. Rouse

The water balance method is frequently used in agricultural and hydrologic studies of evapotranspiration. Potentially it can be useful when evapotranspiration is determined continuously for periods of several weeks or a whole growing season. Over such time intervals the necessary instrumentation is generally more reliable and computational procedures simpler than are required for aerodynamic, heat budget and combination methods.

Several problems can create inaccuracies under certain environmental conditions. Chief among these is the loss of soil water from the measured profile through deep seepage or alternatively water gain through upward capillary flow. Neither of these water movements are accounted for in soil moisture measurement using neutron attenuation techniques and can create errors in evapotranspiration calculations. Other problems include the number of depth intervals and length of monitoring times necessary for soil moisture measurement which is needed to calculate daily evapotranspiration, moisture gain and loss due to subsurface horizontal seepage and any vertical flux of water vapour.

A general assessment of the accuracy of the water-balance method is being undertaken by evaluating vertical and horizontal water movements and comparing daily and longer term evapotranspiration measurements using water-balance techniques to those employing the heat budget method for a sandy loam soil planted in corn.

The quantity of water lost due to evapotranspiration from a vegetated plot of land is calculated as the residual in the water balance equation:

$$E = P - \Delta Sm - U + \Delta Sr + \Delta L. \qquad (26)$$

Normally the last three terms of equation (26) above are disregarded and evapotranspiration is calculated from measurements of precipitation and soil moisture change alone. However, several studies have shown that large errors can arise due to vertical water movement. For example, van Bavel _et al_ (1968) found that neglect of the vertical water flux term resulted in errors in the evapotranspiration estimate ranging between +28 percent and -30 percent during weekly measurement periods. These errors resulted respectively from downward and upward water movements across the terminal depth.

The vertical water flux at terminal depth has been estimated by two methods: the Wilcox method and the hydraulic gradient method. The former, Wilcox (1959, 1960), involves covering an area of bare ground with a tarpaulin and measuring the soil moisture changes of the covered soil. It is assumed that the rate of drainage is the same in the cropped plot as in the covered bare plot when the two plots have equal moisture contents. Because the rate of drainage is a function of moisture gradient as well as moisture content, there are physical limitations in this method since observed gradients in cropped plots are normally different than those in bare plots. Also since any given moisture content in a cropped plot occurs much later in a covered plot, it is necessary to extrapolate the drainage curves for the covered plot beyond the actual measuring period.

The hydraulic gradient method is based on the theory of soil water movement. The vertical flux of water V at a depth z is given as:

$$V(z) = - k_z \frac{\partial \phi}{\partial z} . \tag{27}$$

In unsaturated soil under isothermal conditions the total potential can be expressed as the sum of matric suction Ψ and gravitational potential z so that:

$$\phi = -(\Psi + z) \tag{28}$$

Substituting equation (28) into equation (27) gives:

$$V(z) = k_z \frac{\partial \Psi}{\partial z} + k_z . \tag{29}$$

Thus in order to calculate the vertical flux of water the capillary conductivity and matric suction must be known. The capillary conductivity is a function of soil type and water content. It can be determined using both field and laboratory techniques. The hydraulic gradient can be measured in the field using soil tensiometers in profile.

The hydraulic gradient method is potentially applicable to horizontal subsurface flow. The horizontal flux of water V at a point x is given by:

$$V(x) = - k_x \frac{\partial \Psi}{\partial x} \tag{30}$$

where k_x is the capillary conductivity for horizontal flow. For moist soil k_z will not equal k_x at the same moisture contents due to platy soil structure.

Elements of the water balance are monitored at six sites within the corn field at Simcoe. The soil is Caledon sandy loam overlying Haldimand clay at a depth of 230 cm. A common terminal depth of 160 cm has been selected for the soil moisture measurements.

At the six sites soil moisture contents are measured with a neutron depth probe in intervals of 10 cm from a depth of 20 cm to 200 cm. Both gravimetric and surface neutron probe measurements are being used to determine the moisture content of the 20 cm surface layer.

Vertical moisture movement at the terminal depth is calculated as the product of hydraulic gradient and capillary conductivity. Hydraulic head is measured at 4 depths at each site using soil moisture tensiometers. The hydraulic gradient at the terminal depth is calculated as the average of the gradients between the 4 depths of measurement.

More detailed measurements are made at two of the sites. Hydraulic head is measured at 10 cm intervals to a depth of 80 cm and at 20 cm intervals down to 220 cm. This allows a comparison of the hydraulic gradients and the vertical fluxes of water through the profile. Horizontal subsurface water movement is also measured by installing 2 pairs of tensiometers at each depth to be considered. The pairs are separated by a distance of 1 m.

A time interval of three to four days is used to determine accurately, moisture content changes at the six sites. At one of the sites, however, soil moisture is measured daily to test the feasibility of using the soil moisture method on a daily basis.

Precipitation is measured at the edge of the field with three 5 inch diameter rain gauges. The amount of precipitation at all of the sites within the field is taken as the average measured value.

Evapotranspiration estimates determined by the energy balance method are used as control data. Measurements of temperature and humidity for Bowen Ratio calculations are made at a mast located at the centre of the corn field with a minimum fetch of 65 m. The energy balance measurements are used to determine the conductivity characteristics of the soil and as the standard against which the water balance estimates of evapotranspiration are compared. The Bowen ratio method and measurements have been discussed in an earlier section.

The neutron monitoring equipment includes a depth probe which is lowered down an access tube to any desired depth, a surface probe and a scaler. The depth probe contains an americium-beryllium source of fast neutrons and a boron-trifluoride slow neutron detector. When fast neutrons are emitted into the soil they are slowed down to thermal energies by elastic collisions with other particles. The moderation by the hydrogen nucleii of the water molecule is much more efficient than that by heavier nuclei of other soil elements so that the density of the neutron cloud around the sensor, and hence the count rate of thermal neutrons, is a linear function of volumetric soil moisture. The number of slow neutrons measured in a predetermined time is recorded on the scaler. The depth probe radiates neutrons in a spherical cloud so if it is brought close to the surface some of the neutrons will escape and the results will be invalid. Usually the effective working range for the depth probe is below 20 cm. Surface measurements of soil moisture are determined using both a surface neutron emitter and sensor and gravimetric techniques. With the former the unit is placed on a flat surface and a hemispherical cloud of neutrons are emitted into the soil from a radium-beryllium source. The chief disadvantages of this system are three-fold: firstly, the sphere of influence varies with soil water content; secondly, it is essential that there are no air-pockets between the flat sensor plat and underlying soil; and thirdly, the calibration curve is very flat so that a given neutron count applies to a substantial range of soil moisture. An alternative to the surface probe involves driving a sampling tube into the first 20 cm of soil and determining volumetric soil moisture by gravimetric means. The advantages and disadvantages of this method are thoroughly explored by Hewlett and Douglass (1961).

The tensiometer used in hydraulic head measurements consists of a water filled porous ceramic cup connected by a continuous water column to a manometer. Flow of water through the cup wall will bring the cup water into hydraulic equilibrium with the soil water, so that changes in soil water conditions are reflected by corresponding changes in the manometer reading. The manometer indicates partial vacuum relative to the atmosphere so that the highest possible reading is 1 bar. The manometer scale is calibrated in millibars and using this system readings are accurate to $\pm$ 1.0 mb.

