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Local and Regional Components of Sensible Heat Advection

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LOCAL AND REGIONAL COMPONENTS OF SENSIBLE HEAT ADVECTION

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The energy used in evapotranspiration at the earth's surface may exceed the energy content of the net radiation because of the advection of sensible heat. Detailed knowledge of the advection of sensible heat is necessary in order to understand its effects on evapotranspiration and the energy balance.

The local and regional components of sensible heat advection were studied above an irrigated alfalfa field with relatively dry surroundings upwind at Mead, Nebraska, during the 1976 growing season. Vertical profiles of air temperature and vapor pressure were measured downwind of the leading edge (i.e., the boundary between the dry and irrigated fields). The temperature profiles were generally inverted and the water vapor pressure profiles generally lapse over the irrigated field. The temperatures decreased and the vapor pressures increased at a given elevation downwind from the leading edge with the greatest changes occurring near the leading edge.

Horizontal gradients of air temperature and vapor pressure were incorporated in a modified form of the Bowen ratio-energy balance method to estimate evapotranspiration under conditions of sensible heat advection. Using this modified Bowen ratio-energy balance approach the local and regional components of sensible heat advection were quantified.

On the days studied sensible heat advection contributed 21 to 50% of the energy used in evapotranspiration. Regional sensible heat advection accounted for 7 to 40% of the latent heat flux. Local sensible heat advection at the furthest upwind location in the irrigated field contributed from 1 to 14% of the energy consumed in evapotranspiration.

Regional sensible heat advection was greatest on days with strong winds. Local sensible heat advection did not appear to depend upon windspeed. Neither local nor regional sensible heat advection were influenced by the appearance of clouds. On days when the air was relatively drier than usual the contributions of both regional and local sensible heat advection were most significant.

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CHAPTER I

INTRODUCTION

Detailed knowledge of evapotranspiration is needed for determining water use by vegetation. Energy consumed in evapotranspiration by a vegetated surface is provided by net radiation and by the advection of sensible heat (Fig. 1a). The importance of radiation as a source of energy for evapotranspiration has generally been recognized by researchers investigating the water loss from crops and soils. The effects of advected sensible heat have not always been recognized, however. Net radiation has generally provided an upper limit for evapotranspiration, especially in humid regions. In subhumid and semi-arid regions, however, evapotranspiration by well-watered crops frequently exceeds the energy content of the net radiation by a factor as great as 2 (Rosenberg, 1969a; Rosenberg and Verma, 1977). The additional energy is provided by the advection of sensible heat.

Advection is the process of transport of an atmospheric property solely by the mass motion of the atmosphere (Huschke, 1959). Several workers (e.g. Lemon, Glaser and Satterwhite, 1957; Abdel-Aziz, Taylor and Ashcroft, 1964; Hand, 1964; Lang, Evans and Ho, 1974; and Rosenberg and Verma, 1977) have shown the importance of sensible heat advection as an additional source of energy for evapotranspiration.

Sensible heat advection can be regional and local in nature. The terms local and regional advection are used in an attempt to identify sources of preconditioned air. Regional sensible heat advection occurs when warm, dry air masses are generated over large, hot, dry regions and move across wetter, cooler surfaces in other regions. In the sub-

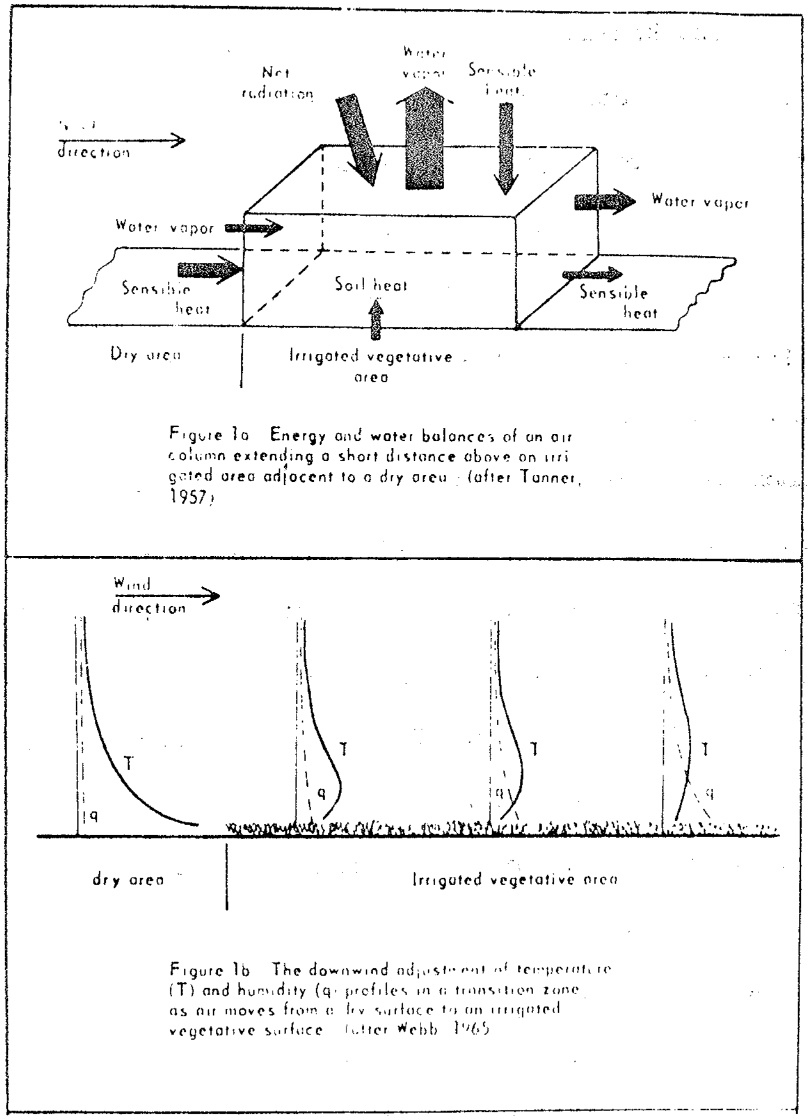

Fig. 1a,b. Schematic representations of advection conditions.

(after Goltz and Pruitt, 1970)

humid east central Great Plains, as an example, a substantial amount of energy is provided by the advection of sensible heat from arid regions primarily to the south and southwest (Rosenberg, 1969b; Rosenberg and Verma, 1977). In some parts of Australia, regional sensible heat advection has been reported to be the cause of large evapotranspiration rates (McIlroy and Angus, 1964).

Local advection occurs when wind blows across a surface discontinuity (i.e., the leading edge) in temperature, humidity or roughness, as from a dry field to an adjacent wetter, cooler field. Local sensible heat advection has been reported by several workers (e.g. Rider, Philip and Bradley, 1963; Dyer and Crawford, 1965; Goltz and Pruitt, 1970) to increase evapotranspiration downwind from a leading edge. The extensive use of irrigation in regions such as the Great Plains has increased the occurrence of local sensible heat advection. Irrigation provides for more marked contrasts in temperature and humidity between adjacent fields than are generally found in humid, non-irrigated areas. These contrasts lead to changes in temperature and humidity profiles as wind blows across a leading edge (Fig. 1b). The vertical fluxes of sensible and latent heat, therefore, are not spatially constant under locally advective conditions. As fetch from the leading edge increases these advective effects decrease until horizontal homogeneity is established far downwind.

It is important to determine the relative magnitudes of the local and regional components of sensible heat advection in order to clearly understand the significance of sensible heat advection and its effects on the energy balance and evapotranspiration. The local and regional components of sensible heat advection may be quantified if the evapotranspiration rates are known along with the radiation and soil heat fluxes. The Bowen ratio-energy balance method (BREB) has been widely used to compute evapotranspiration. The BREB method does not, however, account for horizontal fluxes of sensible and latent heat. The use of this method has resulted in 20-40% errors in evapotranspiration estimation under conditions of local sensible heat advection (Hanks et al. 1971). To accurately predict evapotranspiration and the advection of sensible heat under locally advective conditions requires a two-dimensional model that can account for changes in fluxes both vertically and horizontally.

With these factors in mind a study was designed to meet the following objectives:

1) to observe the modifications of air temperature and vapor pressure[1] profiles downwind of the leading edge of an irrigated field with relatively dry surroundings upwind,
2) to develop and test a modified Bowen ratio-energy balance method (MBREB) to determine sensible and latent heat fluxes under locally advective conditions, and
3) to separate and quantify the contributions of the regional and local components of sensible heat advection and to investigate the influence of pertinent meteorological parameters on these components.

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[1] Vapor pressure refers to the partial pressure of water vapor in air.

CHAPTER II

THEORETICAL AND EXPERIMENTAL BACKGROUND

Studies of evapotranspiration have presented evidence for the existence of sensible heat advection. This evidence has led to investigations of the temperature and vapor pressure profiles downwind of a leading edge and has encouraged the development of mathematical models which consider conditions of sensible heat advection. A brief summary of these investigations is presented in this chapter.

2.1 Experimental Evidence of Sensible Heat Advection

Tanner (1957) discussed some of the factors that affect evapotranspiration from plants and soils. The differences in evapotranspiration rates among crops are due to differences in crop cover and soil moisture availability, and to differential occurrences of the clothesline effect. The clothesline effect occurs when warm air moves through a crop, generally at the border of a well-watered field. The clothesline effect provides additional energy for evapotranspiration and is a component of the local advection of sensible heat. The other source of sensible heat considered by Tanner is the oasis effect. The oasis effect occurs when the air passing over a crop provides heat for evapotranspiration. The oasis effect may be either regional or local in nature, though Tanner did not make this distinction. In the study reported here the oasis effect will be separated into its regional and local components.

Halstead and Covey (1957) also recognized the existence of the oasis effect. They found that sufficient fetch (i.e., distance from the leading edge) is needed to obtain logarithmic vertical profiles of windspeed, temperature and humidity. Difficulties were found in applying equations involving the concept of potential evapotranspiration or consumptive water use in areas of irrigation. Irrigation created isolated areas of above normal soil moisture. This invalidated the assumption, required in potential evapotranspiration equations, of a homogeneous soil moisture regime extending horizontally to infinity. A heat flux equation discussed by Halstead and Covey was later used by Lemon, Glaser and Satterwhite (1957) at College Station, Texas, to determine the net sensible heat exchange (q) between the atmosphere and cotton plants:

$$q = 1/3\ \rho\ C_p \frac{\nu_c}{\nu} (U_2-U_1)(T_2-T_1) \qquad (1)$$

where ν_c and ν are the thermal conductivity and kinematic viscosity of air, respectively, ρ is the density of air, C_p is the specific heat of air at constant pressure, U is the windspeed, and T is the temperature. The subscripts refer to levels of measurement above the ground surface. On a 24-hour basis more energy was taken from the atmosphere than was returned to it by the vegetated land surface. This was considered an example of the oasis effect (i.e., regional sensible heat advection) since the fetch consisted of at least 16 km of cotton plants upwind.

McIlroy and Angus (1964) observed sensible heat advection at Aspendale, Australia. They found that monthly evapotranspiration from lysimeters within a well-watered grass field consistently exceeded that from free water by as much as 50%. The latent heat of evapotranspiration from the grass (LE_{grass}) exceeded the net radiant energy (Rn) available. For June, 1959, $|LE_{grass}/Rn|$ was 2.28. Small sunken water tanks were used to determine the influence of fetch on evapotranspiration. The lack of any definite relationship between evapotranspiration rate and fetch (due to scatter in the data) led McIlroy and Angus to attribute the increase in evapotranspiration from the grass to large scale oasis effects rather than to local or site effects.

Abdel-Aziz, Taylor and Ashcroft (1964) studied the influence of sensible heat advection on irrigated alfalfa near Logan, Utah. A neutron scattering method was used to determine soil moisture to a depth of three meters. The difference in soil moisture between two readings at a level was taken as the consumptive use during that period. The daily evapotranspiration so calculated was sometimes as much as 1.71 Rn. When the crop was tall and well-watered evapotranspiration exceeded evaporation from a class A pan. When the crop was cut or was under moisture stress, evapotranspiration was less than pan evaporation. Comparing their results with Penman and Schofield's (1951) formula Abdel-Aziz et al. found that Penman and Schofield's formula underestimated evapotranspiration. Abdel-Aziz et al. commented that sensible heat advection can provide a significant amount of energy for evapotranspiration.

The effects of local sensible heat advection on the evapotranspiration within a field of Ladino clover was studied by Millar (1964). Four lysimeters (instruments for the measurement of change in soil water content) were located within 14 m downwind of the boundary between irrigated clover and a drier field upwind. Evapotranspiration decreased from about 0.8 mm hr^{-1} near the leading edge to about 0.7 mm hr^{-1} 14 m downwind.

In contrast, Hand (1964) in the Northern Sudan found local advection of sensible heat affecting evaporation from small pans up to 60 m downwind from the leading edge in irrigated lucerne.

Lang, Evans and Ho (1974) found that lysimetric evapotranspiration decreased downwind from a leading edge in flood-irrigated rice in a semi-arid region of New South Wales, Australia. The evapotranspiration rate measured at 15 m downwind was 3 to 38% higher than the rate measured at 790 m downwind.

Rosenberg (1969a) determined that sensible heat advection is an important source of energy for evapotranspiration in the east central Great Plains. He found that evapotranspiration may be as great, at times, as it is in more arid desert or west coast regions. Rosenberg (1969b) found that evapotranspiration from 25 cm tall irrigated alfalfa exceeded the energy available from net radiation by as much as 80%. Rosenberg and Verma (1977) reported that, on most days studied during June and July, 1976, evapotranspiration (LE) from well-watered alfalfa near Mead, Nebraska, exceeded the net radiation plus soil heat flux (Rn+S). $|LE/(Rn+S)|$ ranged from a low of 1.32 on a partly cloudy, relatively humid and calm day to a high of 3.78 on a cloudy, windy and relatively dry day. Regional sensible heat advection was shown to be the major cause of the increase in LE over Rn+S.

2.2 Variation in Vertical Profiles of Air Temperature and Vapor Pressure

Changes in the vertical profiles of air temperature and vapor pressure downwind from a leading edge may indicate the presence of local sensible heat advection. Researchers have studied the extent of these changes downwind of the leading edge and the influence of these changes on evapotranspiration.

Crawford and Dyer (1962) and Dyer and Pruitt (1962) studied temperature and vapor pressure data taken over irrigated rye grass at Davis, California, to determine the suitability of their site for experiments requiring horizontal homogeneity. There occurred a continual cooling and an increase in moisture content of the air as it moved downwind from the leading edge. After sufficient distance downwind of the leading edge the moisture content reached a concentration great enough to suppress the evaporation rate and to cause a warming of the air. The difference in sensible heat flux between the surface and 400 cm above it was computed from:

$$A_o - A_{400} = \rho \ C_p \int_o^{400} U \frac{\partial T}{\partial x} dz \qquad (2)$$

where A_o and A_{400} are the sensible heat fluxes at the surface and at 400 cm, respectively. A state of horizontal uniformity did not exist (i.e., $A_o \neq A_{400}$) in the lower layers of the atmosphere, even for a fetch as long as 110 to 180 m. A_o-A_{400} did decrease with fetch, however. Dyer and Pruitt concluded that a fetch 30 to 50 times the height of measurement is not necessarily sufficient for obtaining horizontal uniformity.

Dyer and Crawford (1965) also found that A_o-A_{400} decreased with fetch. Air temperatures at 5 m above irrigated grass were being modified even at 200 m downwind from the leading edge. Later, Dyer (1968) considered the role of fetch in micrometeorological studies. He suggested that a fetch to height ratio of about 100 to 200 would be required to establish horizontal uniformity up to the height of measurement.

Wiersma (1968) measured evapotranspiration downwind from a sprinkler line. Horizontal homogeneity at the surface was assumed when the sprinkler line was not in operation. Pan evaporation increased steadily from a low value downwind of the wetted area until it was close to, or even slightly greater than, the upwind value. The sprinkler line exerted minimal effect on evapotranspiration at a point 70 m downwind. The vapor pressure of the air was greatest immediately downwind of the sprinkler line and decreased with increasing fetch to approach upwind conditions. Temperature depressions of up to 5 C at 15 cm above the grass occurred immediately downwind of the wetted surface. Thereafter, the temperature increased with increasing fetch downwind to approach the upwind value. At 70 m downwind the vapor pressure was, at times, less and the temperature greater than the upwind values.

Goltz and Pruitt (1970) studied the leading edge problem to determine the horizontal extent of the transition zone and the magnitude and variation of evapotranspiration within this zone. They used three methods [aerodynamic, Philip's (1959) model (discussed below), and equation (2)] to calculate the sensible heat flux from air temperature and windspeed profiles measured above the crop. These three methods gave similar results to indicate that, at 117 m downwind, the evapotranspiration was 20-25% less than it was at 9 m downwind. Goltz and Pruitt hypothesized that as much as one kilometer of fetch might be required before horizontal uniformity is reached at a height of 4 m.

Hanks, Allen and Gardner (1971), on the other hand, found that changes in temperature and vapor pressure profiles above irrigated sorghum near Akron, Colorado, were evident primarily within 40 m of the leading edge.

2.3 Theoretical Models

The change in air temperature T with time t is described by:

$$\rho \ C_p \frac{dT}{dt} = \overline{\nabla} \cdot \overline{A} \tag{3}$$

where ρ is the air density, C_p is the specific heat of air at constant pressure, and $\overline{\nabla} \cdot \overline{A}$ is the divergence of the sensible heat flux $\overline{A}$. The left side of equation (3) may be expanded to:

$$\rho \ C_p \frac{dT}{dt} = \rho \ C_p[\frac{\partial T}{\partial t} + \frac{\partial x}{\partial t}\frac{\partial T}{\partial x} + \frac{\partial y}{\partial t}\frac{\partial T}{\partial y} + \frac{\partial z}{\partial t}\frac{\partial T}{\partial z}] \tag{4}$$

or

$$\rho \ C_p \frac{dT}{dt} = \rho \ C_p[\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial x} + V\frac{\partial T}{\partial y} + W\frac{\partial T}{\partial z}] \tag{5}$$

where x, y and z are the horizontal, crosswind, and vertical coordinates, respectively. U, V and W are the corresponding components of the mean[2] wind velocity. The right side of equation (3) may be written:

$$\overline{\nabla} \cdot \overline{A} = (\frac{\partial}{\partial x}\hat{i} + \frac{\partial}{\partial y}\hat{j} + \frac{\partial}{\partial z}\hat{k}) \cdot (A_x\hat{i} + A_y\hat{j} + A_z\hat{k}) \tag{6}$$

$$= \frac{\partial}{\partial x}A_x + \frac{\partial}{\partial y}A_y + \frac{\partial}{\partial z}A_z \tag{7}$$

where A_x, A_y and A_z are the sensible heat fluxes ($A_\eta = \rho \ C_p K_\eta \partial T/\partial \eta$ where K_η is the exchange coefficient of sensible heat in the 'η' direction) and $\hat{i}$, $\hat{j}$ and $\hat{k}$ are the unit vectors in the x, y and z directions, respectively. Equation (3) then becomes:

$$\rho \ C_p \ [\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial x} + V\frac{\partial T}{\partial y} + W\frac{\partial T}{\partial z}] = \frac{\partial}{\partial x}A_x + \frac{\partial}{\partial y}A_y + \frac{\partial}{\partial z}A_z \tag{8}$$

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[2]Time averaged.

Equation (8) may be simplified for a two-dimensional steady-state heat transfer problem. The first term on the left of equation (8) is the storage term and is zero under steady-state conditions. The second term is the horizontal sensible heat advection term. The third and fourth terms are zero because the mean crosswind (V) and mean vertical (W) windspeeds are assumed to be zero. The first term on the right is the downwind diffusion term and is considered negligible compared to the horizontal sensible heat advection term. The second term on the right is zero because with sufficient crosswind fetch the crosswind diffusion may be assumed to be negligible. The last term describes the vertical diffusion.

Equation (8) thus reduces to a steady-state two-dimensional equation for sensible heat transfer:

$$\rho\ C_p\ U \frac{\partial T}{\partial x} = \frac{\partial}{\partial z} A_z = \frac{\partial}{\partial z} (\rho\ C_p\ K_H \frac{\partial T}{\partial z}) \qquad (9)$$

where K_H is the vertical exchange coefficient for sensible heat. Similarly, the transfer of latent heat may be written as:

$$\frac{L\varepsilon\rho}{P} U \frac{\partial e}{\partial x} = \frac{\partial}{\partial z} LE_z = \frac{\partial}{\partial z} (\frac{L\varepsilon\rho}{P} K_W \frac{\partial e}{\partial z}) \qquad (10)$$

where L is the latent heat of vaporization of water, ε is the ratio of the molecular weights of water to air, ρ is the air density, P is the atmospheric pressure, e is the vapor pressure, E_z is the vertical flux of water vapor, and K_W is the vertical exchange coefficient for latent heat.

Sutton (1953) considered equation (10) for the case of wind blowing from dry ground across a free liquid surface. The boundary conditions were:

$$\lim_{z\to\infty} e(x,z) = e_s \text{ for } 0 \le x \le x_o$$

$$\lim_{x\to 0} e(x,z) = e_o \text{ for } z>0 \qquad (11)$$

$$\lim_{z\to\infty} e(x,z) = e_o \text{ for } 0 \le x \le x_o$$

with the assumptions

$$U(z) = U_1 (\frac{z}{z_1})^m \quad 0 \le m < 1 \qquad (12)$$

and

$$K_W(z) = K_1 (\frac{z}{z_1})^n \quad 0 \le n < 1 \qquad (13)$$

where e_o is the vapor pressure before the air reaches the wet strip of length x_o, e_s is the saturation vapor pressure, and U_1 and K_1 are the values of U and K_W, respectively, at a reference height z_1. The total rate of evaporation over the wetted area per unit of crosswind length was found by Sutton to be:

$$E(U,x_o) = [U_1^{(2-n)/(2+n)} x_o^{2/(2+n)} (e_s-e_o) (\frac{2+n}{2-n})^{(2-n)/(2+n)}] \cdot [\frac{2+n}{2\pi} \sin(\frac{2\pi}{2+n}) \Gamma(\frac{2}{2+n}) a^{2/(2+n)} z_1^{-n^2/(4-n^2)}] \qquad (14)$$

where

$$a=[(\tfrac{1}{2}\pi k^2)^{1-n}(2-n)^{1-n} n^{1-n} \nu^n z_1^{(n^2-n)/(2-n)}]/[(1-n)(2-2n)^{2-2n}], \qquad (15)$$

ν is the kinematic viscosity, k is von Karman's constant, and Γ is the Gamma-function. Equation (14) shows that evapotranspiration decreases with distance from the leading edge and is directly proportional to the windspeed U_1.

Calder (1949) also treated the above mentioned problem but for the case of an aerodynamically rough surface. He obtained similar results. Calder compared his solution with observations of vapor concentrations downwind of an area sprinkled with aniline in conditions of neutral stability. Reasonably good agreement resulted for heights up to 2 m.

De Vries (1959) solved equation (9) for heat transfer downwind of the leading edge of an irrigated area. He treated this transfer as a problem of heat conduction in a semi-infinite medium with radiation type boundary conditions. U and K_H were expressed as functions of z:

$$U = U_1\left(1 + \frac{z}{z_1}\right)^m \tag{16}$$

$$K_H = K_1\left(1 + \frac{z}{z_1}\right) \tag{17}$$

The exchange coefficient at a given height was assumed to be the same upwind and downwind of the leading edge. Such an assumption may not be strictly correct since the sensible heat flux was directed towards the surface downwind and away from the surface upwind. De Vries' solution uses laborious computations and is rather too involved to be included here.

Philip (1959) solved equation (9) for a problem similar to the above with concentration type boundary conditions:

$$\begin{aligned} &x=0,\ z>0,\ T=0 \\ &x\geq 0,\ z=0,\ T=T_o(x) \end{aligned} \tag{18}$$

where $T_o(x)$ is the surface temperature. Assuming:

$$U = U_1 z^m \tag{19}$$

$$K_H = K_1 z^n \tag{20}$$

and that K_H upwind and downwind were identical, Philip showed that:

$$T \propto 1 - \frac{\int_0^{\eta} \eta^{-(1+m)/(2+m-n)} e^{-\eta} d\eta}{\int_0^{\infty} \eta^{-(1+m)/(2+m-n)} e^{-\eta} d\eta} \quad (21)$$

where

$$\eta = \frac{U_1}{(2+m-n)^2 K_1} \cdot \frac{z^{(2+m-n)}}{x} \quad (22)$$

Both Philip and de Vries concluded that advection influences diminished in magnitude rapidly downwind of a leading edge, but that the effect should nevertheless persist for large distances downwind.

Applying his model (1959) to some experimental data, Philip (1960) found that the sensible heat flux was directed towards the surface at distances as far as 1 km downwind from the leading edge. Philip compared his model with Penman's (1948) method and found that Penman's method underestimated evapotranspiration when applied within 100 m of the leading edge.

Dyer (1963) used Philip's model to study the rate of adjustment for profiles downwind of a leading edge. The fetch to height ratio for 90% adjustment was found to vary from 140 at a height of 0.5 m to 530 at a height of 50 m.

Rider, Philip and Bradley (1963) tested Philip's model for grass downwind of tarmac at an airport near Canberra, Australia. Their assumptions were: 1) the surface temperature and vapor pressure were constant with fetch, 2) the upwind evaporation was zero, 3) the crop was well supplied with water, 4) the thermal stability effects were insignificant, and 5) the exchange coefficient of sensible (and latent) heat was the same upwind and downwind. The last assumption was made even though the experimental data indicated that the exchange coefficients over tarmac were different from those over grass.

Temperature profiles were found to be lapse over tarmac and inverted over grass. The observed humidity changes from upwind to downwind were in good agreement with predictions by Philip's model. The measured temperature changes, however, were about half those predicted by the model. This overprediction of temperature by the model was attributed to neglect of the roughness change between the tarmac and grass. Rider et al. state that if the neglect of thermal stability effects was instead the cause of the overprediction the model would underpredict rather than overpredict temperatures.

The evapotranspiration at the surface was calculated from:

$$LE = \frac{\rho L \varepsilon}{P} \int_{0}^{150} U \frac{\partial e}{\partial x} \, dz \qquad (23)$$

assuming that horizontal variations in humidity were negligible above 150 cm. The evapotranspiration calculated within 1 m of the leading edge by equation (23) averaged about 3.7 times Rn+S.

Rao, Wyngaard and Cote (1974) employed a two-dimensional turbulence closure model to investigate local advection of momentum, heat and moisture due to a horizontal inhomogeneity in surface conditions. The model was tested on the Rider et al. (1963) data for flow over grass downwind of tarmac. The following assumptions were made: 1) there was no evapotranspiration upwind, 2) the relative humidity was constant over the field, and 3) Rn+S did not change significantly from the dry to wet area. The additional assumption of saturation at the surface caused the model to underpredict temperature and overpredict humidity. By assuming instead a surface humidity of 60%, good agreement was obtained with the data of Rider, et al. Neglect of thermal stratification by the model resulted in only a small difference in the calculated mean temperature and vapor pressure profiles in the air layer closest to the ground where buoyancy effects were small.

McNaughton (1976a, 1976b) solved the two-dimensional, steady-state atmospheric diffusion equations (9 and 10) for sensible and latent heat using the following boundary conditions: 1) the energy balance at the surface is satisfied and 2) the surface is assumed to be a single extensive leaf with resistance r_s. The model assumed that 1) r_s is constant with fetch, 2) $K_H = K_W$ for all x and z, 3) Rn, U and K_H are known functions of x and z, 4) the initial profiles of T and e at x=0 are known, 5) the Bowen ratio (β) is constant over the field, and 6) available energy at the surface is assumed independent of surface temperature. The equation obtained for the evapotranspiration LE was:

$$LE = -\{\frac{Rn+S}{1+\beta} + (\frac{1}{1+\beta})\ \frac{1}{r_s}\ [r_s'(Rn'+S')-r_s(Rn+S)]\Phi_x\} \qquad (24)$$

where Φ_x is a dimensionless 'exchange function' that decreases from unity to zero as distance increases downwind of the leading edge. Primes signify upwind values. This model was designed for 24 hour periods and large horizontal distances (on the scale of kilometers) and has not yet been tested with experimental data.

Itier and Perrier (1977) developed an analytical model of advection to predict changes in fluxes and concentrations downwind of a leading edge. The model was limited by assumptions (permanent regime, mixing length approach, thermal neutrality, infinite crosswind, and no roughness changes) and by treating heat as passive. Advective fluxes were found to vary as $x^{-0.15}$.

2.4 Summary

It has been shown that advection of sensible heat increases the evapotranspiration of a vegetated or wetted surface. Based on some theoretical assumptions, several models have been developed to describe the transfer of heat and moisture between the surface and the lower atmosphere under conditions of sensible heat advection. The development of a reliable model, however, requires an understanding of local and regional advective effects. The separation and quantification of the regional and local components of sensible heat advection reported in this study should help meet this need.

CHAPTER III

METHODS AND MATERIALS

3.1 Theoretical Details

The energy balance at the earth's surface may be written as:

$$LE = -(Rn + S + A) \tag{25}$$

where L is the latent heat of vaporization of water; E, Rn, S and A are, respectively, the flux densities of water vapor, net radiation, soil heat, and sensible heat at the surface. Fluxes to the surface are positive in sign. The Bowen ratio-energy balance method (BREB) for computing evapotranspiration is derived from equation (25). The Bowen ratio (β) is represented as:

$$\beta = \frac{A}{LE} = \frac{\rho\ C_p\ K_H\ \frac{\partial T}{\partial z}}{\frac{\rho L\varepsilon}{P}\ K_W\ \frac{\partial e}{\partial z}} \tag{26}$$

so that the latent heat flux becomes:

$$LE = LE(BREB) = \frac{-(Rn+S)}{1+\beta} = \frac{-(Rn+S)}{1 + \frac{\rho C_p K_H \partial T/\partial z}{\frac{\rho L\varepsilon}{P} K_W \partial e/\partial z}} \tag{27}$$

with K_H generally assumed to be equal to K_W. The BREB method assumes that fluxes of sensible and latent heat are constant with height. It cannot, therefore, be applied under conditions of local sensible heat advection.

The BREB method may be modified to incorporate the horizontal fluxes of sensible and latent heat with the procedure outlined below.

The two-dimensional steady-state heat transfer equation (9) can be integrated to obtain:

$$\rho C_p \int_o^{z_1} U \frac{\partial T}{\partial x} dz = \int_o^{z_1} \frac{\partial}{\partial z} (\rho C_p K_H \frac{\partial T}{\partial z}) dz$$

$$= \rho C_p K_H \frac{\partial T}{\partial z} \Big/_o^{z_1} \tag{28}$$

$$= A_1 - A_o$$

or

$$A_1 - A_o = \int_o^{z_1} \rho C_p U \frac{\partial T}{\partial x} dz \tag{29}$$

where A_1 and A_o are the vertical sensible heat fluxes at a height z_1 and at the surface, respectively. Similarly, for the latent heat flux we can write:

$$LE_1 - LE_o = \frac{\rho L\varepsilon}{P} \int_o^{z_1} U \frac{\partial e}{\partial x} dz \tag{30}$$

Equations (25), (29) and (30) may be combined with the Bowen ratio at a height z_1:

$$\beta_1 = \frac{A_1}{LE_1} \simeq \frac{\rho C_p}{L\varepsilon} \frac{\partial T}{\partial e} \Big/_{z_1} \tag{31}$$

to yield the latent heat flux at the surface:

$$LE_o = -[Rn+S+\rho \int_o^{z_1} U(\beta_1 \frac{L\varepsilon}{P} \frac{\partial e}{\partial x} - C_p \frac{\partial T}{\partial x}) dz] \frac{1}{1+\beta_1} \tag{32}$$

or

$$LE_o = \frac{-(Rn+S)}{1+\beta_1} - \frac{\rho}{1+\beta_1} \int_o^{z_1} U(\beta_1 \frac{L\varepsilon}{P} \frac{\partial e}{\partial x} - C_p \frac{\partial T}{\partial x}) dz \tag{33}$$

Equation (33) is the evapotranspiration as calculated by the modified Bowen ratio-energy balance method (MBREB). This modification of the

BREB method is similar to a procedure reported by Lang (1973).

The wind direction is included in the MBREB method by replacing U in equation (33) with $U\cos\theta$ where θ is the angle between the wind direction and a line perpendicular to the leading edge. The windspeed is assumed to be zero at $z=z_o+d$ where z_o is the roughness parameter and d is the zero plane displacement. Equation (33) thus becomes:

$$LE_o = LE(MBREB) = \frac{-(Rn+S)}{1+\beta_1} - \frac{\rho}{1+\beta_1}\int_{z_o+d}^{z_1} U\cos\theta(\beta_1\frac{L\varepsilon}{P}\frac{\partial e}{\partial x} - C_p\frac{\partial T}{\partial x})dz \qquad (34)$$

The first term on the right of equation (34) is the latent heat flux estimated by the BREB method. The second term on the right is the 'correction term' and thus represents the improvement effected by use of the MBREB method.

Using values of LE(MBREB) calculated from equation (34) and measurements of Rn and S, the surface heat flux A_o may be calculated from the energy balance equation (25):

$$A_o = -[LE(MBREB) + Rn + S] \qquad (35)$$

A_o decreases rapidly downwind from the leading edge (Fig. 2), reaching a constant value (A_r) asymtotically far downwind where the local sensible heat advection (A_l) becomes negligible. This constant value (A_r) represents regional sensible heat advection. The regional (A_r) and local (A_l) sensible heat advection components at any distance downwind of the leading edge can thus be separated:

$$A_l = A_o - A_r \qquad (36)$$

SYMBOL	FLUX DENSITY
LE_o	LATENT HEAT
A_r	SENSIBLE HEAT ADVECTION, REGIONAL
A_l	SENSIBLE HEAT ADVECTION, LOCAL
R_n	NET RADIATION
S	SOIL HEAT

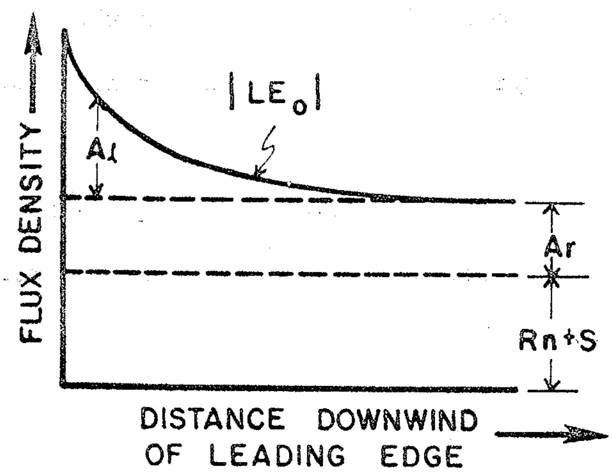

Fig. 2. Schematic of energy partitioning at the surface.

3.2 Experimental Details

Measurements were made over an irrigated alfalfa field, with relatively dry surroundings upwind, at the University of Nebraska Agricultural Meteorology field laboratory near Mead (41° 09' N, 96° 30' W; 354 m above m.s.l.) during the 1976 growing season. The field of Sharpsburg silty clay loam is approximately 1.9 ha in size. The field is equipped for sprinkler irrigation. Alfalfa (Medicago sativa L.) of the Dawson cultivar was planted in the spring of 1975. Unirrigated alfalfa of the same age surrounds the field from the east through the southwest. A 30 m alfalfa strip on the west separates the field from a large field of warm season grass. Warm season grass is also located north of the field. Data presented here were obtained during 6 days [June 9, 10, 13, 21, and 25 (Study 76-1) and July 10 (Study 76-2)] when the winds were primarily from the SE to SW quadrant.

Figure 3 shows crop height, leaf area index (LAI), precipitation, and irrigation amounts for the two studies. During the five days in June the crop height ranged from 40 to 60 cm, and on July 10 the crop height was approximately 20 cm after harvesting on July 1. The field was irrigated with 42 mm of water on June 4, with 82 mm on June 19, and with 82 mm on July 3. The greatest rainfall occurred on June 23 and 27 (13.97 and 36.58 mm, respectively).

Measurements of air temperature and vapor pressure above the canopy were made with self-checking, aspirated, shielded psychrometers (Rosenberg and Brown, 1974) at four stations (1, 3, 4 and 5) during Study 76-1 (Fig. 4). A fifth psychrometer (station 2) was added between stations 1 and 3 during Study 76-2. Measurements were made at four levels within

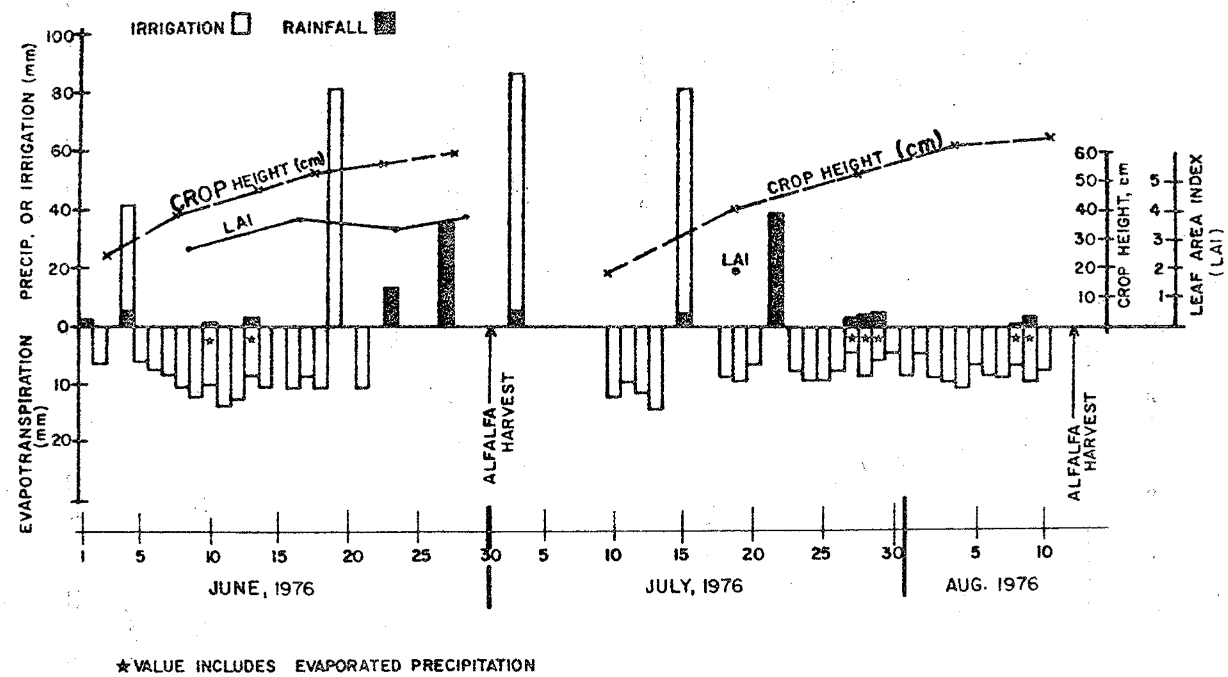

Fig. 3. Rainfall, irrigation and crop height for the alfalfa field at Mead, Nebraska, 1976. Lysimetric evapotranspiration and leaf area index are also shown.