4. Eddy Flux Divergence Studies - T. R. Oke

The complexity of a three-dimensional crop-atmosphere model is apparent from Fig. 1. Even without the complications introduced by vegetation, the analysis of a three-dimensional model of the atmosphere remains a formidable mathematical and physical problem. It is not surprising therefore, that micrometeorologists have tended to concentrate their efforts in refining their one-dimensional model with the assumptions of flux constancy with height, and the absence of horizontal divergence. This approach has yielded relatively sophisticated results in situations where these assumptions may be expected to hold (e.g. Swinbank and Dyer (1967)). Unfortunately, however, these situations are rarely found in nature.

Recently, workers have begun to grapple with the problems posed by inconstancy of fluxes with height (such as the work within crop canopies outlined in section 1), and horizontal divergence (such as the small-scale advection studies reported in this section). Ultimately we must seek to be involved in 'dimensional micrometeorology'. Such extrapolation in time and space is fundamental to the development of a quantitative microclimatology which truly models nature.

Advection is defined as"the exchange of energy, moisture or momentum as a result of horizontal heterogeneity" (Philip (1959)). Advection may operate on all scales from the truly microscale (cm) up to that of the global circulation. The research reported here is concerned with relatively small-scale effects extending up to a few hundred metres at the most. The terminology surrounding this type of advection is rather confused. The surface moisture, and/or heat, and/or roughness discontinuity initiating the horizontal gradients is termed the 'leading edge'. Tanner (1957) terms the horizontal divergence as air passes from a non-cropped surface through a crop volume (Fig. 1) the 'clothes-line effect'. This usually only extends a few metres in from the leading edge. Above the crop the transfer has been termed the 'oasis effect' by some workers but others restrict the use of this title to large scale transport up to km from the boundary involving air mass subsidence. Here we will term the exchange the 'leading edge effect' including transfer within and above the crop canopy.

Fig. 3 illustrates the experimental arrangement used in the Simcoe studies, and serves to further explain the concept of advection. In the hypothetical case shown, air is flowing in the direction of the mean flow, which is normal to a surface moisture discontinuity, X. For purposes of simplicity we assume both the upwind and cross-wind directions to be infinite. Skies are clear, and the wind is steady.

The line of masts A, B, C and D instrumented for the measurement of wind (u), temperature (T) and specific humidity (q) could be expected to record the sequence of profiles shown in Fig. 3. The

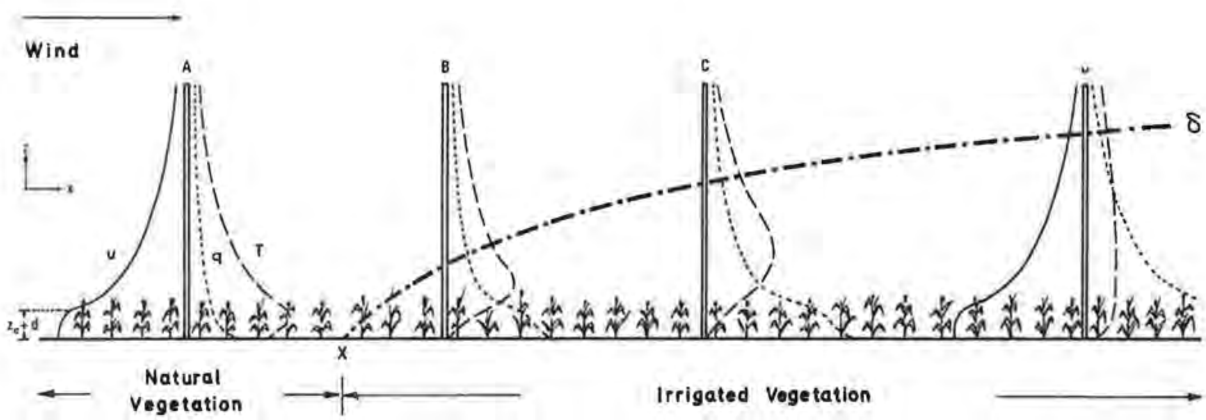

Fig. 3 Adjustment of (a) temperature (— — —), (b) humidity (-------), and (c) wind (————) profiles as air passes from a natural to an irrigated vegetated surface across the boundary X.

wind profile in the upwind region may be expected to conform to the logarithmic law with the usual introduction of a zero-plane displacement (d), and a correction factor to account for the effects of buoyancy. In general it is found that forced convection dominates flow over most vegetated surfaces and hence the deviation from the neutral profile is small. If this is correct, and assuming the crop has the same physical characteristics on both sides of x (i.e. z_o remains constant), then we may expect little change in the form of the wind profile.

The temperature and humidity profiles representative of the natural vegetation surface are shown at mast A (Fig. 3). The temperature profile shows a slight lapse condition and the humidity gradient is relatively small. Downwind of the moisture boundary the profiles of T and q become successively modified (stations B, C, and D). Increased surface evaporation moistens and cools the lowest layers. As a result the humidity gradient steepens and the temperature profile exhibits an inversion. These modifications affect higher levels as distance increases downwind from the discontinuity. Eventually the diffusion to higher levels establishes a new equilibrium set of profiles such as those shown at station D. In the lowest layers the temperature profile shows an adiabatic or slight lapse condition and the humidity gradient shows a more normal variation with height.

Rider, Philip and Bradley (1963) and Dyer and Crawford (1965) have provided the best observations of the modification of the temperature profile under field conditions approximating the hypothetical case given above. The work of Dyer and Crawford (1965) also draws attention to the very important change in the sensible and latent heat fluxes downwind from the leading edge. They show that immediately downwind of the discontinuity the consumption of latent heat is greater than the available net radiation. Equation (1b) (section 1) must be satisfied at all points of the surface. This can only be acheived by a compensating downward sensible heat flux. Thus the necessary energy is drawn from the atmosphere and it is the layer below the height of the temperature inversion that is involved in this exchange.

The air layer of increasing depth downwind of the leading edge that is fully adjusted to the new surface conditions is called the 'internal boundary layer' (δ). Measurements conducted within this layer are fully representative of the new surface. Observations from above this layer must not be incorporated into estimates of the surface fluxes by the aerodynamic, Bowen ratio or eddy correlation methods since it is no longer valid to assume that the fluxes are constant with height (Dyer and Pruitt (1962) , Dyer and Crawford (1965).

In view of the necessity of keeping within the boundary layer it is useful to seek practical guidelines for proper site selection in the field. Many height fetch ratios have been suggested for field use. The most recent estimates suggest a ratio of 1:200 to be necessary in near neutral conditions (Dyer (1965), Bradley (1968)). This ratio may be expected to increase in greater stability and to decrease with greater buoyancy. Wind speed may also affect this ratio (Penman, Angus and van Bavel (1967)).

Recently there has been renewed interest in the effects of a change in surface roughness upon the form of the wind profile

(Nickerson (1968), Bradley (1968), Taylor (1969a, 1969b), Blom and Wartena (1969), Peterson 1969a (1969b)), but little has been published on the effects of changes in the surface moisture or heat inputs. Towards this end the Simcoe advection experiment is designed to gain some understanding of the way in which the components of the energy balance (equation 1b, section 1) are modified by an abrupt change in the availability of moisture.