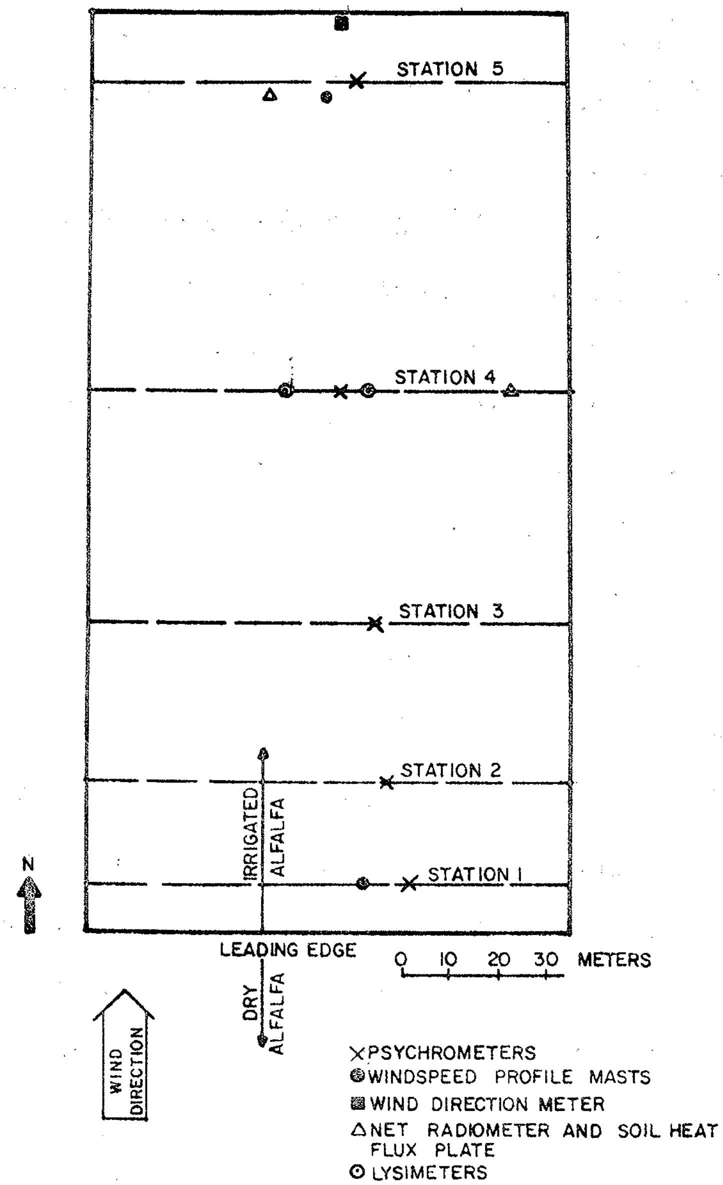

Fig. 4. Plan of the University of Nebraska Agricultural Meteorology experimental field (irrigated alfalfa), June-July, 1976.

a 1-m air layer at stations 1 and 2 and at six levels within a 2-m air layer at stations 3, 4, and 5.

Rosenberg and Brown's self-checking psychrometers provide a resolution of 0.0125 C in differential and of 0.25 C in absolute temperature measurements. Horizontal temperature gradients, however, are relatively low in magnitude as compared to the vertical temperature gradients. In view of this, the thermocouples at the lowest levels of each psychrometer were differentially wired together to measure horizontal temperature differences with a resolution of 0.0125 C. The performance of the horizontal differentials were periodically checked by immersing the appropriate thermocouples in ice baths. The circuitry was designed such that electrical malfunction in any one psychrometer did not affect other psychrometer signals.

Profiles of windspeed were measured at seven levels (station 5) and at five levels (station 1) within the 2-m air layer with three-cup light-chopping casella anemometers [model 442(2)][3]. Net radiation was measured with Swissteco net radiometers (type S-1)[4]. The anemometers and radiometers were calibrated against laboratory standards over the grass north of the main field. Soil heat flux was measured with heat flux plates[5] buried about 4 cm deep in the soil. Two precision weighing lysimeters (Rosenberg and Brown, 1970) are located about 120 m from the southern boundary of the field.

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[3]C. F. Casella Co., Ltd., London, England.

[4]Swissteco Pty. Ltd., E. Hawthorn, Vic. 3123, Melbourne, Australia.

[5]Designed and produced at the Volcani Institute, Bet Dagan, Israel.

Wind direction was determined by means of a wind vane coupled to a variable resistor. The signal was fed to a strip chart recorder from which half-hour mean wind directions were obtained by visual scanning of the output.

Temperature, vapor pressure, net radiation and soil heat flux were measured every 7 minutes during Study 76-1 and every 30 second during Study 76-2. Windspeed and lysimetric weight change were integrated over 15 minute periods. Data were logged on automated analog-to-digital data recording systems. The data were converted with a series of computer programs from the digitized emf or count record of individual sensors into parametric forms. All data were averaged over 30 minute periods in Study 76-1 and 15 minute periods in Study 76-2.

The MBREB method was used to compute the evapotranspiration rates (see Appendix 2 for computer subroutines). Horizontal gradients of temperature and vapor pressure required measurements at two psychrometers. Thus, from the four psychrometers used in Study 76-1, LE(MBREB) values are computed for three locations (A, B and C; see Table 1).

Table 1. Psychrometer stations and locations for modified Bowen ratio-energy balance (MBREB) calculations for Study 76-1 (June, 1976).

Psychrometer Station	Location of MBREB Calculations	Distance from Leading Edge (m)
1	-	10
-	A	38
3	-	65
-	B	89
4	-	113
-	C	146
5	-	180

CHAPTER IV

RESULTS AND DISCUSSION

Measurements of air temperature and vapor pressure were made above irrigated alfalfa during several days in June and July, 1976 (detailed data set is presented in Appendix 3). A modified Bowen ratio-energy balance method is evaluated as a method for computing fluxes of latent and sensible heat under conditions of sensible heat advection. The magnitudes of the local and regional components of sensible heat advection are quantified and related to influences of various meteorological parameters.

4.1 Temperature and Vapor Pressure Profiles Under Advective Conditions

Figure 5 shows a typical set of temperature profiles measured at four stations downwind of the leading edge. The profiles are inverted indicating that the flow of sensible heat is towards the surface. The air temperature is greatest near the leading edge and decreases with increasing fetch. The air is cooled most near the leading edge. The temperature differences for the days studied in June were largest between stations 1 and 3 (ranging from about 0.2 to 1.3 C at the lowest level of measurement). Between stations 3 and 4, and stations 4 and 5, the temperature differences were relatively smaller (ranging from about 0.0 to 0.2 C at the lowest level of measurement -- see Appendix 3 for temperature data). This pattern of air cooling downwind from the leading edge was also observed on 10 July when the crop was relatively shorter than it was earlier in the study (Fig. 6). The decrease in the rate of cooling with increasing distance from the leading edge indicates that

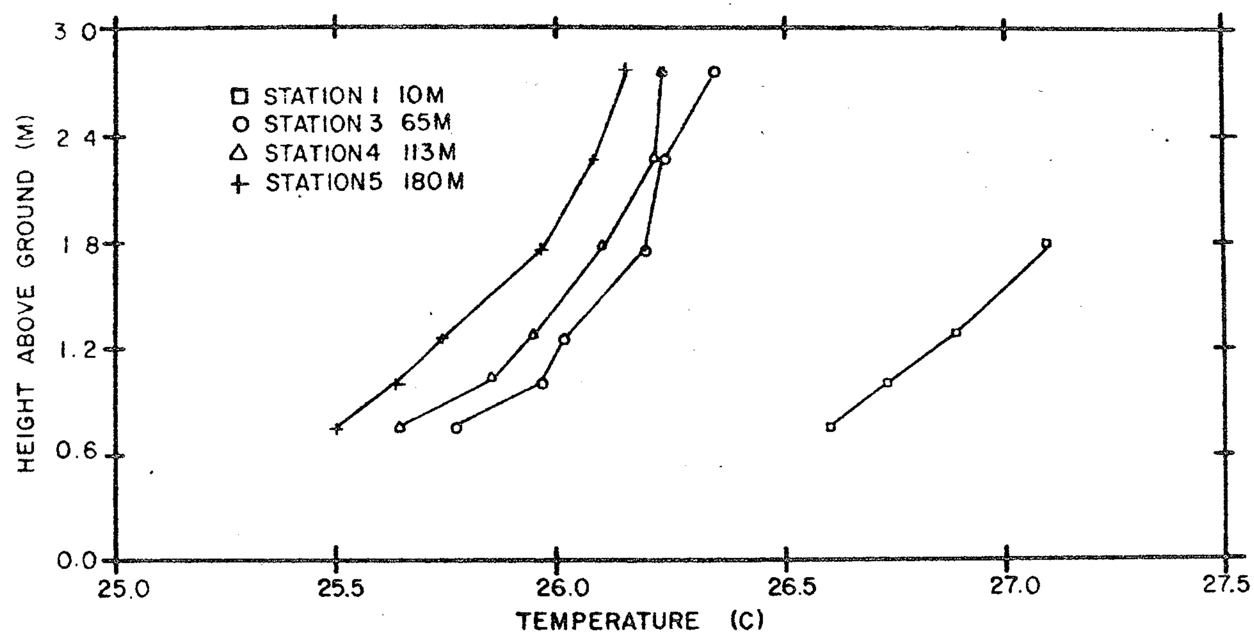

Fig. 5. Typical temperature profiles downwind from a leading edge above irrigated alfalfa at Mead, Nebraska (1115 hrs, solar time, 25 June 1976). Distances from the leading edge are indicated.

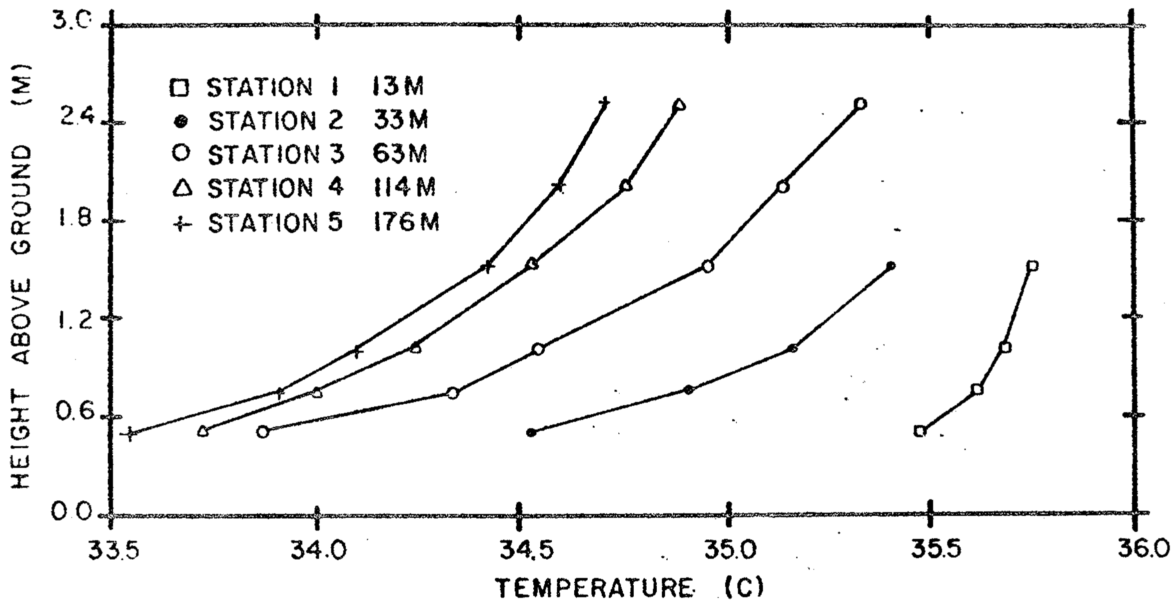

Fig. 6. Temperature profiles downwind from a leading edge above irrigated alfalfa at Mead, Nebraska (1407 hrs, solar time, 10 July 1976). Distances from the leading edge are indicated.

local sensible heat advection is greatest near the leading edge and decreases with increasing distance into the field.

On many days the temperature profiles were inverted most of the time. Figure 7 shows an example of such temperature profiles for various times of the day (June 21). The lack of significant temperature changes between stations 3 and 4, and 4 and 5, indicates the presence of regional sensible heat advection throughout the day. The temperature difference between station 1 and the remaining stations indicates that local sensible heat advection occurred much of the time.

On June 10, however, the temperature profiles were lapse early in the morning. Inversions did not occur until later in the day (Fig. 8). The onset of sensible heat advection may thus be observed on this day. At 0845 hrs[6] (Fig. 8a) the temperature profiles were generally lapse at all four stations. At 0945 hrs (Fig. 8b) the temperature profile at station 1 was becoming slightly inverted. By 1045 hrs (Fig. 8c) both the station 1 and 3 profiles were fully inverted. The air temperature at station 1 was by then significantly warmer than at the other stations. This was due to the influence of local sensible heat advection. By 1145 hrs (Fig. 8d) the influence of local sensible heat advection at station 4 was noticeable as the profile there became completely inverted while the profile at station 5 from level 1 to 2 remained lapse. The inversion at higher elevations is due to regional sensible heat advection because of the lack of a significant temperature change between stations. The temperature profile at station 5 became completely inverted by 1245 hrs

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[6]Solar time is used throughout this report.

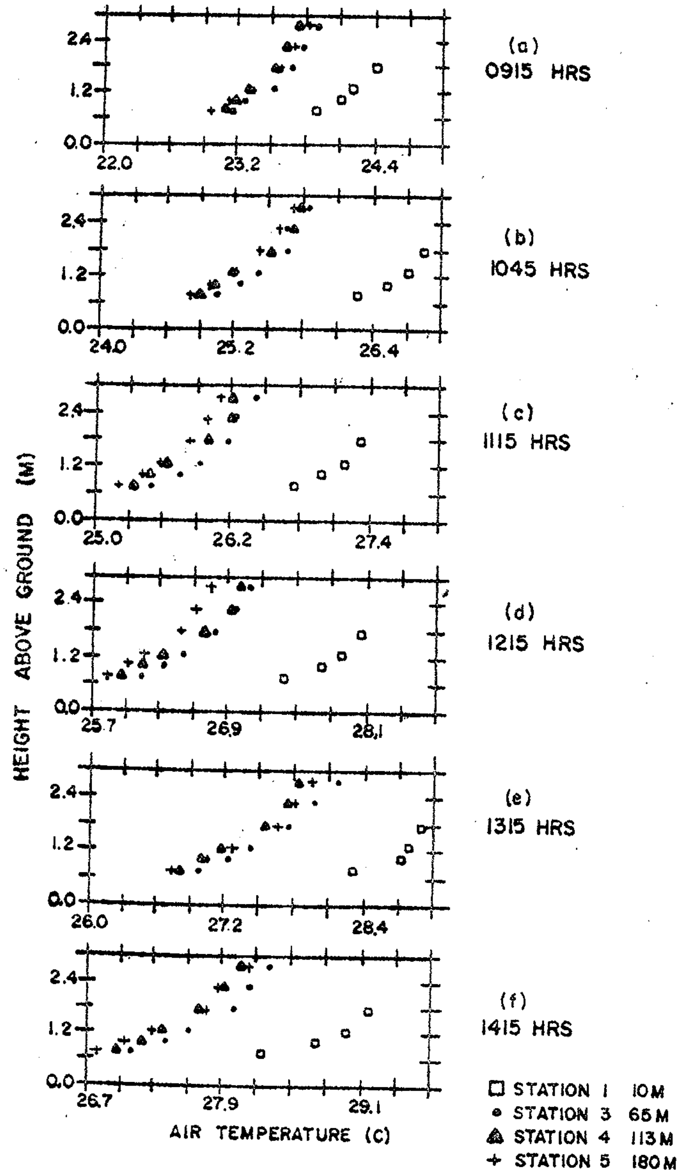

Fig. 7. Hourly temperature profiles (solar time) above irrigated alfalfa at Mead, Nebraska, showing the presence of inverted profiles throughout the day (21 June 1976). Distances from the leading edge are indicated.

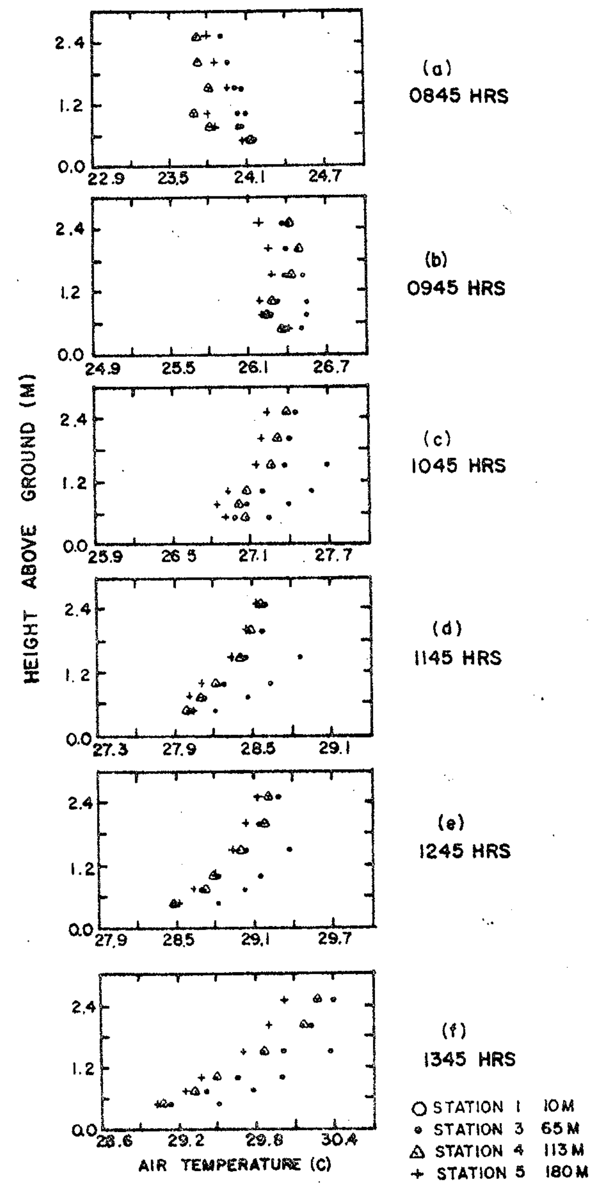

Fig. 8. Hourly temperature profiles (solar time) above irrigated alfalfa at Mead, Nebraska (10 June 1976) showing the transition from lapse to inverted profiles. Distances from the leading edge are indicated.

(Fig. 8e), though the temperature at its lowest level was still greater than at the lowest level at station 4. By 1345 hrs (Fig. 8f) all temperature profiles were inverted and showed the cooling of the air from stations 1 through 5, similar to that occurring on other days.

Figure 9 shows a typical set of vapor pressure profiles measured at four locations downwind from the leading edge. The vapor pressure increased from station 1 to 3 and from station 3 to 4, but decreased from station 4 to 5. This phenomenon was often observed throughout the study, even during Study 76-2 after the alfalfa had been harvested (Fig. 10).

At times the vapor pressure increased from station 1 to 3 but decreased from station 3 to 4 and from 4 to 5. Figure 11 illustrates this effect. This phenomenon of decreased vapor pressure downwind has been observed by other investigators (e.g. Wiersma, 1968; Crawford and Dyer, 1962) but has not been adequately explained. A possible explanation is that somewhere between stations 4 and 5 (and at times between stations 3 and 5) more vapor was being transported vertically than was being evapotranspired at the surface. Thus the vapor pressure would decrease downwind.

The relatively large vapor pressure increases from station 1 to 3 are another indication that the local sensible heat advection is greatest near the leading edge.

4.2 Modification of the Bowen Ratio - Energy Balance Method

Using equation (34) developed in Section 3.1, LE(MBREB) was computed from measurements of windspeed[7], net radiation, wind direction, soil heat

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[7]Measured at station 5.

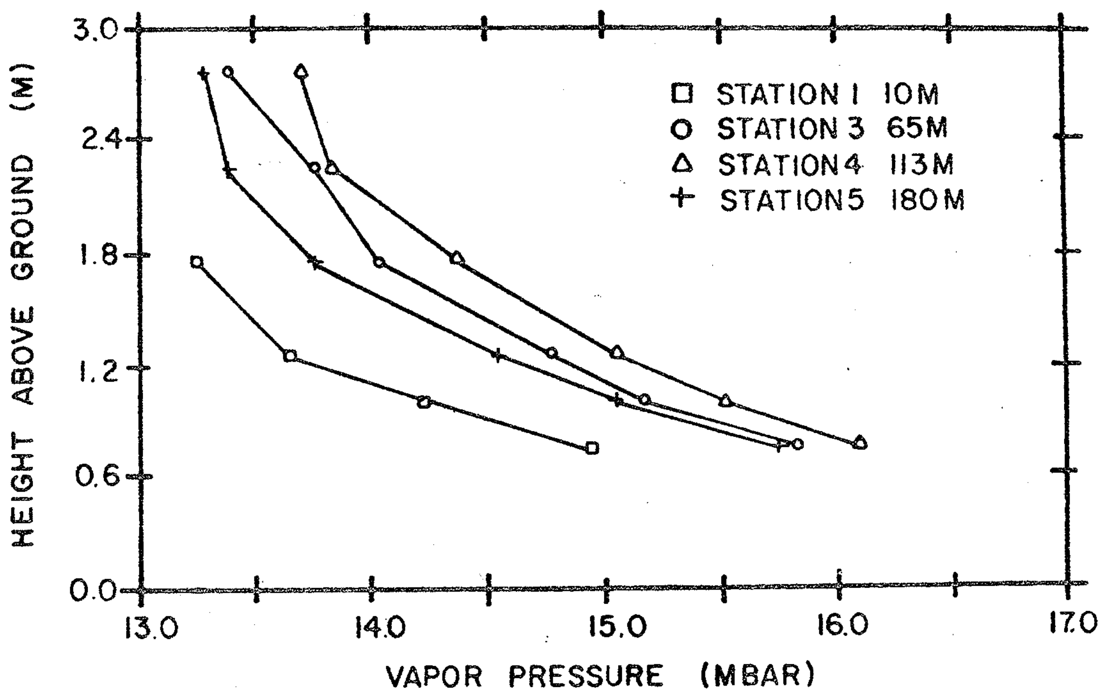

Fig. 9. Typical vapor pressure profiles downwind from a leading edge above irrigated alfalfa at Mead, Nebraska (1345 hrs, solar time, 21 June 1976). Distances from the leading edge are indicated.