The experimental design is as shown in Fig. 3, with masts at $x = 10$ m upwind, and 5, 10 and 25 m, downwind of the leading edge (Fig. 4). The total fetch upwind of the leading edge varies from 100 to 250 m depending on wind direction. The crop surface is composed of immature corn plants (10 to 25cm high), and the moisture change is produced by heavy irrigation (1/2 - 1" water). Observations are conducted on clear days, and results are averaged over a 15 minute period. A full description of the instruments and their placement is given in Table 1.

In accord with Rider et al. (1963), it is assumed that Rn-G is the same for both the natural and irrigated surfaces. This is only an approximation for Rn since we may expect T_s to be lower, and α higher over the irrigated surface (see equation 20, section 2). Further discussion of these terms is provided in de Vries (1959). Measurements of Rn-G reduce the problem to the familiar one of partitioning the remaining energy between that used to drive the sensible (H) and latent (λE) heat fluxes. The problem of estimating H

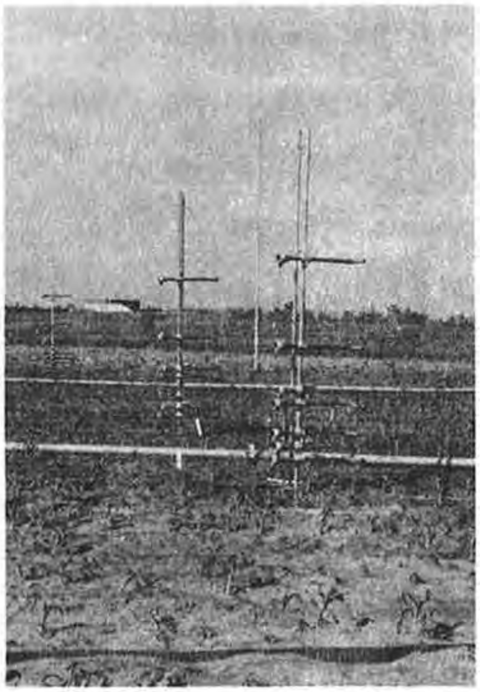

Fig. 4 Masts at 5, 10, and 25 m downwind of the lending edge (lawn edging in foreground). Gradations in soil colour reveal effects of increased evaporation near boundary after only 2 hr. since 1/2" irrigation.

Fig. 5 Close-up of dry and wet-bulb temperature sensors and their radiation/aspiration housings (25¢ coin for scale).

TABLE ONE

Small-scale Advection Instrumentation

Variable	Mast	Height	Instruments
T*	A,B,C,D	25,50,75 125,200	1/8" diameter steel-encased copper-constantan thermo-couple. (Thermoelectric Canada Ltd.)
q*	A,B,C,D	25,75	As above enclosed in ceramic pencil tensiometers with water supply.
u	A,D	25,50,75 125,200,400	Sensitive cup anemometers (C.W. Thornthwaite Associates).
G^+		-2.5	Heat flux plates (Middleton Pty. Ltd.)
Rn^+		100	Thornthwaite Model 601 and Swissteco Type S-1 (Swissteco Pty. Ltd.) net radiometers.
Wind Direction			Wind vane (Rochester Instr.)

* Sensors housed in P.V.C. tubing, shielded from radiation by aluminised tape, and aspirated at > 3m sec^{-1} (Fig. 5)

\+ One station for natural and one for irrigated vegetation.

and λE is a complicated one since we are concerned with conditions which by definition do not fulfill the assumptions necessary to properly implement the aerodynamic or Bowen ratio approaches.

The ideal procedure would be to use direct methods of estimating surface fluxes, such as lysimetry which makes no reference to flux-gradient relationships and their restricting assumptions. In the absence of such techniques we have followed the method of Dyer and

Crawford (1965), requiring measurements of the temperature profile from a series of masts as shown in Fgi. 3. They show that the sensible heat flux difference between the surface and any height z is given by:

$$H_o - H_z = C_p \int_o^z \mu u \frac{\partial T}{\partial x} \delta z \qquad (31)$$

Thus when horizontal gradients are negligible the flux is constant with height. When there is an inversion in the profile, as in a dry/moist advective situation (Fig. 3), there is zero heat flux through the inflexion (z_i) and the surface flux H_o is given by equation 31 integrated from the surface to z_i . The equation can be evaluated numerically using successive pairs of temperature profiles in the x-direction.

Following the above analysis the surface evaporation (E_o) can be obtained as a function of x from the simple energy balance equation. During the period immediately following irrigation, when the whole irrigated surface is evapotranspiring at the potential rate, it may be expected that H_o and E_o will be exponentially related to x. At some time later however, immediately in the lee of the leading edge, the excessive evaporation rate causes the soil to begin drying out (Fig. 4). The downwind variation of E_o is then governed by the availability of water as well as energy. Interest will therefore centre on the partitioning of H and λE with time as well as distance.

Rider and Philip (1960) emphasize the importance of this

'Bowen ratio effect' over changes in the radiation balance in studying evaporation in areas affected by advection. They find that the downwind variation of the Bowen ratio (B) is given by:

$$B = B' - \frac{a(1 + B')^2}{Rn(x)^{1/9} + a(1 + B')} \qquad (32)$$

where a is a constant determined by the upwind surface temperature and humidity, and the prime denotes upwind values. This relation will be tested using B' values from mast A calculated via equation 2, section 1. Downwind values of B will be computed from:

a) values of H_o and λE_o obtained from the Dyer and Crawford (1965) analysis,

b) gradients of T and e between 25 and 75 cm at masts B, C and D and equation 2 section 1.

As Dyer and Crawford (1965) point out, the downwind partitioning of H and λE using gradient relations is stricting incorrect since they have been derived for horizontally uniform conditions and require constancy of fluxes with height. Hence B values using (b) above should give erroneous results. These calculations will still be made however firstly to gauge the errors to be expected by ignoring advection, and secondly to test the possibility that the Bowen ratio formulation may fortuitously include a compensation effect.

Just as it is possible to calculate H_o values from equation (31) if there is an inversion in the profile, similarly the heat flux at the topmost measuring point (200 cm) is given by:

$$H_{200} = - C_p \int_{z_i}^{200} \rho u \frac{\partial T}{\partial x} \partial z \qquad (33)$$

Then assuming that $K_H = K_W$ (Swinbank and Dyer 1967) we are able to obtain E_{200}. Thus we have values of H_o, E_o and H_{200}, E_{200} as a function of distance and can check on the constancy of the fluxes with height since in the absence of advection $H_o = H_{200}$ and $E_o = E_{200}$.

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APPENDIX OF SYMBOLS

B	Bowen ratio, -----------
C	Heat capacity of soil, cal $cm^{-3}\,°C^{-1}$,
E	Evapotranspiration, cal $cm^{-2}\ sec^{-1}$,
F	Leaf area density, $cm^{-2}cm^{-3}$,
G	Soil heat flux, cal $cm^{-2}\ sec^{-1}$,
H	Sensible heat flux, cal $cm^{-2}sec^{-1}$,
K_H	Eddy diffusivity for heat, cm^2sec^{-1},
K_W	Eddy diffusivity for water vapour, cm^2sec^{-1},
Li	Incoming long-wave radiation flux, cal $cm^{-2}sec^{-1}$,
Ln	Net long-wave radiation flux, cal $cm^{-2}sec^{-1}$,
Lo	Outgoing long-wave radiation flux, cal $cm^{-2}sec^{-1}$,
L	Lateral subsurface water movement, cm,
P	Precipitation, cm,
Ph	Energy used in photosynthesis, cal $cm^{-2}sec^{-1}$,

Qi	Incoming short-wave radiation flux, cal $cm^{-2}sec^{-1}$,
Qo	Outgoing short-wave radiation flux, cal $cm^{-2}min^{-1}$,
R	Specific gas constant, mb $cm^3g^{-1}C^{-1}$,
Ri	Gradient form of the Richardson number, ------------
Rn	Net radiation flux, cal $cm^{-2}sec^{-1}$,
S	Slope of the saturation vapour pressure-temperature curve at a given temperature, mb$^\circ C^{-1}$,
Sm	Soil moisture, cm,
Sr	Surface flow of water, cm,
T	Temperature, °C,
T_s	Surface temperature, °C,
T_o	Effective surface temperature obtained by profile extrapolation, °C,
U	Net water transfer across a horizontal plane at the terminal depth of a soil column, cm,
V	Vertical flux of water, cm,
C_p	Specific heat of air at constant pressure, cal $g^{-1}{}^\circ C^{-1}$,
Cp_c	Heat capacity of the crop material, cal $g^{-1}{}^\circ C^{-1}$,
d	Zero-plane displacement, cm,
e	Vapour pressure, mbs,
e_ℓ	Vapour pressure at a leaf surface, mbs,
e_m	Vapour pressure within the mesophyll, mbs,
e_o	Effective surface vapour pressure obtained by profile extrapolation, mbs,
$e_s(T_o)$	Saturation vapour pressure at temperature T_o, mbs,

g	Gravitational constant, cm sec^{-2},
h	Crop height, cm,
k	Von Karman constant, -----------,
k_z	Capillary conductivity at depth z in the soil, cm sec^{-1},
p	Total pressure, mbs,
q	Specific humidity, --------,
r_a	Aerodynamic diffusion resistance, sec cm^{-1},
r_ℓ	Stomatal diffusion resistance of a single leaf, sec cm^{-1},
r_s	Surface diffusion resistance, sec cm^{-1},
t	Time, min,
u	Wind velocity, cm sec^{-1},
x	Downwind ordinate, cm,
z	Height, cm,
z_i	Height of inversion, cm
z_o	Roughness parameter, cm,
α	Surface reflection coefficient for short-wave radiation, --------,
β	Heating coefficient, -----------,
γ	Psychrometric constant, mb $°C^{-1}$,
ε	Emissivity, --------,
η	Extinction coefficients -----------,
λ	Latent heat of vaporization, cal g^{-1},
ρ	Density of air, g cm^{-3},
σ	Stefan-Boltzmann constant, cal $min^{-1}K^{-4}$,
ϕ	Total water potential (hydraulic head), bars,
ψ	Matric suction, bars,
ω	Ratio of mole weight of water vapour to dry air -----------,

Mathematical notation

Δ	Finite difference over an interval of height or time,
∇_H	$(\partial/\partial x + \partial/\partial y)$.

LA DISTRIBUTION TOPOGRAPHIQUE DU RAYONNEMENT SOLAIRE AU MONT ST.HILAIRE POUR LA PERIODE ESTIVALE DE 1968

par

Daniel Lafleur*

Depuis l'origine de la vie, le rayonnement solaire n'a cessé de jouer un rôle primordial. Grâce à l'énergie qu'il transmet, il a permis a l'être vivant de sa réchauffer, de croître et de se nourrir ...

Son influence est déterminante sur le système climatique dans lequel nous vivons. A cause des lois astronomiques de notre système solaire, le rayonnement favorise les régions tropicales et équatoriales plutôt que polaires. L'énergie qui s'accumule dans ces premières régions se voit alors transportée vers les pôles en vue de réaliser un certain équilibre.

Enfin, le rayonnement et l'énergie qu'il transmet offrent d'immenses possibilités à la science du XXè sciècle. C'est pourquoi leur étude devienne souvent des priorités.

1. Climatologie Ecologique

L'objet de cette présente étude porte sur les variations

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topographiques du rayonnement solaire à ondes-courtes. Les conséquences d'une telle étude sont nombreuses autant sur le plan d'une macroclimatologie que sur celui d'une microclimatologie écologique.

Une meilleure connaissance de la distribution spatiale de l'insolation nous permettra de mieux comprendre les relations qui existent entre l'être vivant et son milieu. C'est pourquoi le géographe-climatologue peut être amené à planifier et à organiser l'espace en fonction de: (1) sa végétation naturelle (l'exploitation forestière retirerait de nombreux renseignements d'une carte d'insolation); (2) l'agriculture (certains agronomes, à l'aide de tels documents pourraient mieux conseiller l'agriculteur d'un secteur ou celui d'un autre); (3) activité humaine , tel que le tourisme régional, par exemple.

L'étude du bilan radiatif a de nombreuses répercussions sur celle du bilan d'eau. C'est ainsi que l'insolation déterminera souvent le degré d'évapotranspiration potentielle. La possibilité de connaître la distribution spatiale du rayonnement solaire grâce à l'informatique nous porte à espérer qu'une telle approche puisse s'appliquer au bilan d'eau. Dès lors, grâce à ces deux paramètres climatologiques représentés cartographiquement, de nombreuses recherches écologiques seraient de beaucoup facilitées.

Ainsi, l'hydrologue comprendrait mieux l'alimentation des cours d'eau et ses prévisions en seraient plus précises. Le biologiste et l'agriculteur sauraient mieux expliquer la croissance des plantes et pourraient poursuivre leurs activités grâce à une meilleure connaissance du bilan d'eau des plantes en culture, et de leurs besoins d'irrigation. Enfin, l'urbaniste, l'architecte et le géographe-urbain, pourraient plus rationnellement organiser l'espace urbain en fonction de ces deux paramètres physiques qui ont une influence déterminante sur l'activité humaine et l'habitât.

2. Brève Explication de la Méthode Employée

Les nombreuses applications d'une telle étude de distribution spatiale nous amènent à expliquer brièvement la méthode employée dans cette nouvelle approche de la climatologie contemporaine. Nous essayerons dans cette partie de faire la synthèse des articles parus sous les plumes de B. J. Garnier et de Atsumu Ohmura (Garnier and Ohmura, 1968).

Notons d'abord que le but de cette méthode est de se libérer des longues observations à différents points qui exigeaient des instruments fort coûteux. Notre travail s'effectue à l'aide d'une seule station mesurant le rayonnement d'une carte topographique et d'un ordinateur. Ceci en vue de connaître les interrelations entre certains paramètres physiques (topographie) et climatologiques (insolation) à l'aide des formules suivantes:

(a) Rayonnement solaire direct (ondes-courtes):

$$I_{st} = I_o \sum_{t=t_1}^{t_2} p^m \cos(X \wedge S) \, dt \qquad (1)$$

où :

I_{st} : rayonnement solaire direct total pour une journée.

I_o : constante solaire (2.0 ly.)

p : facteur d'opacité de l'atmosphère.

m : masse optique de l'air.

X : unité de vecteur à angle droit de l'angle d'une pente et pointant vers l'extérieur du sol.