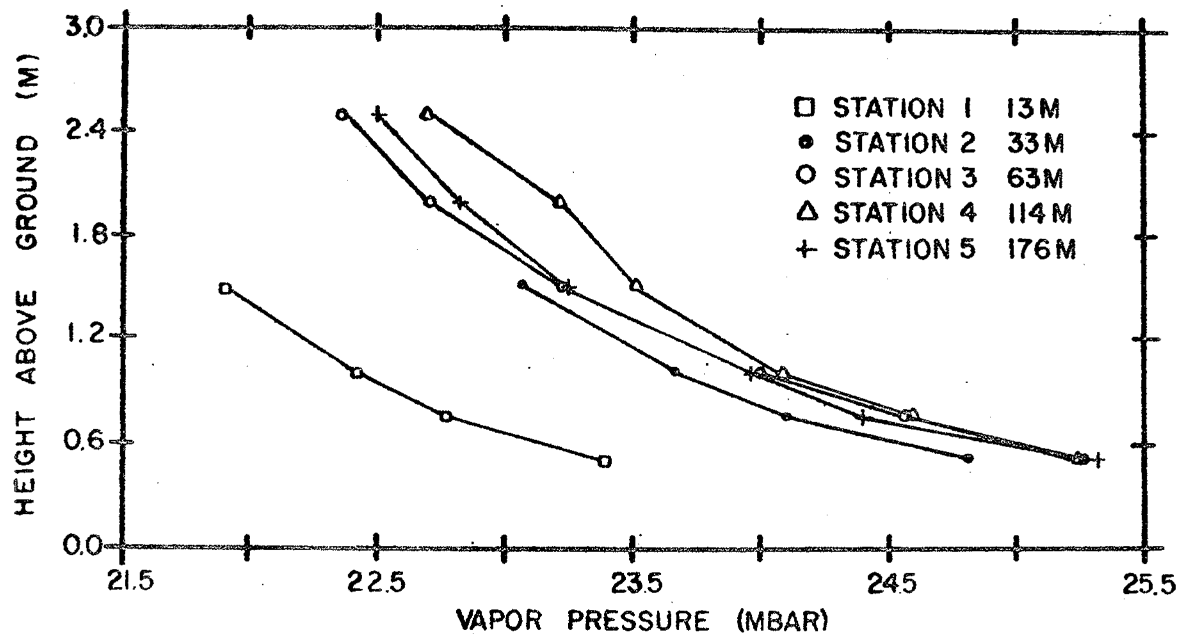

Fig. 10. Vapor pressure profiles downwind from a leading edge above irrigated alfalfa at Mead, Nebraska (1407 hrs, solar time, 10 July 1976) showing the vapor pressure decrease at station 5. Distances from the leading edge are indicated.

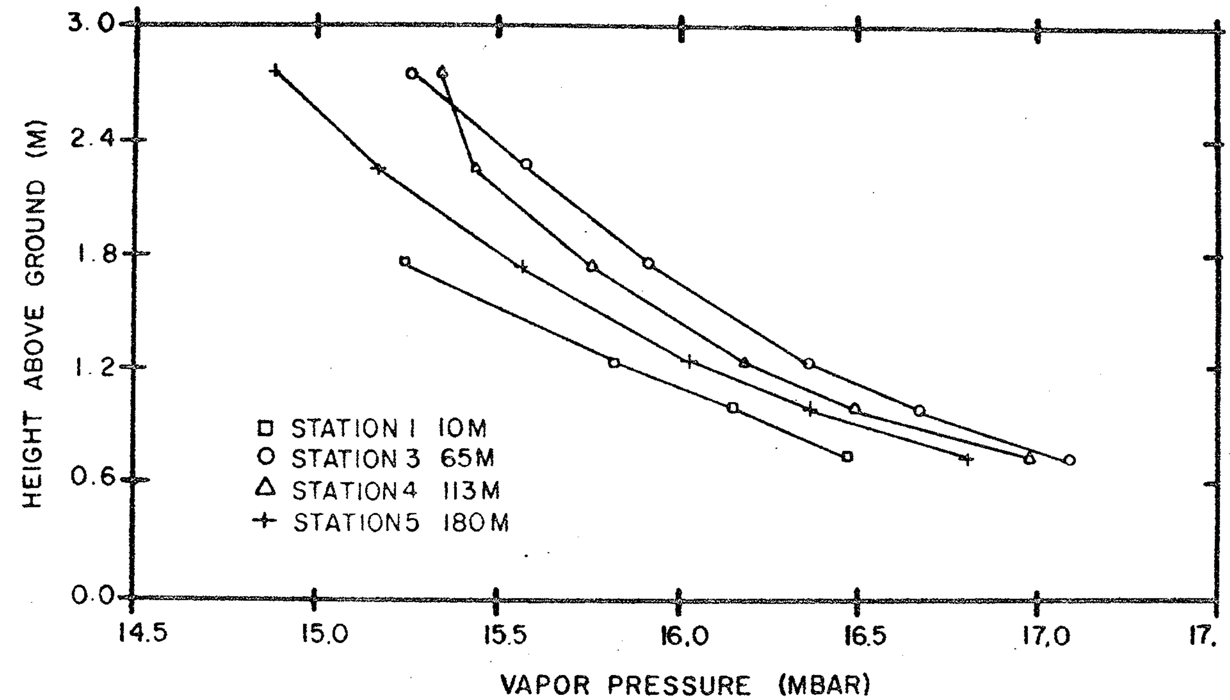

Fig. 11. Vapor pressure profiles above irrigated alfalfa at Mead, Nebraska (1145 hrs, solar time, 25 June 1976) showing the vapor pressure decrease at both stations 4 and 5. Distances from the leading edge are indicated.

flux and vertical and horizontal gradients of air temperature and vapor pressure. Table 2 shows typical comparisons between average values of LE(BREB) (eq. 27) and LE(MBREB) for June 21. The difference between the two methods is the correction term [i.e., the second term on the right of equation (34)]. The correction term is greatest when LE(MBREB) is calculated close to the leading edge, where the largest local advective effects are experienced. Also, the correction term increases when the temperatures, vapor pressures and windspeeds measured at higher levels are used to calculate LE(MBREB). This results from the fact that the total horizontal fluxes of sensible and latent heat within a volume between the surface and a level z_1 increase with increasing z_1.

A limitation of the MBREB method is shown by the increase in LE(MBREB) with increasing z_1 (Table 2). This increase is similar to that reported by Lang (1973) who applied a similar method to the data of Rider et al. (1963). Theoretically, any change in the LE(BREB) term [i.e., the first term on the right of equation (34)] due to a change in height should be compensated by a change in the correction term. Therefore, LE(MBREB) should be insensitive to the value of z_1. Part of this difficulty [increasing LE(MBREB) with height] may have been caused by the necessity of using finite measurements of the vertical temperature and vapor pressure gradients to calculate the Bowen ratio.

Due to this limitation, data from only the lowest elevations of measurements will be used in LE(MBREB) calculations to minimize computational errors.

The values of LE(MBREB) at the far downwind location (C) were checked against lysimetrically measured fluxes [LE(LYS)]. Figure 12

Table 2. Comparison of daily averages of MBREB and BREB estimates of evapotranspiration (LE) for different heights at locations A, B and C (1045-1415 hrs, solar time, 21 June 1976).

z_1 (cm)	LE(MBREB) ($ly\ min^{-1}$) Locations			LE(BREB) ($ly\ min^{-1}$) Locations			Correction Term ($ly\ min^{-1}$) Locations		
	A	B	C	A	B	C	A	B	C
150.0	-1.15	-1.13	-1.18	-1.04	-1.10	-1.13	0.11	0.03	0.05
112.5	-1.07	-1.01	-1.02	-1.01	-1.00	-1.00	0.06	0.01	0.02
87.5	-1.08	-0.96	-0.95	-1.05	-0.95	-0.94	0.03	0.01	0.01

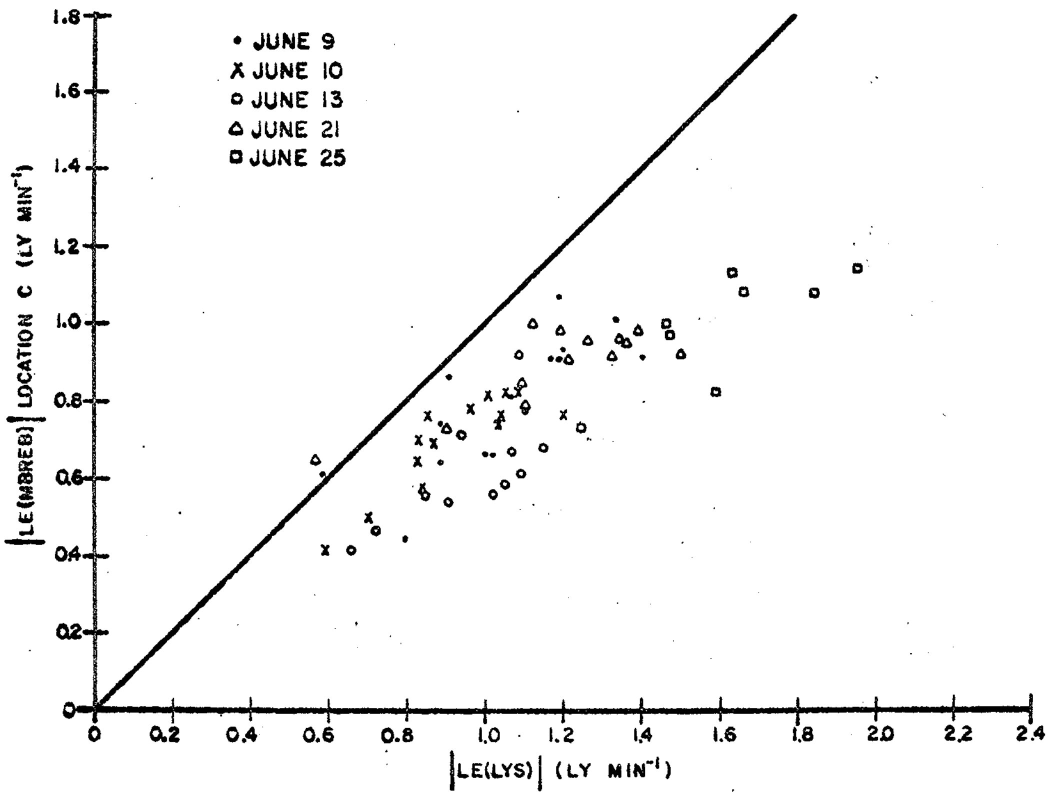

Fig. 12. Modified Bowen ratio-energy balance method (MBREB) estimated LE compared with lysimetrically measured LE over irrigated alfalfa at Mead, Nebraska during five days in June, 1976.

shows the comparison between LE(MBREB) and LE(LYS). LE(MBREB) underestimates LE(LYS) by 10 to 40%. This is primarily due to the assumption used in the MBREB method of equality of the exchange coefficients for heat (K_H) and water vapor (K_W). Recent investigations under conditions of sensible heat advection (Blad and Rosenberg, 1974; Verma, Rosenberg and Blad, 1977) indicate that K_H is generally greater than K_W. To correct for the underestimation in LE by the MBREB method, an expression for K_H/K_W derived by Verma et al. (1977) is used here:

$$K_H/K_W = 2.95 + 3.72(\Delta T/\Delta e) + 1.72(\Delta T/\Delta e)^2 \qquad (37)$$

where ΔT and Δe are the vertical gradients of temperature and vapor pressure, respectively. Equation (37) was derived for use under conditions of regional sensible heat advection such as prevailed at stations 4 and 5. The equation has been applied at all the stations even though it is not entirely correct for application under conditions of local advection prevailing at stations 1 and 3. Equation (37) is definitely not applicable at any station in the absence of regional sensible heat advection.

Equation (37) was used to calculate a new Bowen ratio β_1 from equation (26). The new β_1 was then used in equation (34) to create a second modified Bowen ratio-energy balance method (M2BREB) for calculating evapotranspiration [LE(M2BREB)]. The resulting LE(M2BREB) values are scattered on both sides of a 1:1 correlation line and are generally within 20% of LE(LYS) (Fig. 13). Because of the requirement stated above, the M2BREB method is not applicable to data taken on June 13 nor on the morning of June 10. Therefore, the following discussion will

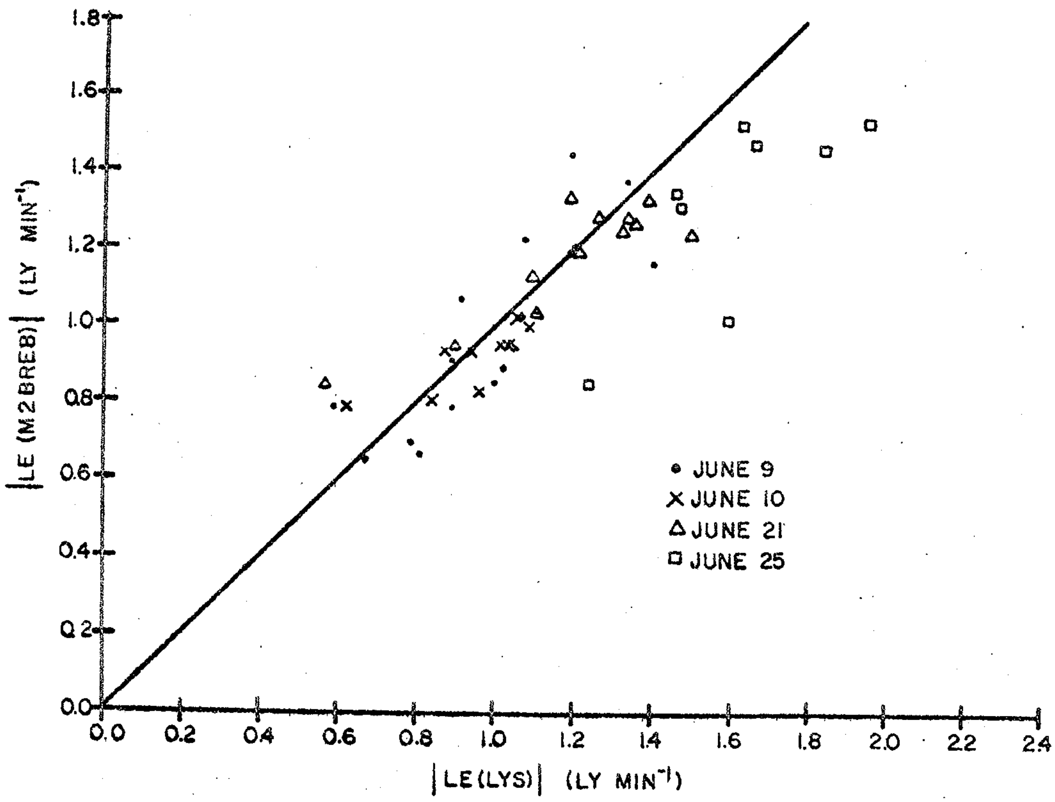

Fig. 13. The 'modified modified' Bowen ratio-energy balance method (M2BREB) estimated LE compared with lysimetrically measured LE over irrigated alfalfa at Mead, Nebraska, during four days in June, 1976.

consider results from both the MBREB method and the M2BREB method.

4.3 Local and Regional Sensible Heat Advection

Figure 14 shows the influence of fetch (distance from the leading edge) on values of LE(MBREB) on a typical day. LE(MBREB) decreases as the effect of local sensible heat advection decreases with increasing fetch. At the far downwind location (C) LE(MBREB) still exceeds Rn+S, indicating the presence of regional sensible heat advection.

Based on the analytical procedure outlined in Section 3.1 (eq. 36), local and regional sensible heat advection components were separated. Figures 15 through 19 show the variation of the regional (A_r) and local (A_l) components of sensible heat advection (obtained by the MBREB method) as functions of time of day for June 9, 10, 13, 21 and 25, respectively. Windspeed (measured at 1.5 m, station 5), air temperature and vapor pressure (both measured at 0.75 m, station 5), and the sum of net radiation plus soil heat flux are also shown to help indicate relationships between meteorological parameters and sensible heat advection.

The local component of sensible heat advection at the location nearest the leading edge (location A) was generally greater than that measured downwind (location B). The regional component generally increased in the afternoon (Fig. 15-18). In the late afternoon this increase may be, in part, an artifact of a rapid decrease in the net radiation and the absence of steady-state conditions. If the net radiation term (eq. 25) decreases more rapidly than does the evapotranspiration, the difference in energy is assigned to the sensible heat advection term. Actually, that energy may be due to heat from the storage term in equation (8) which is zero under steady-state conditions.

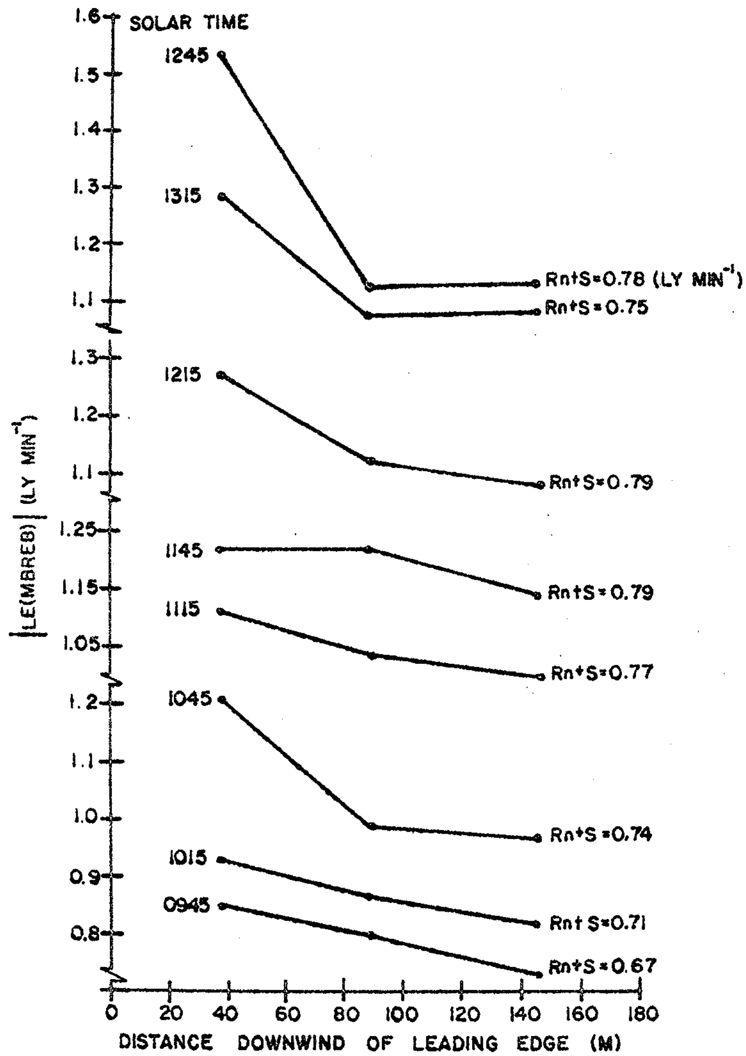

Fig. 14. Variation in LE(MBREB) flux over irrigated alfalfa at Mead, Nebraska (25 June 1976).