S : unité vectorielle donnant la position du soleil sur le méridien du soleil de midi.

t' et t_2 : temps (en angle horaire) des premier et dernier moments où le soleil brille sur une surface pour une journée donnée.

(b) Rayonnement solaire diffus - Equation de Kondrat'yev (1965)

$$Ds = D \cos^2 \frac{\theta}{2} \qquad (2)$$

Ds : rayonnement solaire diffus total (ondes-courtes) sur une pente pour une journée.

D : rayonnement solaire diffus total pour une journée.sur une surface horizontale.

θ : angle de la pente.

Il est à noter que l'intensité de la radiation dans l'espace dépend surtout de la topographie (pente et orientation face au rayonnement). Comme ceci se calcule en laboratoire, il est dès lors possible à l'aide d'un seul site d'observation de connaître la distribution géographique de la radiation globale pour toute une région pour laquelle le site est représentatif.

3. Les Cartes du Mont St. Hilaire

Pour illustrer d'un exemple une telle étude, nous nous sommes

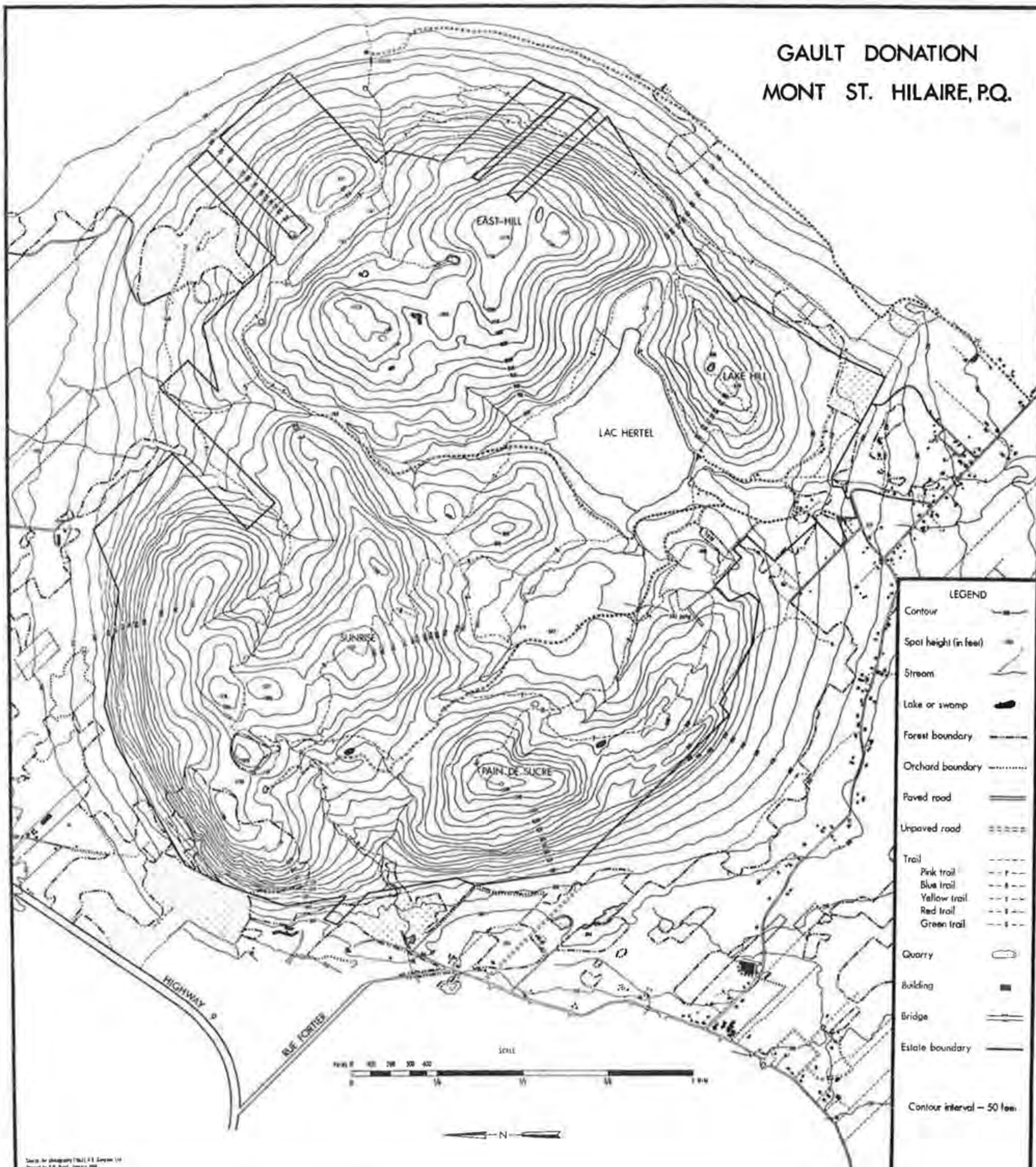

Fig. 1 Carte Topographique du Mont St. Hilaire

servis de mesures enregistrées à la station 758 du Mont St-Hilaire des mois d'avril à septembre 1968. Les courbes représentées sur les graphiques des enregistreurs furent analysées (intégration au planimètre) et compilées par Serge Garneau.

Nous avons décidé d'utiliser la moyenne journalière du rayonnement direct et du rayonnement diffus pour les périodes indiquées ci-dessous:

Périodes		Ray. direct	Ray. diffus
1 avril	au 21 avril	327.6 ly.	112.8 ly.
22 avril	au 18 mai	338.4	106.8
19 mai	au 21 juillet	329.4	104.4
26 juillet	au 22 août	331.8	130.8
23 août	au 12 septembre	249.6	85.8

Ces périodes furent établies en fonction de la latitude de la déclinaison du soleil et leurs limites correspondent à un changement supérieur du rayonnement extra-terrestre de 5%, ce qui correspond à l'erreur toléré par nos instruments (Ohmura, 1969).

Bien que les chiffres pour le rayonnement global au Mont St-Hilaire furent disponibles pour toute la période, sauf pour le 22 au 25 juillet, le 11 août et le 28 août au 2 septembre, ceux du rayonnement diffus étaient inexistants.

Nous avons été obligés d'utiliser les données du collège

Fig. 2 Carte du ler au 21 Avril, 1968

Jean Brébeuf à Montréal (Ministère des Transports, 1968) pour obtenir le rapport entre ces deux types de rayonnement.

Connaissant le rayonnement global au Mont St-Hilaire, nous pouvions introduire le pourcentage du rayonnement diffus sur le global de la station du collège pour compléter nos données chiffrées. Ceci était possible car ce dit pourcentage demeure sensiblement le même d'une région à une autre pour les mêmes périodes d'observation.

Pour préparer les cartes de la variation topographique du rayonnement au Mont St-Hilaire il était nécessaire au début d'établir un quadrillage sur une carte de base où à chaque point d'intersection apparaissaient les valeurs d'orientation et d'intensité de pente . Un programme sur calculatrice électronique réalisé par Atsumu Ohmura (Ohmura, 1969) fut employé pour calculer le rayonnement à chaque point de ce quadrillage et tracer une carte du rayonnement global.

La méthode suivie dans la préparation de cette carte de base nous est décrite en appendice par Louise Marcotte.