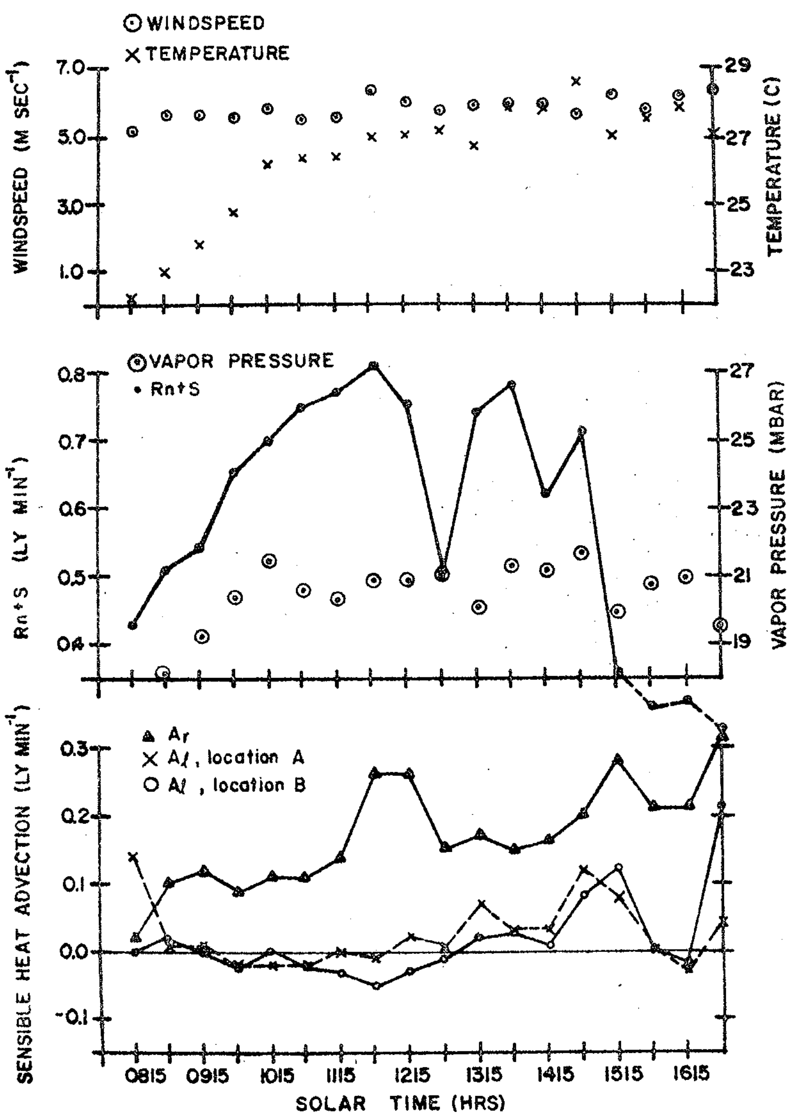

Fig. 15. Local (A_l) and regional (A_r) components of sensible heat advection over irrigated alfalfa at Mead, Nebraska (9 June 1976). Daily patterns of Rn+S, U (1.5 m, station 5), T (0.75 m, station 5), and e (0.75 m, station 5) are also shown.

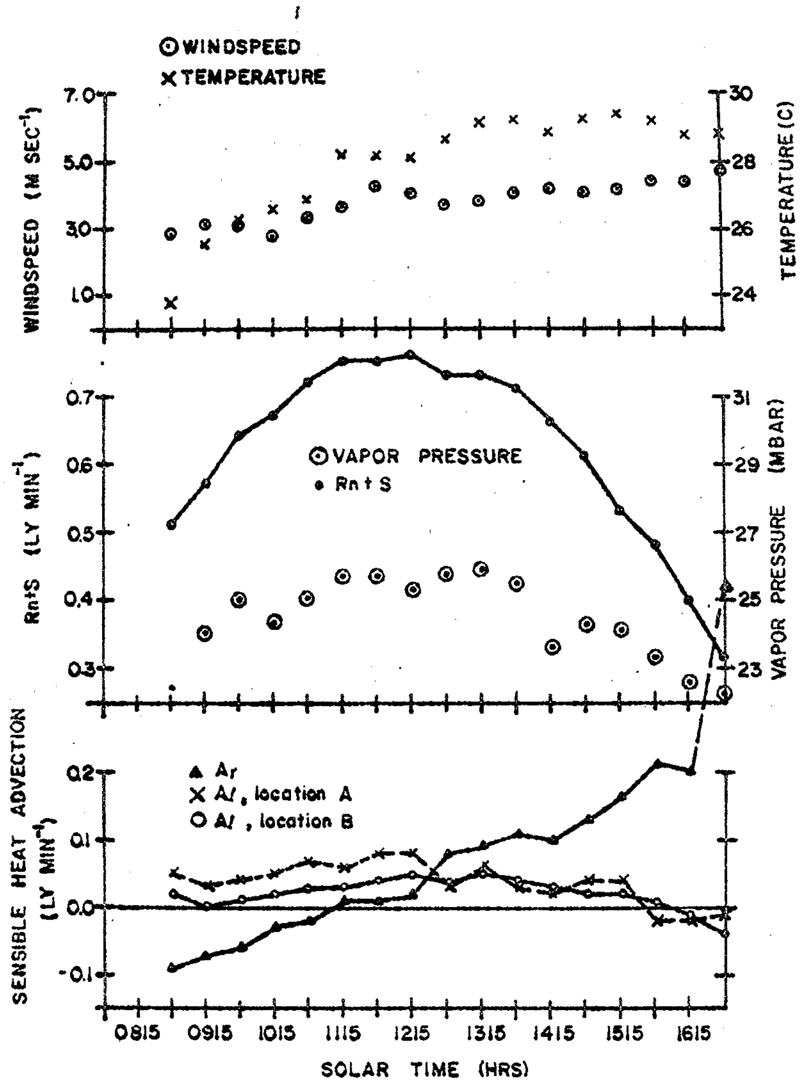

Fig. 16. As in Figure 15 except on 10 June 1976.

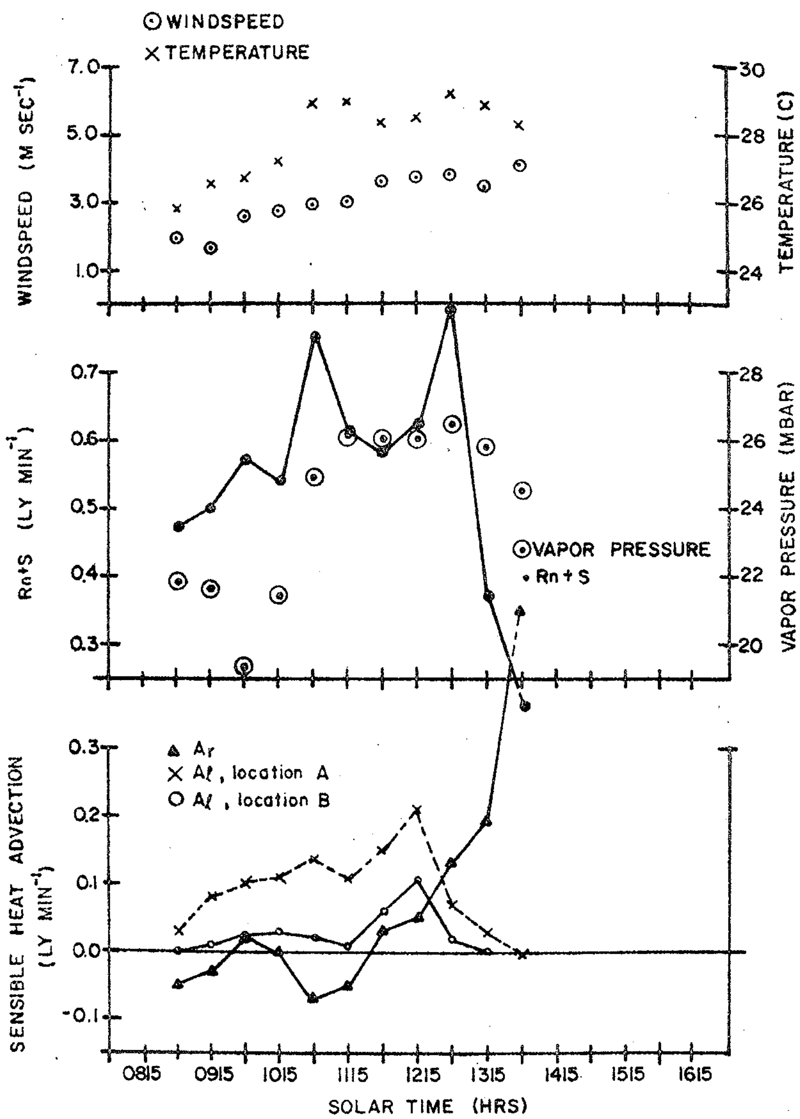

Fig. 17. As in Figure 15 except on 13 June 1976.

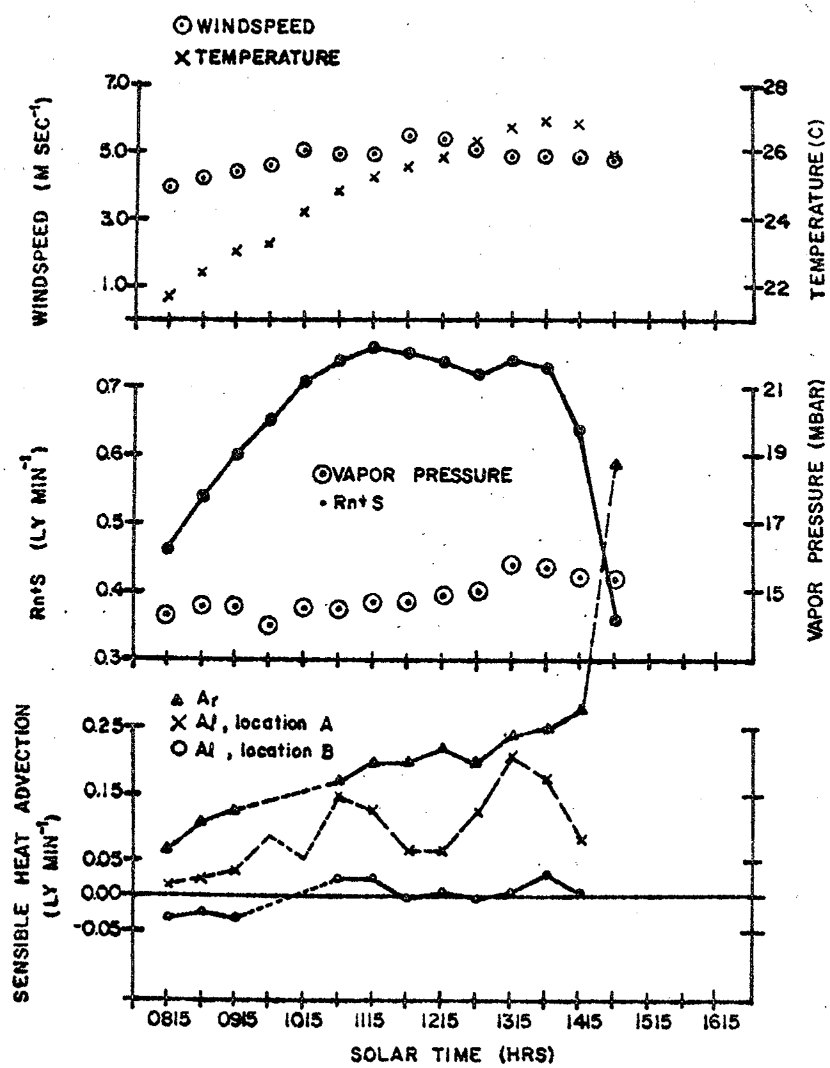

Fig. 18. As in Figure 15 except on 21 June 1976.

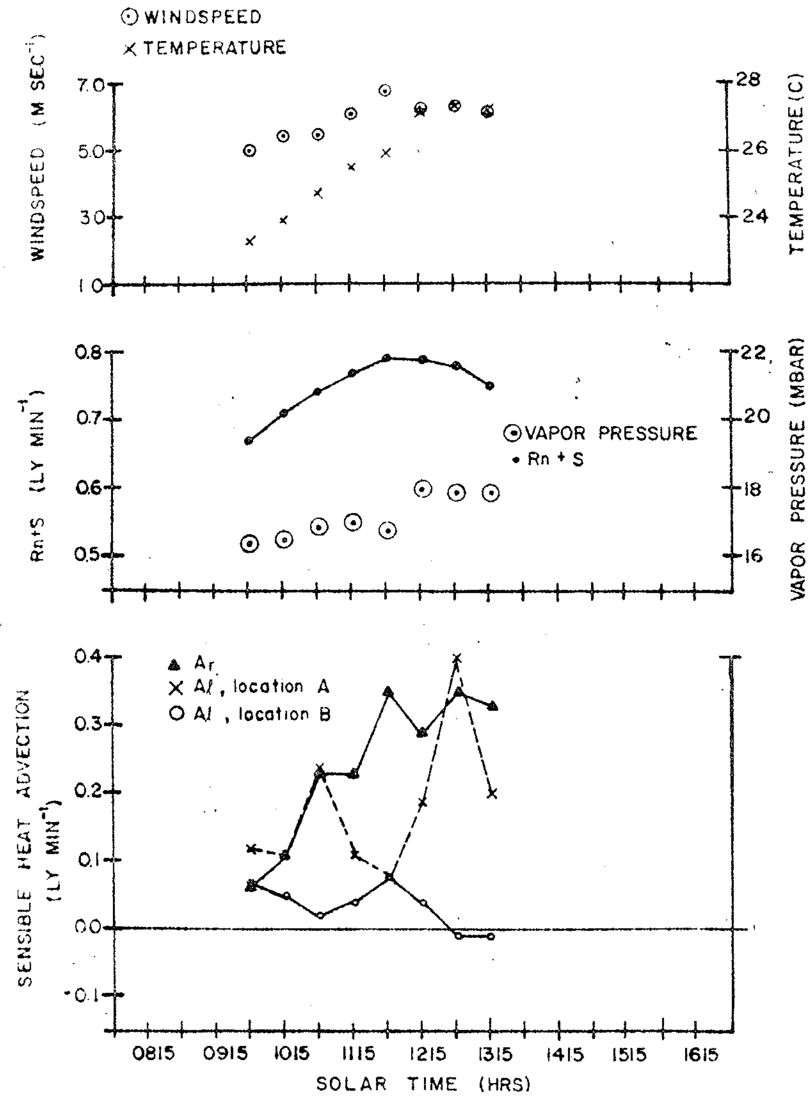

Fig. 19. As in Figure 15 except on 25 June 1976.

On the morning of June 9 slightly negative local sensible heat advection was observed at locations A and B (Fig. 15). The local sensible heat advection is not actually negative, although calculated to be so from equation (36), due to a slight increase in evapotranspiration downwind (similar to a phenomenon observed by Wiersma, 1968).

Table 3 gives the daily values (obtained by the M2BREB method for the five days in June, 1976) of evapotranspiration (LE), sensible heat advection (A) and sensible heat advection as a fraction of evapotranspiration (A/LE). June 25 was a day with strong sensible heat advection; 50% of the evapotranspiration at location A was due to sensible heat advection. 38% of the evapotranspiration was due to regional sensible heat advection and 12% was due to the local sensible heat advection. On June 9, the regional component was again quite significant (40%) but the local component (at location A) contributed only 1%. The regional components on June 10 and 21 were slightly smaller (33 and 36%, respectively) and the local components were slightly larger (6 and 10%, respectively) than they were on June 9 at location A. Regional sensible heat advection was not always greater than the local component of sensible heat advection, however. On June 13[8], local sensible heat advection contributed 14% of the evapotranspiration as compared to 7% from the regional component of sensible heat advection.

On June 9, 21 and 25 (Fig. 15, 18 and 19) relatively strong regional sensible heat advection was measured. Throughout most of these days the windspeeds (at 1.5 m) ranged around 5 to 6 m sec^{-1}. On June 10 and 13

---

[8]Calculated by the MBREB method rather than the M2BREB method.

Table 3. Daily values of evapotranspiration (LE), total sensible heat flux (A_o), regional sensible heat flux (A_r) and local sensible heat flux (A_l) above irrigated alfalfa at locations A, B and C as computed by the 'modified modified' Bowen ratio-energy balance method (M2BREB). The sensible heat flux terms are also expressed as fractions of the evapotranspiration.

		Location A					Location B					Location C	
Time Period	A_r (ly)	LE (ly)	A_l (ly)	A_l/LE	A_r/LE	A_o/LE	LE (ly)	A_l (ly)	A_l/LE	A_r/LE	A_o/LE	LE (ly)	A_r/LE
9 June 1976 0845 - 1645	194	488	3	0.01	0.40	0.40	483	-1	0.00	0.40	0.40	485	0.40
10 June 1976 1215 - 1645	89	265	15	0.06	0.33	0.39	264	14	0.05	0.33	0.39	250	0.35
13 June 1976 0845 - 1345	15*	215*	30*	0.14*	0.07*	0.21*	199*	5*	0.03*	0.08*	0.11*	185*	0.08*
21 June 1976 0815 - 1415	166	459	47	0.10	0.36	0.46	413	3	0.01	0.40	0.41	413	0.40
25 June 1976 0945 - 1315	121	319	40	0.12	0.38	0.50	290	10	0.04	0.42	0.45	280	0.43

*MBREB values.

(Fig. 16 and 17), when regional sensible heat advection was smaller, winds were lighter (3 to 4 m sec^{-1}). Figure 20 shows regional sensible heat advection plotted as a function of windspeed. Regional sensible heat advection and windspeed appear to be positively related in an approximately linear fashion.

There is no apparent relationship, however, between regional sensible heat advection and cloudiness. For example, strong regional sensible heat advection occurred on cloudy (June 9, Fig. 15) as well as on clear days (June 21 and 25; Fig. 18 and 19, respectively).

Local sensible heat advection was strong on June 13, 21 and 25 (Fig. 17, 18 and 19). June 21 and 25 were windy and clear days. June 13, however, was a cloudy and relatively calm day. Figure 21 indicates the absence of any clear correlation between local sensible heat advection and windspeed.

On days when both local and regional sensible heat advection components were strong (June 21 and 25; Fig. 18 and 19, respectively), vapor pressures were relatively low (14-18 mbar) as compared to conditions on three other days (June 9, 10 and 13; Fig. 15, 16 and 17, respectively) when vapor pressures greater than 20 mbar were measured. Thus it seems that sensible heat advection contributes more to evapotranspiration when the air is relatively dry.

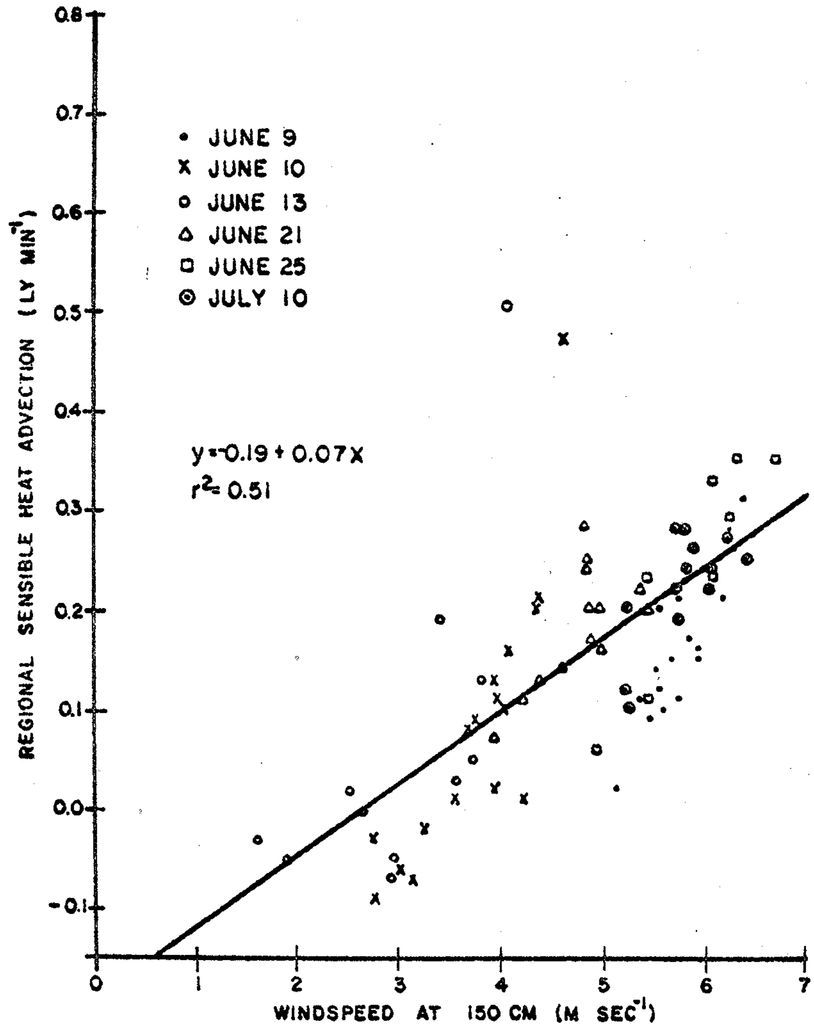

Fig. 20. Dependence of regional sensible heat advection on windspeed above irrigated alfalfa at Mead, Nebraska, for six days in June and July, 1976. The two points way above the line are from the late afternoon increase in regional sensible heat advection.