Nous avons alors obtenu les cinq cartes d'insolation suivantes que nous commenterons très sommairement.

(1) Carte d'insolation du 1er au 21 avril: cette carte présente des valeurs d'insolation allant de 175 ly. à 475 langleys. La topographie effectue alors une ségrégation de près de 300 ly. On note une grande diversité dans la répartition des rayonnements à ondes courtes. Enfin, tous les versants exposés au Nord se voient défavorisés devant les autres versants du point de vue radiatif.

(2) Carte du 22 avril au 18 mai 1968: le bilan des rayonnements direct et diffus s'échelonne topographiquement de 250 à 450 ly. L'amplitude y est alors de 200 ly. La diversité y est encore fort importante.

Fig. 3 Carte du 22 Avril au 18 Mai 1968

(3) Carte du 19 mai au 21 juillet: cette carte d'insolation nous montre des valeurs allant de 250 à 425 ly. La différence y est alors de 175 langleys. La diversité est finalement à son minimum si on compare ces cinq cartes ensembles.

(4) Carte du 26 juillet au 22 août: les valeurs d'insolation sont à leurs extrêmes de 225 ly. à 475 ly. L'amplitude du rayonnement atteint alors le chiffre de 250 langleys.

(5) Carte du 23 août au 12 septembre: enfin, cette dernière carte d'insolation nous présente des valeurs de 125 ly. à 350 ly. pour offrir une différence entre les extrêmes de l'ordre de 225 langleys.

D'une façon générale nous pouvons constater que la diversité est à son maximum pendant les périodes plus raprochées des mois d'hiver. Ceci s'explique par l'angle du soleil qui est plus faible lors de ces périodes en hémisphère Nord, d'où un rayonnement plus oblique que la topographie amplifie et par la durée d'insolation qui est également plus courte.

Cette observation explique jusqu'à un certain point les plus grandes valeurs minimums qu'on retrouve durant les périodes plus rapprochées de l'hiver. Cependant, on explique mal le fait que les plus grandes valeurs maximums se retrouvent durant ces mêmes périodes. S'agit-il de l'influence de la turbidité de l'atmosphère ou de celle de la topographie ou les deux à la fois?

La présentation de courbes cumulatives, pour toute cette période d'analyse, selon certains points caractéristiques de la topographie nous montreraient l'importance de cette dernière sur le bilan radiatif. En effet, les régions exposées au Nord verraient leurs valeurs en déficit comparativement à celles des autres versants. Il est à noter que ce genre d'étude fera l'objet d'un prochain article de cette revue.

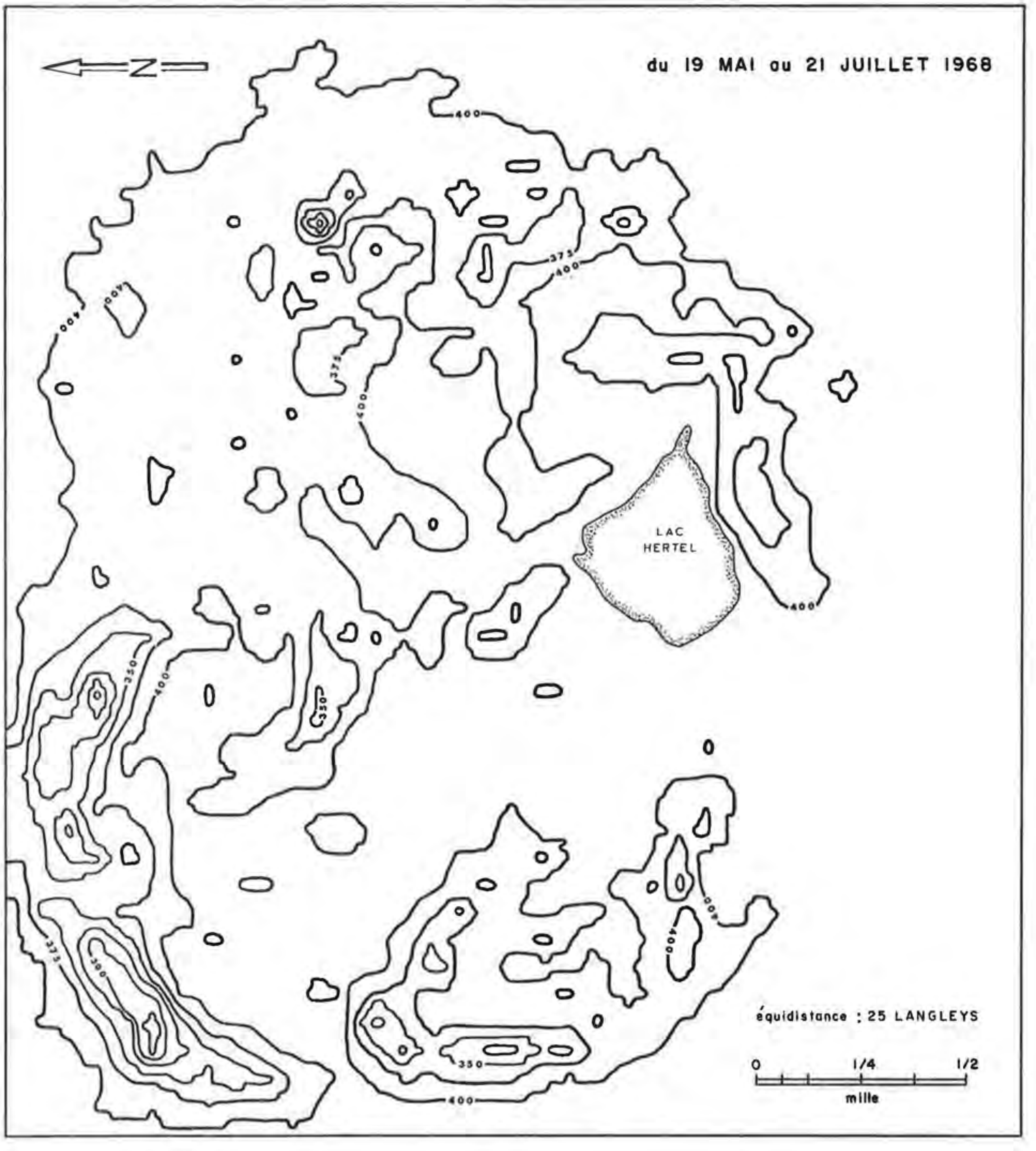

Fig. 4 Carte du 19 Mai au 21 Juillet 1968

Fig. 5 Carte du 26 Juillet au 22 Août, 1968

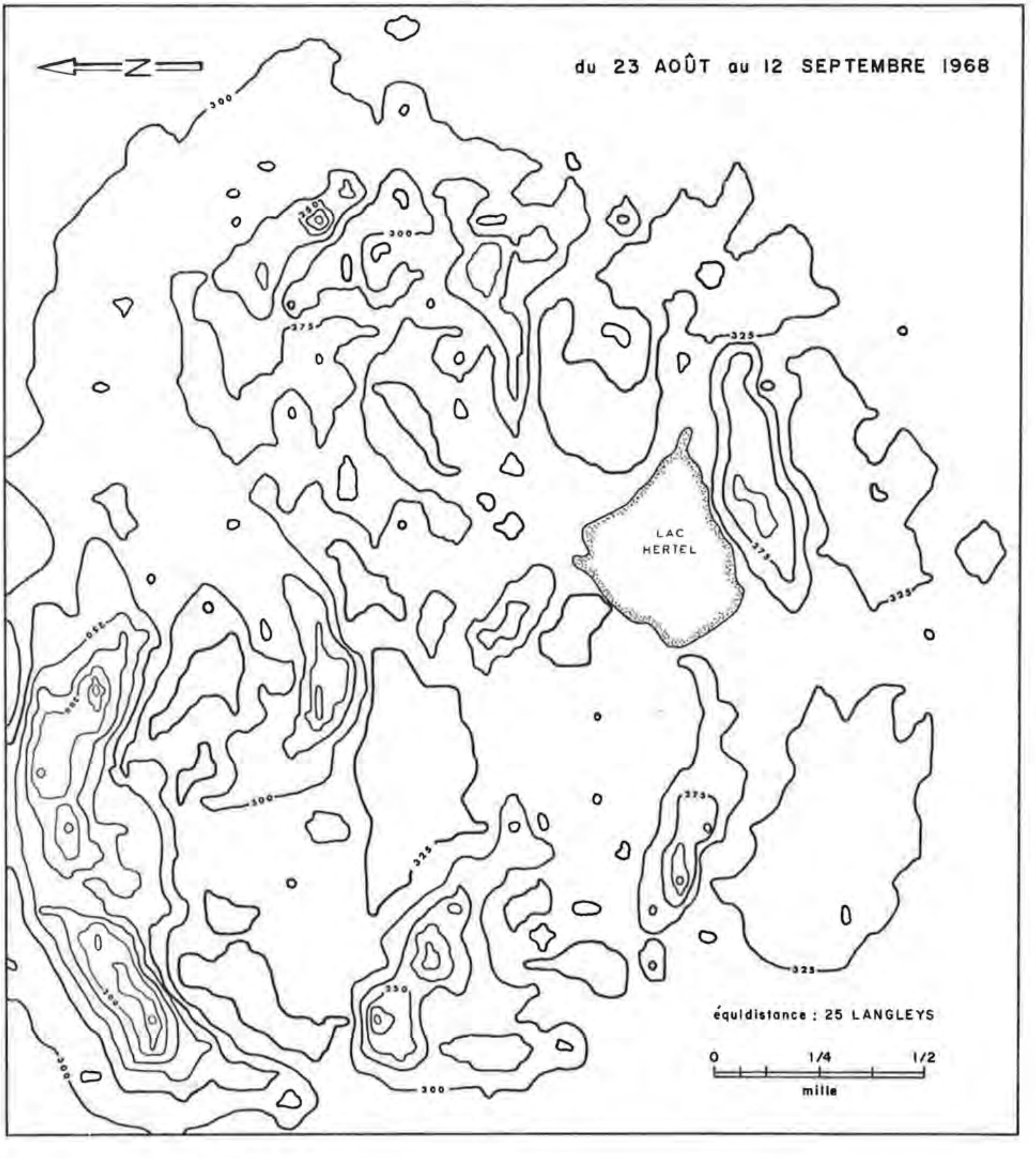

Fig. 6 Carte du 23 Août au 12 Septembre, 1968

Si nous portons notre attention sur certains points de détail du Mont St-Hilaire, nous pouvons mieux illustrer l'importance de la topographie.

Le Lac Hertel (surface horizontale) ne présente qu'une valeur de langleys selon chacune des cartes. Jamais on ne pourra y déceler plus d'une isoligne. D'autre part, les différents sommets (Pain de Sucre, Lake Hill, Sunrise et East Hill) présentent des contrastes frappants entre leurs différents versants. On remarque que la diversité est plus forte sur le versant Nord du "Sunrise" où les pentes atteignent des valeurs de l'ordre de 45^{o}.

Ainsi, plus les valeurs de pente sont grandes et plus la diversité sera importante entre les versants. Bref, une pente recevra plus ou moins d'énergie solaire selon sa position face au rayonnement.

4. Perspectives d'Application

Cette nouvelle approche de l'étude du climat que nous venons brièvement d'exposer nous permet d'entrevoir d'immenses possibilités d'application surtout dans les secteurs de foresterie, d'agriculture et d'urbanisation.

Nous pensons que la connaissance d'une représentation cartographique du bilan radiatif résultant ("net radiation") et du bilan d'eau serait rentable économiquement.

Par exemple, l'ingénieur forestier avec de telles cartes au 1:50,000 ou au 1:250,000 (avec corrections) mettraient plus de soins à observer certains secteurs plutôt que d'autres en vue de prévenir les incendies. L'agriculteur, ayant une telle carte au 1:10,000, pourrait mieux choisir les plantes à cultiver selon leurs besoins en eau et en énergie sur sa terre. Enfin, l'urbaniste organiserait l'espace urbain selon ces paramètres climatologiques. Il favoriserait, par exemple, l'emplacement d'un quartier résidentiel là où le rayonnement y est à son maximum ou celui d'un secteur industriel là où le rayonnement fait défaut mais non les resources en eau, etc....

APPENDICE

LA PREPARATION D'UNE CARTE DE BASE POUR MONTRER LES VARIATIONS TOPOGRAPHIQUES DU RAYONNEMENT SOLAIRE

par

Louise Marcotte

M. Atsumu Ohmura a déjà expliqué quels principes fondamentaux dans la préparation des cartes de base nous permettent d'obtenir une représentation cartographique et spatiale de l'insolation à ondes-courtes (Ohmura, 1969).

Le véritable problème consiste à choisir un espacement adéquat pour les mailles du quadrillage. Pour les cartes du Mont St-Hilaire, nous avons choisi de travailler à une échelle de 1:9,600, soit sensiblement la même que celle utilisée pour l'étude des Barbades (Basnayake, 1968). La carte du Mont St-Hilaire, préparée et dessinée par M. A.E. Simpson d'après des photographies aériennes de 1961, dont les courbes de niveau présentaient une équidistance de 25 pieds, permettait des mesures précises des pentes et de leur orientation. Les variations topographiques étant très importantes, le quadrillage se devait d'être fin, comme de plus un relief accidenté occupait la totalité de la carte de base. D'autre part, le programme permettant de réaliser les cartes par plages est prévu pour rendre l'image des points de mesure à une distance constante d'un demi-pouce et cela, quelque soit la finesse du quadrillage choisi. Pour obtenir des cartes des résultats ayant sensiblement la même précision que la carte de base, nous devions prendre en considération cet ordre de grandeur.

Nous avons aussi tenu compte du fait que la manipulation des données est grandement facilitée lorsque les 80 colonnes des cartes perforées sont occupées.

Ces considérations nous ont guidé vers le choix d'un espacement de 11 millimètres pour le quadrillage de référence. Nous avons ainsi obtenu 40 points de lecture se répétant sur 88 lignes. Un tel nombre de mesures d'orientation et d'intensité de pente nous permettait d'espérer obtenir une image valable de la variation topographique

(A) Orientation: pour mesurer l'orientation de pente nous avons tracé, aux intersections du quadrillage, des flèches orientées vers le bas de la pente et selon sa direction; nous pouvions ensuite à l'aide d'un rapporteur d'angle de 360^{o} mesurer cette orientation par rapport au Nord géographique. Aux pentes orientées plein Nord étaient attribuées la valeur 0 tandis que les mesures dans la moitié Est puis Ouest du rapporteur étaient respectivement positives et négatives. La valeur d'orientation 0 était aussi attribuée aux pentes évaluées nulles.