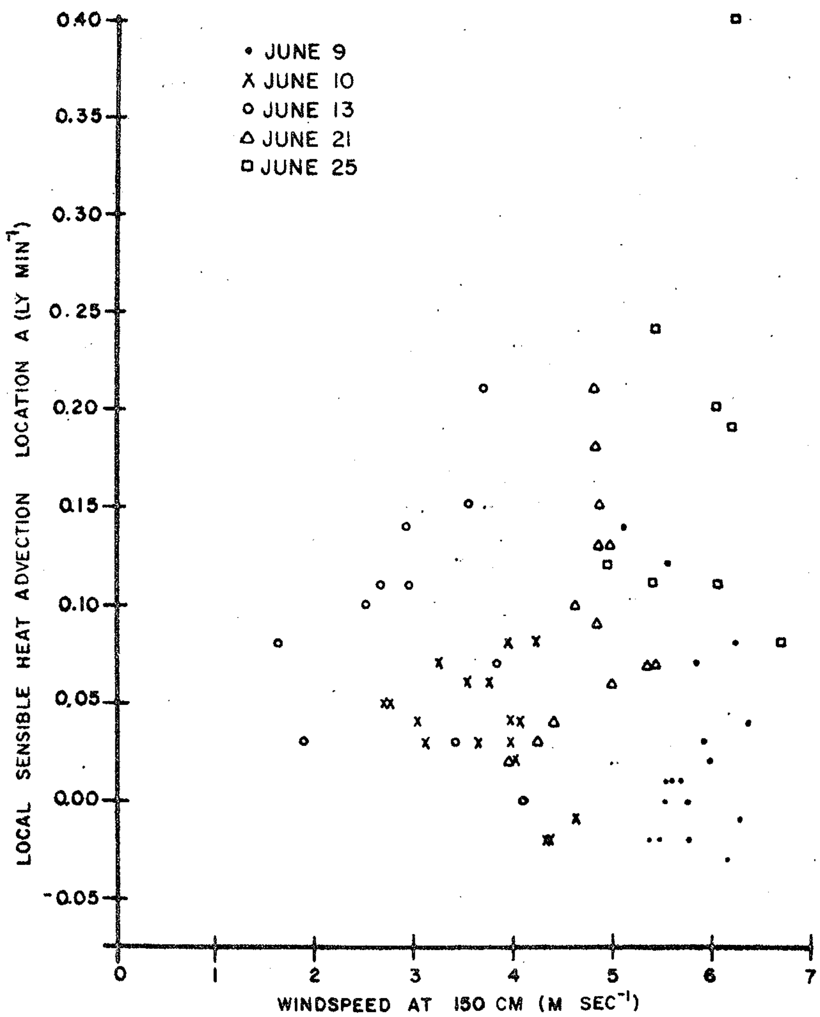

Fig. 21. Relationship between local sensible heat advection and windspeed above irrigated alfalfa at Mead, Nebraska, for five days in June, 1976.

CHAPTER V

SUMMARY AND CONCLUSIONS

Profiles of air temperature and vapor pressure were measured, as were windspeed and net radiation, above an irrigated alfalfa field located downwind of a relatively dry alfalfa field. The transfer of sensible heat downwards caused the temperature profiles to be generally inverted. Air temperature above the crop decreased downwind from the leading edge with the greatest rate of cooling occurring near the leading edge. The vapor pressure profiles were lapse. Vapor pressure above the crop generally increased downwind from the leading edge. A slight decrease in vapor pressure was often observed at a distance of approximately 180 m downwind.

Horizontal gradients of temperature and vapor pressure were incorporated in a modified form of the Bowen ratio-energy balance method (MBREB) to improve the estimation of evapotranspiration under conditions of local sensible heat advection. Analyses indicate that in order to avoid computational errors measurements for use in the MBREB method should be made as close to the crop or land surface as possible. The method seems to be most useful close to the leading edge. Farther downwind (approximately 146 m) the improvement over the BREB method was not significant enough to justify the additional measurements required to apply the MBREB method.

The values of LE(MBREB) calculated for a location approximately 146 m downwind were crosschecked with lysimetrically measured evapotranspiration values [LE(LYS)]. LE(MBREB) underestimated LE(LYS) by 10 to 40%. This underestimation was primarily caused by the assumption of equality of exchange coefficients for heat and water vapor under conditions of sensible heat advection (Blad and Rosenberg, 1974; Verma, Rosenberg and Blad, 1977). LE(MBREB) was, therefore, modified [LE(M2BREB)] with an expression derived by Verma, Rosenberg and Blad (1977) for the ratio of the exchange coefficients (K_H/K_W) under conditions of sensible heat advection. The resulting LE(M2BREB) values generally agreed better with LE(LYS).

Sensible heat advection contributed 21 to 50% of the energy used in evapotranspiration on a daily basis. Regional sensible heat advection accounted for 7 to 40% of this evapotranspiration energy. Local sensible heat advection at the most upwind location (A) in the irrigated field contributed from 1 to 14% of the energy consumed in evapotranspiration.

Regional sensible heat advection was greatest on days with strong winds. Local sensible heat advection did not appear to be dependent upon windspeed. Neither local nor regional sensible heat advection seemed to be influenced by the appearance of clouds. On days when the air was relatively drier than usual (vapor pressures were about 14-18 mbar as compared to over 20 mbar measured on other days) both regional and local sensible heat advection were strong.

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APPENDIX I: LIST OF SYMBOLS

Symbol	Definition	Units
A	sensible heat flux	cal cm^{-2} min^{-1}
A_l	local sensible heat advection	cal cm^{-2} min^{-1}
A_o	surface sensible heat flux	cal cm^{-2} min^{-1}
A_r	regional sensible heat advection	cal cm^{-2} min^{-1}
A_x, A_y, A_z	sensible heat fluxes in the x, y, and z directions, respectively	cal cm^{-2} min^{-1}
C_p	specific heat of air at constant pressure	cal g^{-1} deg^{-1}
d	zero plane displacement	cm
e	vapor pressure of water in air	mbar
E	water vapor flux	g cm^{-2} min^{-1}
e_o	initial vapor pressure (eq. 11)	mbar
e_s	saturation vapor pressure	mbar
$\hat{i}$, $\hat{j}$, $\hat{k}$	unit vectors in the x, y and z directions, respectively	---
k	von Karman's constant	---
K_H	exchange coefficient for sensible heat	cm^2 sec^{-1}
K_W	exchange coefficient for water vapor	cm^2 sec^{-1}
K_1	constant in equation (13)	cm^2 sec^{-1}
L	heat of vaporization of water	cal gm^{-1}
LE	latent heat flux (subscripts o and z refer to the surface and a height z, respectively)	cal cm^{-2} min^{-1}
m	exponent in equation (12)	---
n	exponent in equation (13)	---
P	air pressure	mbar

Symbol	Definition	Units
q	net sensible heat exchange (eq. 1)	cal cm^{-2} sec^{-1}
Rn	net radiation	cal cm^{-2} min^{-1}
r_s	surface diffusion resistance	sec cm^{-1}
S	soil heat flux	cal cm^{-2} min^{-1}
t	time	sec
T	temperature	C
T_o	surface temperature (eq. 18)	C
U	mean windspeed in x-direction	cm sec^{-1}
U_1	constant in equation (12)	cm sec^{-1}
V	mean windspeed in y-direction	cm sec^{-1}
W	mean windspeed in z-direction	cm sec^{-1}
x	downwind distance from leading edge	cm
x_o	constant in equation (11)	cm
z	vertical distance	cm
z_o	roughness parameter	cm
z_1	reference height in equation (12) and upper limit of integration in equation (28)	cm
β	Bowen ratio	---
β_1	Bowen ratio at a height z_1	---
Γ	Gamma function $[\Gamma(x+1) = \int_0^\infty e^{-T} T^x \, dT]$	---
$\overline{\nabla}$	Del operator	---
Δ	change in a variable	---

Symbol	Definition	Units
ε	ratio of molecular weights of water vapor to air	---
θ	wind direction	degrees (0°=due south)
ν	kinematic viscosity of air	$cm^2\ sec^{-1}$
ν_c	thermal conductivity of air	$cal\ sec^{-1}\ cm^{-1}\ C^{-1}$
ρ	air density	$g\ cm^{-3}$
Φ_x	dimensionless exchange function	---

Appendix II. Computer subroutine for the modified Bowen ratio-energy balance method.

```
      SUBROUTINE LANG(IP1,IP2,DX,TH,RN,S,ZO,E,Z1,Z2,Z3,Z4,Z5,Z6,TA1,TA2,
     1TA3,TA4,TA5,TA6,TB1,TB2,TB3,TB4,TB5,TB6,VPA1,VPA2,VPA3,VPA4,VPA5,
     1VPA6,VPB1,VPB2,VPB3,VPB4,VPB5,VPB6,U1,U2,U3,U4,U5,U6)
      REAL BETA(6),T(2,6),VP(2,6),U(6),Z(6),THGRAD(10),VHGRAD(10),ITRAP,
     1INT(5)
      COMMON /C1/ D(99,14),DTIME
      INTEGER DTIME
C     SUBROUTINE LANG COMPUTES LE(MBREB), A, BETA, AND LE(BREB)-LE(MBREB).
C     IP1 AND IP2 ARE THE OUTPUT PAGES.  DX (CM) IS THE DISTANCE BETWEEN STATION
C     ONE AND STATION TWO.  TH IS THE ANGLE (DEGREES) THE WIND DIRECTION MAKES
C     WITH THE X-AXIS.  RN IS THE NET RADIATION (LY/MIN), S THE SOIL HEAT FLUX
C     (LY/MIN), ZO IS THE ROUGHNESS PARAMETER (CM), AND E IS THE ZERO PLANE DIS-
C     PACEMENT (CM).  Z1 THROUGH Z6 ARE SIX HEIGHTS (MAXIMUM) OF PROFILE MEA-
C     SUREMENTS (CM).  TA1 THROUGH TA6, TB1 THROUGH TB6, VPA1 THROUGH VPA6 AND
C     VPB1 THROUGH VPB6 ARE THE CORRESPONDING TEMPERATURES (C) AND VAPOR PRES-
C     SURES (MBAR) FOR STATIONS ONE AND TWO, RESPECTIVELY.  U1 THROUGH U6 ARE
C     THE CORRESPONDING WINDSPEEDS (M/SEC).
      DO 101 I=1,10
      D(IP1,I)=999.99
  101 D(IP2,I)=999.99
      D(IP1,11)=999.99
      IF(DX .EQ. 0.0)GOTO 50
      IF(TH .EQ. 999.99)GOTO 50
C     ASSIGNING VARIABLES TO MATRIX
      T(1,1)=TA1
      T(1,2)=TA2
      T(1,3)=TA3
      T(1,4)=TA4
      T(1,5)=TA5
      T(1,6)=TA6
      T(2,1)=TB1
      T(2,2)=TB2
      T(2,3)=TB3
      T(2,4)=TB4
      T(2,5)=TB5
      T(2,6)=TB6
      VP(1,1)=VPA1
      VP(1,2)=VPA2
      VP(1,3)=VPA3
      VP(1,4)=VPA4
      VP(1,5)=VPA5
      VP(1,6)=VPA6
      VP(2,1)=VPB1
      VP(2,2)=VPB2
      VP(2,3)=VPB3
      VP(2,4)=VPB4
      VP(2,5)=VPB5
      VP(2,6)=VPB6
C     CHANGING WINDSPEED TO CM/SEC.
      U(1)=U1*100
```

Appendix II. (con't)

```
      U(2)=U2*100
      U(3)=U3*100
      U(4)=U4*100
      U(5)=U5*100
      U(6)=U6*100
      Z(1)=Z1
      Z(2)=Z2
      Z(3)=Z3
      Z(4)=Z4
      Z(5)=Z5
      Z(6)=Z6
      DO 10  I=1,6
C     TESTING FOR BAD DATA.
      IF(T(1,I).GT.999.99)GOTO 50
      IF(T(1,I).LT.-99.99)GOTO 50
      IF(T(2,I).GT.999.99)GOTO 50
      IF(T(2,I).LT.-99.99)GOTO 50
      IF(VP(1,I).GT.999.99)GOTO 50
      IF(VP(1,I).LT.-99.99)GOTO 50
      IF(VP(2,I).GT.999.99)GOTO 50
      IF(VP(2,I).LT.-99.99)GOTO 50
      IF(U(I).GT.99999.)GOTO 50
      IF(U(I).LT.-9999.)GOTO 50
   10 CONTINUE
      IF(RN.GT.999.99)GOTO 50
      IF(RN.LT.-99.99)GOTO 50
      IF(S.GT.999.99)GOTO 50
      IF(S.LT.-99.99)GOTO 50
      IF(TH.GT.999.99)GOTO 50
      IF(TH.LT.-99.99)GOTO 50
      IF(Z0.GT.999.99)GOTO 50
      IF(Z0.LT.-99.99)GOTO 50
      IF(E.GT.999.99)GOTO 50
      IF(E.LT.-99.99)GOTO 50
C     TESTING FOR NUMBER OF LEVELS OF MEASUREMENT.
      N=5
      IF(Z6.EQ.0.0)N=4
      IF(Z5.EQ.0.0)N=3
      IF(Z4.EQ.0.0)N=2
      IF(Z3.EQ.0.0)N=1
      DO 20 I=1,N
C     TESTING TO AVOID DIVIDING BY ZERO WHEN CALCULATING BETA.
      IF(VP(1,I+1) .EQ. VP(1,I))GOTO 15
      IF(VP(2,I+1) .EQ. VP(2,I))GOTO 15
      BETA(I)=(.6492)*(.5)*((T(1,I+1)-T(1,I))/(VP(1,I+1)-VP(1,I))+(T(2,I
     1+1)-T(2,I))/(VP(2,I+1)-VP(2,I)))
      GOTO 17
   15 BETA(I)=999.99
   17 THGRAD(2*I-1)=(.0165)*(T(2,I)-T(1,I))/DX
      THGRAD(2*I)=(.0165)*((.5)*(T(2,I)+T(2,I+1))-((.5)*(T(1,I)+T(1,I+1)
     1)))/DX
      VHGRAD(2*I-1)=(.02542)*(VP(2,I)-VP(1,I))/DX
```

```
      VHGRAD(2*I)=(.02542)*((.5)*(VP(2,I)+VP(2,I+1))-((.5)*(VP(1,I)+VP(1
     1,I+1))))/DX
   20 CONTINUE
      DO 40 I=1,N
C     ITRAP IS EVALUATING THE INTEGRAL BY THE TRAPEZOIDAL METHOD.
      ITRAP=(.5)*(Z(1)-(ZO+E))*(U(1))*((BETA(I))*(VHGRAD(1))-THGRAD(1))
      IF(I.EQ.1)GOTO 355
      K=I-1
      DO 35 J=1,K
      ITRAP=ITRAP+(.5*(Z(J+1)-Z(J))*((U(J))*((BETA(I))*(VHGRAD(2*J-1))-(
     1THGRAD(2*J-1)))+(U(J+1))*((BETA(I))*(VHGRAD(2*J+1))-(THGRAD(2*J+1
     1))))))
   35 CONTINUE
  355 CONTINUE
      ITRAP=ITRAP+(.25*(Z(I+1)-Z(I))*((U(I))*((BETA(I))*(VHGRAD(2*I-1))-
     1(
     1THGRAD(2*I-1)))+.5*(U(I)+U(I+1))*((BETA(I))*(VHGRAD(2*I))-(THGRAD(
     12*I)))))
      INT(I)=ITRAP*COS(TH*3.14159/180.0)
      IF(BETA(I) .EQ. 999.99)GOTO 37
      IF(BETA(I) .EQ. -1.0)GOTO 37
      GOTO 38
C     999.99 APPEARS IF THERE IS NO OUTPUT DATA.
   37 D(IP1,I)=999.99
      D(IP2,I)=999.99
      D(IP1,I+5)=999.99
      D(IP2,I+5)=BETA(I)
      GOTO 40
   38 D(IP1,I)=-(RN+S+INT(I))/(1+BETA(I))
      D(IP2,I)=-D(IP1,I)-RN-S
      D(IP1,I+5)=INT(I)/(1+BETA(I))
      D(IP2,I+5)=BETA(I)
   40 CONTINUE
C     LE APPEARS ON IP1 COLUMNS 1-5; LE(BREB)-LE(MBREB) ON IP1 COLUMNS 6-10.
C     A APPEARS ON IP2 COLUMNS 1-5; BETA ON IP2 COLUMNS 6-10.
C     RN+S APPEARS ON IP1, COLUMN 11.
      D(IP1,11)=RN+S
      DO 55 I=1,11
      IF(D(IP1,I) .GT. 999.99)D(IP1,I)=999.99
      IF(D(IP2,I) .GT. 999.99)D(IP2,I)=999.99
      IF(D(IP1,I) .LT. -99.99)D(IP1,I)=999.99
   55 IF(D(IP2,I) .LT. -99.99)D(IP2,I)=999.99
   50 CONTINUE
      RETURN
      END
```

APPENDIX III

TEMPERATURE, VAPOR PRESSURE, WINDSPEED

AND MISCELLANEOUS DATA

Table A-1. Zero plane displacement (d) and roughness parameter (z_o) for irrigated alfalfa at Mead, Nebraska (1976).

Date	d (cm)	z_o (cm)
June 9	18	5.6
June 10	18	5.6
June 13	19	6.7
June 21	21	9.2
June 25	23	10.3
July 10	6	4.0

Table A-2. Psychrometer location at Mead, Nebraska (1976).

Station #	Psychrometer Distance From Leading Edge (m)		
	June 6-June 11	June 11-July 1	July 10
1	9.9	9.9	12.6
2	---	---	33.0
3	65.4	65.4	62.5
4	113.7	112.0	113.7
5	180.5	177.8	176.2

Table A-3. Constants used in Bowen ratio-energy balance calculation.

$C_p = .24$ cal gm^{-1} deg^{-1}

$L = 580$ cal g^{-1}

$P = 973$ mbar

$\varepsilon = .622$

$\rho = 1.145 \times 10^{-3}$ g cm^{-3}

Table A-4. Air temperature at Stations 1, 3 and 4 for June, 1976.