(B) Intensité: L'intensité de la pente, également mesurée à toutes les intersections du quadrillage, est donnée par la tangente de l'angle compris entre une base dont nous avions à déterminer la longueur et la hauteur constituée par la dénivellation. Afin de faciliter les calculs nous avons choisi pour la base des unités dans le même système quel'échelle, soit 1/2 et 1/4 de pouce, ou 400' et 200' sur le terrain, à l'échelle de 1:9,600, ou 1" = 800'. La dénivellation se déduisait facilement des courbes de niveau. Nous avons donc dressé deux tableaux des tangentes (400' et 200' de base) pour les valeurs de dénivellation à tous les 10 pieds. Les lectures ont été effectuées à l'aide d'un instrument simple: deux cercles de 1/2 et 1/4 de pouce de diamètre respectivement, dessinés sur un papier transparent. En plaçant le centre du cercle aux intersections du quadrillage, nous calculions la dénivellation à 10' près, le long de la flèche de l'orientation. La valeur de l'intensité de la pente était obtenue en référant à la table des tangentes correspondant au cercle utilisé. Afin d'obtenir la mesure la plus conforme à la réalité pour le point précis de la lecture, nous utilisions le cercle qui englobait des courbes de niveau dont l'espacement présentait la plus grande régularité.

(C) La Cartographie automatique: Le programme permettait d'obtenir directement et avec rapidité des cartes par plages de la variation topographique de la radiation. Ce programme, en plus d'effectuer les calculs associant aux points de lecture les différentes variables, permet d'extrapoler les valeurs entre ces points, d'où la grande précision. Il permet de répartir les valeurs en 47 classes représentées par autant de symboles. Dans notre étude, nous avons retrouvé 14 de ces symboles. Il ne reste plus au cartographe qu'à tracer les isolignes autour des plages et au climatologue qu'à y commenter les résultats.

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RESEARCH REPORT

A second successful joint McGill-McMaster field programme was conducted at Simcoe, Ontario from May to July 1969. The details of the research objectives, and the experimental set-up are to be found in this BULLETIN (see pp 1-43). The good fetch characteristics of the site (100-250m depending on wind direction), and the comprehensive array of instrumentation, provide an opportunity to calibrate new measurement techniques with the more conventional methods. This summer a simplified eddy correlation approach to the measurement of the sensible heat flux was operated. The instrument consisted of a Gill propellor anemometer and a fine-wire thermopile (Fig.1). The instrument thus records the instantaneous vertical wind speed and temperature. Analysis of these results will follow that of McBean (1968). The sensible heat flux values obtained via the eddy correlation technique will be compared with the values computed from the wind, temperature and humidity profiles using the Bowen ratio and aerodynamic approaches. The accuracy of Bowen ratio estimates using Assmann psychrometers will also be tested.


Fig.1 Vertical anemometer and fine-wire thermocouple for eddy correlation experiment.

The urban climate studies outlined in BULLETIN No.5 have continued to gather data through the summer months. The infra-red radiation studies both in Montreal and at a rural site on the MacDonald College farm have yielded very interesting results which require intensive analysis. The urban station located on the roof of the Montreal Department of Health building is now able to monitor wind, temperature and humidity profiles up to 8 m as well as the component radiation fluxes. Work is being concentrated on the nocturnal case. Mobile temperature and radiation surveys continue.

Energy budget investigations in Barbados have been continued and included a remote sensing experiment during June in association with BOMEX. The aim of introducing the remote sensing experiment into the programme was to try to throw light on the long-wave radiation emission term ($L\uparrow$) with particular reference to its topographic variations in the equation

$$R_N = (Q + q)(1-a) + L\downarrow - L\uparrow)$$

where R_N is the net radiation, $(Q + q)$ is global (short-wave) radiation, a is albedo, $L\uparrow$ is long-wave emission from the atmosphere and $L\downarrow$ is long-wave emission from the ground. A rational way to solve this equation is needed if topographic variations in the radiation and energy balances are to be understood. The evaluation of surface variations in $(Q + q)(1-a)$ can now be achieved from measurements of global and sky-diffuse radiation at a single, representative, site and appropriate analysis of surface conditions (Garnier and Ohmura- in press). Topographic variations in the long-wave radiation balance, however, need yet to be rationalised.

A primary objective of the remote sensing experiment, therefore, was to measure long-wave radiation emission by means of a series of traverses over the island. A PRT 5, supplied by the Barnes Engineering Company, was used for this purpose. It was attached to the step of a light Cessna aircraft, and recordings were effected on a portable digital recorder supplied by Weather Science Inc. of Norman Oklahoma. The climatological station at Waterford was used as a "ground truth" station. Here a second PRT 5 was set up pointing at a patch of grass where ground temperatures were being measured by thermistors. A hand-operated PRT 10 was used to obtain surface temperatures in the vicinity of the site. The traverses across the island sampled the major types of surface in Barbados under different relief conditions, and also crossed the centre of Bridgetown, thus obtaining the long-wave radiation emission from a tropical city. Results of the experiment are currently being analysed and will be reported on in due course.

At Mont St.Hilaire a start was made early in July on measurements to examine the topographic variations in short-wave radiation income over an area of about 200 square miles. Sites at Rougemont and Yamaska, 8 and 15 miles respectively from Mont St.Hilaire were used, observations being made by means of Kipp and Zonen pyranometers and Lintronic dome solarimeters. The major part of the experiment will be in August and September,1969 and will be noted more fully in the next number of this Bulletin.

B.J.Garnier,
Professor of Climatology.

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NEWS AND COMMENTS

Dr. T.R. Oke attended the Third Annual Congress of Canadian Meteorological Society at Toronto from May 27-29 1969, and also the Ninth Conference on Agricultural Meteorology sponsored by the American Meteorological Society and held at Seattle, Wash., from September 8-10 1969.

David Yap has completed his M.Sc. research "Air pollution and vertical temperature distribution over Montreal" under the supervision of Dr. K.L.S. Gunn in the Meteorology Department at McGill University, and has joined the climatological programme in the Department of Geography to continue studies on the urban climate of Montreal for his doctoral research.

D. Scott Munro was employed during the summer by the Glaciology Section of the Department of Energy, Mines and Resources, Ottawa. He helped to organize field studies on the Barnes Ice-cap on Baffin Island, and on the Peyto Clacier in Glacier National Park, Alberta.

Professor Michael Garstang of Florida State University visited McGill University at the end of February. He gave several seminars and addressed the Montreal Branch of Canadian Meteorological Society on the Florida State Barbados Experiment.

Professor B. J. Garnier attended the Fourth Hudson Symposium at Plattsburgh in March and gave a paper on "Evaluating Surface Variations in Solar Radiation Income". He also gave a paper entitled "Some Thoughts on Evaluating the Distribution of Potential Evapotranspiration" to the Canadian Meteorological Congress held at Toronto in May.

Atsumu Ohmura has received the M.Sc. degree in Geography (Climatology). His thesis was entitled "Computation and Mapping the Short-Wave Radiation on a Slope".

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