	Air Temperature (C)															
	Station 1				Station 3						Station 4					
Date	50 cm	75 cm	100 cm	150 cm	50 cm	75 cm	100 cm	150 cm	200 cm	250 cm	50 cm	75 cm	100 cm	150 cm	200 cm	250 cm
6090845	23.18	23.29	23.42	23.56	22.87	22.98	23.12	23.38	23.36	23.49	22.82	22.98	23.15	23.35	23.47	23.61
6090915	23.95	24.09	24.23	24.40	23.59	23.70	23.85	24.07	24.11	24.27	23.59	23.76	23.93	24.11	24.28	24.43
6090945	25.03	25.14	25.31	25.49	24.67	24.72	24.87	25.07	25.14	25.23	24.69	24.84	24.97	25.14	25.23	25.35
6091015	26.36	26.47	26.63	26.79	26.08	26.18	26.34	26.54	26.61	26.67	26.10	26.28	26.44	26.66	26.76	26.90
6091045	26.69	26.79	26.96	27.08	26.28	26.37	26.52	26.69	26.71	26.77	26.19	26.32	26.42	26.63	26.72	26.82
6091115	26.75	26.95	27.14	27.34	26.25	26.36	26.53	26.72	26.80	26.90	26.19	26.36	26.49	26.74	26.86	26.97
6091145	27.48	27.74	27.94	28.12	26.84	26.99	27.19	27.34	27.44	27.57	26.79	27.06	27.26	27.52	27.75	27.88
6091215	27.48	27.72	27.91	28.10	26.84	27.03	27.28	27.47	27.59	27.72	26.87	27.19	27.39	27.69	27.87	28.05
6091245	27.36	27.75	27.97	28.29	27.02	27.15	27.34	27.53	27.76	27.70	26.89	27.06	27.40	27.65	27.57	27.89
6091315	27.24	27.61	27.81	28.10	26.73	26.93	27.10	27.27	27.44	27.41	26.63	26.85	27.09	27.34	27.32	27.53
6091345	28.46	28.68	28.85	29.04	27.85	28.11	28.33	28.51	28.58	28.62	27.72	27.94	28.06	28.34	28.54	28.55
6091415	28.31	28.58	28.78	29.02	27.76	28.05	28.28	28.54	28.64	28.74	27.65	27.91	28.07	28.37	28.61	28.63
6091445	28.95	29.27	29.50	29.84	28.45	28.77	29.02	29.42	29.53	29.71	28.46	28.68	28.88	29.19	29.43	29.53
6091515	27.29	27.72	28.09	28.54	26.83	27.22	27.57	28.02	28.24	28.50	26.71	27.08	27.35	27.77	28.12	28.24
6091545	27.61	27.98	28.29	28.57	27.34	27.63	27.95	28.36	28.52	28.75	27.19	27.54	27.76	28.04	28.24	28.30
6091615	28.02	28.38	28.64	28.89	27.74	28.02	28.29	28.62	28.82	29.02	27.72	28.04	28.24	28.48	28.67	28.73
6091645	27.06	27.50	27.82	28.17	26.76	27.11	27.44	27.69	28.00	28.15	26.76	27.13	27.45	27.85	28.06	28.21
6100845	24.17	24.07	24.10	24.02	24.11	24.05	24.04	24.07	23.96	23.92	24.15	23.82	23.70	23.82	23.73	23.72
6100915	25.82	25.70	25.72	25.65	25.67	25.54	25.53	25.54	25.39	25.35	25.71	25.44	25.34	25.48	25.39	25.37
6100945	26.51	26.55	26.55	26.53	26.39	26.28	26.33	26.39	26.40	26.37	26.37	26.25	26.28	26.43	26.49	26.42
6101015	26.75	26.87	26.89	26.94	26.53	26.50	26.65	26.77	26.78	26.79	26.61	26.58	26.58	26.80	26.93	26.90
6101045	27.24	27.39	27.57	27.69	26.97	27.07	27.19	27.36	27.40	27.45	27.05	27.00	27.06	27.26	27.31	27.38
6101115	28.31	28.53	28.73	28.92	28.16	28.26	28.42	28.60	28.66	28.72	28.16	28.22	28.37	28.62	28.68	28.78
6101145	28.22	28.46	28.63	28.86	28.03	28.13	28.29	28.45	28.58	28.61	28.00	28.09	28.22	28.40	28.48	28.58
6101215	28.46	28.72	28.82	29.03	28.04	28.17	28.35	28.53	28.68	28.75	27.99	28.09	28.21	28.36	28.41	28.50
6101245	28.83	29.02	29.14	29.36	28.48	28.70	28.83	29.04	29.14	29.29	28.48	28.72	28.78	28.99	29.17	29.21
6101315	29.10	29.41	29.64	29.91	28.88	29.14	29.32	29.59	29.73	29.81	28.87	29.11	29.24	29.49	29.70	29.74
6101345	29.50	29.75	29.97	30.34	29.12	29.40	29.64	29.99	30.20	30.37	29.06	29.31	29.48	29.84	30.14	30.25
6101415	29.20	29.45	29.66	30.02	28.78	29.03	29.28	29.64	29.82	29.98	28.70	28.97	29.11	29.49	29.72	29.82
6101445	29.32	29.75	30.13	30.61	29.02	29.39	29.68	30.13	30.34	30.54	28.99	29.35	29.56	29.98	30.12	30.31
6101515	29.39	29.89	30.35	30.86	29.02	29.42	29.76	30.21	30.49	30.71	28.95	29.33	29.61	30.12	30.34	30.49
6101545	29.20	29.71	30.08	30.52	28.89	29.26	29.66	30.07	30.38	30.61	28.78	29.23	29.60	30.04	30.34	30.55
6101615	28.85	29.39	29.77	30.22	28.49	28.89	29.29	29.70	30.02	30.22	28.46	28.91	29.30	29.74	29.96	30.21
6101645	28.71	29.27	29.68	30.17	28.40	28.87	29.33	29.84	30.29	30.54	28.38	28.92	29.29	29.81	30.12	30.42
	75 cm	100 cm	125 cm	175 cm	75 cm	100 cm	125 cm	175 cm	225 cm	275 cm	75 cm	100 cm	125 cm	175 cm	225 cm	275 cm
6130845	25.89	25.89	26.25	26.42	25.70	25.64	25.80	25.93	26.01	25.97	25.81	25.70	25.79	26.06	26.23	26.30
6130915	26.55	26.83	26.91	27.14	26.42	26.41	26.54	26.72	26.83	26.77	26.60	26.52	26.57	26.93	26.98	27.09
6130945	26.75	27.12	27.24	27.55	26.49	26.59	26.79	27.09	27.28	27.28	26.68	26.73	26.84	27.22	27.41	27.51
6131015	27.63	27.97	28.08	28.33	27.21	27.34	27.51	27.78	27.98	27.94	27.32	27.33	27.47	27.84	27.98	28.06
6131045	29.20	29.40	29.56	29.66	28.75	28.76	28.85	29.14	29.27	29.26	28.91	28.75	28.80	29.15	29.22	29.31
6131115	29.39	29.61	29.75	29.89	28.80	28.80	28.90	29.15	29.26	29.24	28.90	28.75	28.85	29.19	29.29	29.33
6131145	28.95	29.28	29.49	29.71	28.38	28.54	28.75	29.05	29.13	29.23	28.37	28.45	28.61	28.96	29.09	29.24
6131215	29.19	29.54	29.75	30.02	28.51	28.73	28.94	29.24	29.41	29.49	28.41	28.51	28.69	29.08	29.22	29.38
6131245	29.99	30.22	30.41	30.56	29.31	29.53	29.71	29.89	30.01	30.13	29.26	29.38	29.52	29.79	30.05	30.00
6131315	29.54	29.94	30.16	30.50	29.00	29.34	29.62	29.91	30.11	30.30	28.88	29.14	29.35	29.75	30.05	30.14
6131345	29.14	29.75	30.06	30.51	28.48	28.97	29.36	29.89	30.14	30.39	28.27	28.73	29.04	29.49	29.88	30.04
6210815	22.41	22.55	22.68	22.78	21.93	21.95	22.03	22.18	22.27	22.34	21.80	21.88	21.93	22.15	22.26	22.40
6210845	23.24	23.46	23.50	23.34	22.62	22.74	22.98	23.09	23.18	23.32	22.49	22.60	22.70	22.91	23.02	23.12
6210915	23.90	24.11	24.21	24.42	23.16	23.28	23.53	23.68	23.78	23.93	23.09	23.19	23.30	23.54	23.64	23.74
6210945	24.35	24.63	24.86	25.08	23.58	23.72	24.00	24.22	24.38	24.53	23.54	23.55	23.66	23.91	24.25	24.03
6211015	25.47	25.72	25.90	26.08	24.52	24.65	24.87	25.10	25.15	25.31	24.60	24.57	24.61	24.79	24.98	24.76
6211045	26.26	26.52	26.70	26.85	25.05	25.25	25.42	25.67	25.67	25.85	24.90	25.03	25.18	25.53	25.71	25.78
6211115	26.75	26.99	27.18	27.31	25.51	25.76	25.93	26.19	26.21	26.42	25.33	25.48	25.63	26.00	26.20	26.21
6211145	27.06	27.33	27.49	27.68	25.80	26.03	26.21	26.42	26.58	26.72	25.59	25.75	25.91	26.24	26.45	26.51
6211215	27.39	27.71	27.87	28.04	26.15	26.35	26.52	26.79	26.96	27.09	25.97	26.16	26.33	26.69	26.94	27.00
6211245	27.91	28.26	28.46	28.61	26.56	26.77	26.96	27.27	27.45	27.61	26.35	26.51	26.68	27.05	27.18	27.28
6211315	28.31	28.72	28.79	28.90	26.97	27.24	27.44	27.77	27.99	28.18	26.81	26.99	27.18	27.56	27.74	27.84
6211345	28.28	28.71	28.98	29.16	26.99	27.31	27.52	27.94	28.03	28.28	26.80	27.02	27.22	27.65	27.93	28.01
6211415	28.31	28.77	29.02	29.22	27.11	27.42	27.66	28.06	28.19	28.39	26.97	27.21	27.38	27.76	28.01	28.12
6250945	24.05	24.23	24.36	24.57	23.48	23.64	23.76	23.88	23.91	24.03	23.41	23.48	23.61	23.83	23.92	23.97
6251015	24.88	25.04	25.21	25.43	24.19	24.40	24.53	24.71	24.75	24.88	24.02	24.12	24.26	24.47	24.57	24.60
6251045	25.65	25.85	26.04	26.27	24.93	25.14	25.23	25.45	25.51	25.64	24.78	24.96	25.07	25.25	25.40	25.40
6251115	26.60	26.73	26.88	27.09	25.77	25.96	26.01	26.19	26.23	26.35	25.64	25.85	25.94	26.10	26.22	26.23
6251145	27.18	27.33	27.54	27.79	26.37	26.60	26.69	26.86	26.96	27.18	26.10	26.34	26.48	26.69	26.85	26.97
6251215	28.31	28.49	28.75	28.99	27.46	27.68	27.78	27.96	28.06	28.27	27.35	27.57	27.73	27.94	28.10	28.20
6251245	28.40	28.63	28.84	29.07	27.57	27.75	27.87	27.97	28.11	28.28	27.46	27.68	27.82	28.05	28.27	28.39
6251315	28.46	28.65	28.86	29.09	27.57	27.77	27.92	28.08	28.19	28.39	27.40	27.63	27.76	28.00	28.19	28.36

Table A-5. Air temperature and windspeed at Station 5 for June, 1976. Net radiation (Rn), soil heat flux (S) and wind direction (θ) are also shown.

	Air Temperature (C) Station 5						Windspeed ($m\ sec^{-1}$) Station 5							Rn	S	θ
Date	50 cm	75 cm	100 cm	150 cm	200 cm	250 cm	50 cm	75 cm	100 cm	1[illegible] cm	150 cm	200 cm	250 cm	(ly/min)	(ly/min)	(degrees)
6090845	22.75	22.85	22.95	23.15	23.19	23.22	3.07	4.09	4.76	5.17	5.59	6.08	6.61	0.55	-0.04	15.12
6090915	23.56	23.70	23.82	24.01	24.07	24.12	3.11	4.09	4.70	5.14	5.55	6.06	6.54	0.59	-0.05	19.67
6090945	24.61	24.72	24.87	25.04	25.09	25.15	3.03	4.03	4.67	5.12	5.48	6.02	6.46	0.71	-0.06	17.14
6091015	25.99	26.13	26.28	26.50	26.55	26.61	3.16	4.18	4.88	5.31	5.75	6.27	6.75	0.76	-0.06	16.26
6091045	26.07	26.26	26.38	26.61	26.65	26.71	2.98	3.92	4.59	4.96	5.39	5.85	6.30	0.81	-0.06	14.34
6091115	26.08	26.31	26.43	26.69	26.77	26.84	3.11	4.06	4.69	5.16	5.52	6.05	6.51	0.83	-0.06	12.31
6091145	26.66	26.90	27.04	27.29	27.45	27.54	3.46	4.54	5.34	5.79	6.29	6.81	7.41	0.88	-0.07	17.08
6091215	26.79	27.03	27.22	27.47	27.61	27.69	3.31	4.36	5.12	5.51	5.98	6.48	7.02	0.82	-0.07	22.88
6091245	26.83	27.07	27.15	27.49	27.62	27.68	3.17	4.16	4.83	5.28	5.68	6.23	6.77	0.58	-0.07	27.89
6091315	26.52	26.71	26.81	27.02	27.14	27.21	3.21	4.25	4.98	5.38	5.85	6.34	6.89	0.80	-0.06	21.22
6091345	27.61	27.82	27.93	28.19	28.29	28.44	3.29	4.37	5.04	5.52	5.91	6.49	7.00	0.84	-0.06	18.17
6091415	27.51	27.77	27.93	28.25	28.38	28.55	3.24	4.30	5.00	5.48	5.91	6.45	6.98	0.67	-0.05	22.85
6091445	28.29	28.56	28.78	29.09	29.26	29.39	3.11	4.13	4.72	5.20	5.56	6.10	6.57	0.76	-0.05	16.22
6091515	26.56	26.96	27.28	27.61	27.86	28.03	3.39	4.49	5.27	5.71	6.23	6.76	7.35	0.40	-0.04	17.64
6091545	27.09	27.46	27.72	27.96	28.17	28.30	3.16	4.21	4.87	5.34	5.73	6.29	6.77	0.34	-0.03	21.04
6091615	27.58	27.87	28.11	28.34	28.50	28.62	3.33	4.42	5.23	5.66	6.16	6.69	7.25	0.34	-0.02	8.76
6091645	26.73	27.07	27.34	27.71	27.94	28.09	3.48	4.63	5.37	5.91	6.37	7.01	7.58	0.31	-0.03	19.59
6100845	24.07	23.84	23.81	23.96	23.86	23.80	1.59	2.11	2.38	2.61	2.78	3.02	3.22	0.56	-0.05	18.63
6100915	25.70	25.52	25.45	25.60	25.49	25.44	1.74	2.35	2.67	2.91	3.12	3.40	3.63	0.63	-0.06	17.54
6100945	26.40	26.20	26.19	26.28	26.26	26.19	1.72	2.30	2.61	2.86	3.04	3.33	3.55	0.70	-0.06	20.40
6101015	26.62	26.51	26.54	26.64	26.64	26.65	1.56	2.09	2.37	2.58	2.75	3.03	3.24	0.73	-0.06	13.01
6101045	26.90	26.84	26.92	27.13	27.18	27.23	1.83	2.46	2.80	3.06	3.27	3.59	3.85	0.79	-0.07	19.30
6101115	28.17	28.17	28.28	28.54	28.60	28.72	1.97	2.64	3.01	3.32	3.56	3.92	4.20	0.83	-0.08	11.58
6101145	28.04	28.01	28.10	28.34	28.45	28.56	2.28	3.10	3.57	3.94	4.22	4.63	4.99	0.83	-0.08	18.89
6101215	28.05	28.05	28.15	28.38	28.48	28.60	2.13	2.89	3.35	3.67	3.95	4.32	4.64	0.84	-0.08	14.45
6101245	28.52	28.63	28.79	28.93	29.03	29.13	1.98	2.72	3.12	3.44	3.68	4.04	4.32	0.83	-0.10	18.75
6101315	28.91	29.10	29.22	29.47	29.64	29.77	2.00	2.77	3.18	3.52	3.76	4.16	4.48	0.80	-0.07	16.52
6101345	29.02	29.23	29.35	29.68	29.87	29.99	2.12	2.91	3.36	3.71	3.98	4.39	4.74	0.77	-0.06	22.33
6101415	28.60	28.79	28.92	29.25	29.43	29.53	2.12	2.94	3.43	3.75	4.05	4.43	4.76	0.72	-0.06	20.87
6101445	28.95	29.22	29.45	29.87	30.12	30.28	2.07	2.90	3.36	3.69	3.97	4.37	4.71	0.67	-0.06	19.64
6101515	28.96	29.32	29.64	30.10	30.38	30.57	2.12	2.94	3.43	3.77	4.07	4.49	4.83	0.59	-0.06	16.03
6101545	28.74	29.14	29.46	29.87	30.14	30.35	2.30	3.18	3.69	4.07	4.37	4.82	5.17	0.52	-0.04	25.97
6101615	28.34	28.74	29.05	29.46	29.71	29.88	2.27	3.17	3.69	4.05	4.35	4.81	5.17	0.43	-0.03	12.16
6101645	28.34	28.79	29.20	29.68	30.05	30.26	2.42	3.37	3.92	4.31	4.64	5.11	5.50	0.35	-0.03	23.10
	75 cm	100 cm	125 cm	175 cm	225 cm	275 cm	75 cm	100 cm	125 cm	150 cm	175 cm	225 cm	275 cm			
6130845	25.78	25.68	25.85	26.04	26.21	26.21	1.55	1.82	1.91	1.90	2.21	2.38	2.52	0.52	-0.05	9.87
6130915	26.51	26.41	26.51	26.79	26.86	26.89	1.45	1.68	1.77	1.64	2.03	2.17	2.30	0.56	-0.06	13.20
6130945	26.67	26.69	26.86	27.25	27.45	27.68	1.96	2.29	2.51	2.52	2.85	3.05	3.24	0.64	-0.07	51.45
6131015	27.23	27.23	27.36	27.70	27.83	27.99	2.05	2.37	2.61	2.67	2.97	3.20	3.38	0.60	-0.06	33.10
6131045	28.95	28.88	28.99	29.23	29.32	29.34	2.25	2.64	2.88	2.94	3.28	3.53	3.74	0.83	-0.08	32.00
6131115	28.96	28.88	28.96	29.17	29.23	29.25	2.29	2.65	2.93	2.97	3.33	3.59	3.81	0.69	-0.08	25.51
6131145	28.36	28.35	28.41	28.76	28.93	29.08	2.65	3.13	3.41	3.57	3.90	4.23	4.46	0.66	-0.08	23.32
6131215	28.45	28.43	28.51	28.87	29.06	29.24	2.77	3.26	3.59	3.73	4.09	4.42	4.69	0.70	-0.08	25.77
6131245	29.17	29.32	29.50	29.66	29.75	29.90	2.87	3.30	3.71	3.81	4.22	4.53	4.88	0.87	-0.08	19.54
6131315	28.86	29.08	29.29	29.59	29.76	29.97	2.59	3.02	3.31	3.41	3.76	4.07	4.35	0.43	-0.06	19.36
6131345	28.27	28.70	29.07	29.44	29.66	29.93	3.07	3.57	3.91	4.10	4.48	4.83	5.16	0.26	-0.05	19.67
6210815	21.68	21.77	21.89	22.09	22.18	22.28	2.72	3.23	3.66	3.95	4.23	4.59	4.88	0.49	-0.03	16.67
6210845	22.37	22.52	22.71	22.92	23.07	23.18	2.85	3.46	3.92	4.23	4.55	4.95	5.27	0.57	-0.03	31.94
6210915	22.96	23.13	23.31	23.58	23.72	23.84	3.00	3.57	4.12	4.40	4.77	5.17	5.54	0.64	-0.04	23.23
6210945	23.27	23.41	23.64	24.01	24.13	24.33	3.12	3.73	4.25	4.61	4.94	5.36	5.72	0.70	-0.05	22.22
6211015	24.16	24.26	24.41	24.73	24.83	24.96	3.33	4.01	4.63	4.97	5.40	5.82	6.31	0.77	-0.06	9.37
6211045	24.82	25.01	25.20	25.44	25.60	25.72	3.26	3.95	4.52	4.87	5.24	5.69	6.07	0.81	-0.07	18.80
6211115	25.20	25.42	25.58	25.84	25.97	26.10	3.27	3.95	4.51	4.86	5.23	5.66	6.07	0.84	-0.08	24.35
6211145	25.48	25.68	25.82	26.13	26.23	26.31	3.62	4.42	5.05	5.44	5.86	6.33	6.84	0.86	-0.11	25.13
6211215	25.83	26.01	26.17	26.49	26.60	26.73	3.58	4.33	5.00	5.37	5.81	6.26	6.81	0.87	-0.13	40.18
6211245	26.26	26.47	26.71	27.07	27.16	27.35	3.35	4.04	4.62	4.97	5.36	5.78	6.25	0.86	-0.14	34.41
6211315	26.74	27.00	27.28	27.68	27.81	27.97	3.27	3.91	4.50	4.82	5.20	5.63	6.06	0.83	-0.09	17.15
6211345	26.86	27.13	27.37	27.85	27.97	28.13	3.26	3.93	4.52	4.84	5.24	5.65	6.06	0.80	-0.07	25.35
6211415	26.76	27.04	27.31	27.78	27.99	28.17	3.25	3.93	4.49	4.84	5.24	5.68	6.15	0.70	-0.06	27.60
6250945	23.32	23.35	23.40	23.57	23.70	23.81	3.29	4.00	4.56	4.95	5.39	5.88	6.34	0.73	-0.06	23.73
6251015	23.90	23.98	24.04	24.25	24.38	24.49	3.60	4.39	5.04	5.41	5.87	6.42	6.91	0.79	-0.08	22.52
6251045	24.66	24.82	24.92	25.14	25.26	25.36	3.65	4.41	5.07	5.42	5.94	6.41	6.93	0.82	-0.08	26.57
6251115	25.50	25.64	25.74	25.96	26.08	26.15	3.99	4.94	5.67	6.06	6.61	7.16	7.75	0.85	-0.08	21.99
6251145	25.85	26.03	26.12	26.38	26.55	26.62	4.42	5.43	6.25	6.69	7.30	7.84	8.53	0.87	-0.08	27.42
6251215	27.14	27.32	27.42	27.67	27.82	27.90	4.16	5.07	5.80	6.22	6.76	7.32	7.90	0.87	-0.08	31.54
6251245	27.27	27.45	27.57	27.81	27.97	28.09	4.19	5.15	5.88	6.32	6.89	7.38	8.04	0.86	-0.08	22.78
6251315	27.23	27.43	27.57	27.77	27.91	28.02	4.02	4.97	5.63	6.06	6.55	7.11	7.68	0.83	-0.08	35.31

Table A-6. Vapor pressure at Stations 1, 3 and 4 for June, 1976.

	Vapor Pressure (mbar)															
	Station 1				Station 3						Station 4					
Date	50 cm	75 cm	100 cm	150 cm	50 cm	75 cm	100 cm	150 cm	200 cm	250 cm	50 cm	75 cm	100 cm	150 cm	200 cm	250 cm
6090845	18.78	18.23	17.84	17.51	18.94	18.59	18.57	18.17	17.94	17.89	19.24	18.63	18.41	18.07	18.03	18.00
6090915	19.56	19.02	18.62	18.26	19.70	19.33	19.27	18.79	18.52	18.39	20.03	19.39	19.18	18.84	18.71	18.67
6090945	20.66	20.00	19.61	19.06	20.99	20.50	20.26	19.67	19.32	19.05	21.10	20.41	20.08	19.65	19.32	19.28
6091015	21.75	21.09	20.61	19.97	22.38	21.82	21.53	20.93	20.58	20.23	22.56	21.82	21.37	20.81	20.41	20.26
6091045	21.67	20.89	20.44	19.80	22.04	21.45	21.04	20.33	19.90	19.52	21.92	21.09	20.48	19.72	19.22	18.90
6091115	21.05	20.28	19.88	19.19	21.31	20.75	20.33	19.69	19.37	19.19	21.60	20.70	20.14	19.44	18.92	18.66
6091145	21.18	20.51	20.19	19.62	21.66	21.17	20.76	20.08	19.76	19.51	21.92	21.13	20.78	20.39	19.93	19.68
6091215	20.84	20.33	19.96	19.40	21.72	21.17	20.63	19.94	19.63	19.41	21.97	21.15	20.74	20.26	19.88	19.63
6091245	21.47	20.65	19.93	19.03	22.33	21.77	20.99	20.27	20.00	19.92	22.38	21.96	21.26	20.34	19.90	19.59
6091315	20.60	19.72	18.97	18.13	21.44	20.81	20.10	19.40	19.00	18.79	21.52	20.81	20.21	19.46	19.16	18.60
6091345	22.09	21.00	20.37	19.80	22.71	21.96	21.40	20.65	20.19	19.88	22.61	21.52	21.07	20.57	19.84	19.46
6091415	21.38	20.43	19.90	19.35	22.04	21.33	20.82	20.19	19.80	19.51	22.18	21.15	20.81	20.35	19.65	19.37
6091445	21.99	21.08	20.66	19.96	22.54	22.00	21.62	21.01	20.54	20.31	22.65	21.85	21.71	21.25	20.84	20.57
6091515	20.15	19.35	19.03	18.45	20.67	20.28	20.00	19.49	19.11	18.97	20.52	19.90	19.89	19.57	19.26	19.01
6091545	20.52	19.88	19.47	18.94	21.26	20.84	20.29	19.63	19.22	18.96	21.34	20.70	20.36	20.00	19.53	19.18
6091615	21.05	20.40	20.00	19.46	21.62	21.17	20.67	20.09	19.69	19.44	21.78	21.20	20.79	20.44	19.97	19.65
6091645	19.35	18.67	18.38	17.98	20.22	19.91	19.66	19.34	19.13	18.84	20.48	20.07	19.72	19.29	18.96	18.85
6100845	23.36	22.42	21.86	20.99	25.16	24.65	24.47	23.96	23.74	23.52	23.57	22.54	22.13	21.26	21.03	20.93
6100915	25.35	24.30	23.67	22.71	25.42	24.57	24.25	23.45	23.00	22.67	25.46	24.42	24.00	23.29	22.93	22.72
6100945	25.91	24.89	24.43	23.34	25.83	25.02	24.65	23.72	22.94	22.43	25.88	24.85	24.58	24.10	23.61	23.38
6101015	25.03	24.00	23.23	22.24	24.93	24.00	23.40	22.48	21.81	21.36	25.17	24.16	23.86	23.32	22.77	22.42
6101045	25.03	23.73	22.80	21.90	25.27	24.17	23.77	22.94	22.48	22.20	25.61	24.42	23.96	23.27	22.67	22.16
6101115	26.24	24.94	24.06	23.16	26.90	25.83	25.11	24.08	23.48	23.28	27.31	26.12	25.68	24.78	24.14	23.63
6101145	26.07	24.83	24.32	23.28	26.62	25.77	25.02	24.01	23.43	23.12	26.92	25.85	25.17	23.82	23.09	22.96
6101215	26.48	25.12	24.47	23.34	26.04	25.16	24.40	23.35	22.83	22.37	26.63	25.60	24.96	23.86	23.22	22.92
6101245	26.15	24.99	24.28	23.43	26.55	25.65	25.09	24.02	23.45	22.98	27.16	25.94	25.55	24.92	24.42	23.79
6101315	25.99	24.67	23.93	23.05	26.82	25.94	25.36	24.32	23.71	23.08	27.54	26.33	25.96	25.17	24.46	23.93
6101345	25.91	24.60	23.87	22.62	26.58	25.72	25.11	24.06	23.41	22.83	26.76	25.55	24.81	23.68	22.66	22.15
6101415	24.63	23.21	22.48	21.24	24.88	23.97	23.27	22.11	21.39	20.84	25.16	23.97	23.13	22.08	21.05	20.44
6101445	24.26	22.90	22.12	20.98	25.01	23.98	23.43	22.23	21.54	21.09	25.69	24.28	23.65	22.91	22.18	21.58
6101515	24.02	22.79	22.08	21.07	25.18	24.23	23.81	22.83	22.14	21.79	25.25	24.18	23.61	22.85	22.20	21.78
6101545	24.21	23.09	22.45	21.57	25.19	24.30	23.69	22.86	22.46	22.20	24.67	23.79	23.24	22.42	21.81	21.55
6101615	23.45	22.41	21.77	20.96	23.91	23.04	22.55	21.82	21.43	21.11	23.94	23.12	22.58	21.91	21.48	21.09
6101645	22.55	22.03	21.50	21.07	23.15	22.53	22.12	21.67	21.20	20.93	23.49	22.97	22.71	22.47	22.11	21.82
	75 cm	100 cm	125 cm	175 cm	75 cm	100 cm	125 cm	175 cm	225 cm	275 cm	75 cm	100 cm	125 cm	175 cm	225 cm	275 cm
6130845	21.60	20.62	19.77	18.86	21.71	21.20	20.52	19.60	19.28	19.01	22.16	21.65	21.07	20.50	19.96	20.25
6130915	20.73	19.61	18.69	17.69	21.24	20.51	19.76	18.70	18.23	17.86	21.39	20.65	19.95	19.09	18.57	18.71
6130945	18.68	17.80	17.15	16.60	19.18	18.46	17.86	16.99	16.50	16.17	19.71	18.92	18.01	17.18	16.45	16.58
6131015	20.85	19.96	19.46	18.77	21.56	20.66	20.12	19.25	18.72	18.40	21.70	21.01	20.19	19.42	18.71	18.76
6131045	24.03	23.14	22.42	21.76	24.76	23.92	23.02	21.95	21.52	20.97	25.30	24.64	23.93	22.96	22.10	21.68
6131115	25.47	24.47	23.82	23.37	25.97	25.31	24.47	23.40	22.99	22.50	26.37	25.65	25.04	24.18	23.38	23.00
6131145	24.82	24.07	23.71	23.51	25.55	24.94	24.35	23.65	23.42	23.21	26.04	25.53	24.90	24.25	23.86	23.68
6131215	24.92	24.27	23.99	23.79	25.80	25.19	24.67	24.02	23.84	23.69	25.91	25.53	24.92	24.34	23.98	23.63
6131245	26.21	25.46	25.17	24.79	26.63	25.86	25.34	24.76	24.38	24.06	26.96	26.36	25.73	24.91	23.78	23.07
6131315	25.39	24.75	24.58	24.14	25.99	25.30	24.80	24.46	24.14	23.94	26.07	25.60	25.11	24.49	23.58	22.93
6131345	23.06	22.61	22.39	21.94	23.99	23.42	22.91	22.57	22.26	22.06	24.34	23.86	23.61	23.15	22.75	22.43
6210815	13.49	13.15	12.69	12.40	14.19	13.75	13.37	12.90	12.84	12.67	14.54	14.10	13.79	13.29	13.02	12.73
6210845	13.73	13.11	12.80	12.71	14.33	13.81	13.31	12.80	12.72	12.48	14.78	14.28	13.75	13.27	13.02	12.69
6210915	13.45	12.91	12.56	12.15	14.54	14.04	13.47	12.98	12.83	12.58	14.81	14.33	13.85	13.33	13.09	12.84
6210945	13.25	12.66	12.21	12.01	14.20	13.76	13.26	12.71	12.52	12.28	14.21	13.95	13.73	13.27	13.60	12.93
6211015	13.43	12.84	12.36	11.98	14.58	14.04	13.51	12.91	12.62	12.36	13.80	13.65	13.51	13.18	13.79	12.63
6211045	13.44	12.89	12.46	11.86	14.56	14.03	13.64	12.96	12.79	12.43	14.64	14.12	13.70	12.94	12.46	12.25
6211115	13.53	12.99	12.57	11.96	14.74	14.17	13.78	13.15	12.94	12.57	15.09	14.54	14.07	13.24	12.73	12.58
6211145	13.79	13.09	12.67	12.27	15.03	14.36	13.83	13.18	12.84	12.41	15.11	14.56	14.04	13.28	12.84	12.69
6211215	13.97	13.27	12.87	12.50	15.32	14.74	14.26	13.72	13.34	12.96	15.61	15.09	14.66	13.92	13.48	13.23
6211245	14.25	13.59	13.22	12.91	15.63	15.07	14.66	14.22	13.92	13.57	15.78	15.21	14.76	14.05	13.68	13.28
6211315	14.61	14.00	13.55	13.30	16.18	15.59	15.17	14.63	14.23	13.88	16.30	15.73	15.33	14.63	14.17	13.77
6211345	14.95	14.22	13.65	13.25	15.83	15.18	14.78	14.04	13.77	13.39	16.10	15.52	15.05	14.38	13.84	13.70
6211415	15.05	14.28	13.69	13.30	16.13	15.48	15.03	14.33	14.02	13.60	15.89	15.37	14.94	14.37	13.91	13.89
6250945	15.88	15.26	14.97	14.49	16.28	15.78	15.45	15.05	14.63	14.38	16.57	16.15	15.69	15.28	15.00	14.85
6251015	16.14	15.58	15.24	14.62	16.44	15.87	15.60	15.13	14.71	14.49	16.67	16.15	15.65	15.23	14.89	14.78
6251045	16.35	16.09	15.73	15.11	16.65	16.11	15.89	15.40	15.01	14.80	17.15	16.68	16.19	15.70	15.28	15.22
6251115	16.61	16.33	15.95	15.29	16.97	16.49	16.25	15.73	15.33	15.08	17.13	16.61	16.14	15.67	15.25	15.13
6251145	16.46	16.15	15.82	15.25	17.07	16.66	16.35	15.92	15.58	15.27	16.97	16.48	16.18	15.77	15.44	15.35
6251215	17.54	17.25	16.88	16.27	17.96	17.51	17.25	16.76	16.46	16.14	18.35	17.83	17.51	17.04	16.72	16.54
6251245	17.08	16.84	16.50	15.95	17.63	17.28	17.06	16.63	16.30	16.08	18.33	17.84	17.45	16.95	16.57	16.23
6251315	16.79	16.53	16.23	15.66	17.62	17.24	16.97	16.51	16.19	15.97	18.27	17.71	17.36	16.85	16.50	16.15

Table A-7. Vapor pressure at Station 5 for June, 1976.

Date	Vapor Pressure (mbar) Station 5					
	50 cm	75 cm	100 cm	150 cm	200 cm	250 cm
6090845	18.61	18.16	17.87	17.60	17.36	17.14
6090915	19.73	19.21	18.97	18.70	18.42	18.23
6090945	20.95	20.25	19.80	19.52	19.16	19.10
6091015	22.28	21.49	21.00	20.66	20.39	20.17
6091045	21.48	20.63	20.08	19.49	19.21	18.87
6091115	21.09	20.28	19.81	19.22	18.98	18.63
6091145	21.48	20.85	20.41	19.91	19.49	19.26
6091215	21.48	20.87	20.41	19.90	19.55	19.22
6091245	21.79	20.96	20.40	19.89	19.52	19.32
6091315	20.89	20.08	19.55	18.96	18.44	18.08
6091345	22.07	21.33	20.83	20.12	19.50	18.91
6091415	21.88	21.15	20.64	19.90	19.30	18.84
6091445	22.37	21.69	21.29	20.88	20.40	20.29
6091515	20.47	19.93	19.63	19.36	18.97	18.87
6091545	21.25	20.72	20.29	20.01	19.76	19.33
6091615	21.39	20.93	20.52	20.16	19.90	19.48
6091645	20.03	19.53	19.31	18.93	18.76	18.56
6100845	22.99	22.36	21.75	21.00	20.49	20.27
6100915	24.89	23.98	23.43	22.54	21.99	21.68
6100945	25.99	25.00	24.29	23.35	22.63	22.23
6101015	25.28	24.29	23.60	22.59	21.95	21.42
6101045	25.00	23.97	23.22	22.52	22.15	21.64
6101115	26.75	25.74	25.05	24.30	23.97	23.39
6101145	26.66	25.72	24.91	24.02	23.44	22.84
6101215	26.32	25.34	24.58	23.56	22.91	22.21
6101245	26.98	25.84	25.09	23.97	23.26	22.57
6101315	27.12	25.86	25.16	24.03	23.31	22.72
6101345	26.48	25.47	24.96	24.00	23.50	23.12
6101415	24.67	23.64	23.02	22.02	21.45	20.93
6101445	25.30	24.29	23.58	22.65	21.92	21.41
6101515	25.03	24.06	23.34	22.60	21.99	21.54
6101545	24.27	23.32	22.78	22.31	21.76	21.30
6101615	23.58	22.69	22.21	21.69	21.14	20.71
6101645	22.85	22.26	21.87	21.49	20.96	20.66
	75 cm	100 cm	125 cm	175 cm	225 cm	275 cm
6130845	21.82	21.03	20.34	19.34	18.73	18.60
6130915	21.62	20.78	20.06	18.84	18.30	17.82
6130945	19.27	18.47	17.89	16.88	16.54	15.84
6131015	21.28	20.47	19.94	19.04	18.77	18.18
6131045	24.86	23.82	23.10	22.32	21.95	21.80
6131115	26.21	25.27	24.54	23.82	23.31	23.05
6131145	25.96	25.34	24.92	24.27	23.62	23.43
6131215	25.98	25.41	25.01	24.44	23.84	23.63
6131245	26.50	25.80	25.22	24.55	24.24	23.73
6131315	25.81	25.33	25.01	24.45	24.24	23.72
6131345	24.51	24.16	23.88	23.36	23.12	22.59
6210815	14.25	13.77	13.51	13.11	12.92	12.73
6210845	14.52	14.00	13.54	13.08	12.70	12.35
6210915	14.52	13.98	13.55	13.01	12.66	12.36
6210945	13.97	13.59	13.27	12.78	12.52	12.34
6211015	14.48	14.05	13.68	13.14	12.78	12.42
6211045	14.48	13.88	13.38	12.88	12.40	11.94
6211115	14.66	14.04	13.57	13.03	12.56	12.10
6211145	14.65	14.05	13.64	12.87	12.44	12.13
6211215	14.93	14.34	13.92	13.25	12.85	12.48
6211245	15.02	14.45	14.02	13.51	13.18	12.76
6211315	15.81	15.20	14.69	14.12	13.75	13.28
6211345	15.75	15.06	14.55	13.76	13.39	13.02
6211415	15.47	14.83	14.35	13.62	13.20	12.84
6250945	16.39	15.96	15.60	15.20	14.85	14.59
6251015	16.49	16.09	15.69	15.28	14.99	14.63
6251045	16.92	16.43	16.03	15.59	15.21	14.85
6251115	16.97	16.48	16.09	15.62	15.24	14.88
6251145	16.79	16.36	16.03	15.56	15.17	14.88
6251215	18.03	17.56	17.22	16.73	16.34	16.03
6251245	17.88	17.49	17.11	16.66	16.08	15.66
6251315	17.87	17.47	17.10	16.70	16.25	15.86

Table A-8. Vapor pressure at Stations 1, 2 and 3 for July 10, 1976.

Date	Vapor Pressure (mbar) Station 1 50 cm	75 cm	100 cm	150 cm	Station 2 50 cm	75 cm	100 cm	150 cm	Station 3 50 cm	75 cm	100 cm	150 cm	200 cm	250 cm
7101007	23.67	23.16	22.84	22.32	25.06	24.48	24.17	24.51	25.30	24.63	24.26	23.67	23.23	22.97
7101022	23.64	23.12	22.78	22.28	24.91	24.32	23.96	24.06	25.27	24.58	24.17	23.56	23.11	22.83
7101037	24.08	23.43	23.07	22.46	25.00	24.35	23.93	23.01	24.91	24.19	23.78	23.12	22.69	22.35
7101107	23.60	23.08	22.67	22.16	24.89	24.24	23.82	24.31	25.23	24.52	24.09	23.40	22.94	22.66
7101122	23.32	22.89	22.40	21.91	24.53	23.87	23.39	33.94	24.91	24.18	23.78	23.12	22.62	22.34
7101137	23.03	22.38	22.32	21.95	24.15	23.55	23.07	41.55	24.65	23.98	23.55	22.98	22.47	22.17
7101207	22.99	22.59	22.03	21.51	24.25	23.60	23.15	22.52	24.69	23.94	23.45	22.74	22.20	21.89
7101222	23.57	23.04	22.51	21.96	24.55	23.83	23.37	22.72	25.29	24.48	23.97	23.29	22.71	22.39
7101237	23.31	22.66	22.29	21.79	24.62	23.91	23.52	22.89	25.22	24.45	23.94	23.26	22.79	22.45
7101307	23.36	22.74	22.28	21.74	24.55	23.77	23.32	22.68	25.06	24.26	23.70	23.02	22.53	22.18
7101322	23.09	22.49	22.07	21.56	24.29	23.58	23.17	22.57	24.80	24.04	23.52	22.79	22.34	22.01
7101337	23.31	22.65	22.28	21.71	24.33	23.65	23.26	22.63	24.75	24.03	23.50	22.71	22.20	21.79
7101407	23.39	22.78	22.42	21.91	24.81	24.10	23.66	23.06	25.27	24.56	23.99	23.23	22.72	22.38
7101422	21.77	21.19	20.92	20.46	25.03	24.38	24.01	23.43	25.48	24.80	24.26	23.58	23.09	22.81
7101437	22.40	21.79	21.46	20.94	25.44	24.76	24.33	23.69	25.83	25.10	24.52	23.78	23.28	23.02
7101507	22.04	21.45	21.14	20.63	25.05	24.40	24.01	23.47	25.50	24.82	24.28	23.60	23.12	22.87

Table A-9. Vapor pressure at Stations 4 and 5 and air temperature at Station 1 for July 10, 1976.

Date	Vapor Pressure (mbar) Station 4 50 cm	75 cm	100 cm	150 cm	200 cm	250 cm	Station 5 50 cm	75 cm	100 cm	150 cm	200 cm	250 cm	Air Temperature (C) Station 1 50 cm	75 cm	100 cm	150 cm
7101007	25.15	24.58	24.22	23.72	23.38	23.11	25.24	24.61	24.21	23.70	23.32	23.09	32.15	32.19	32.18	32.26
7101022	25.12	24.51	24.09	23.53	23.16	22.90	25.30	24.68	24.27	23.71	23.31	23.05	32.52	32.57	32.58	32.66
7101037	25.03	24.42	23.97	23.38	22.95	22.67	24.94	24.26	23.82	23.20	22.77	22.48	32.86	32.89	32.89	32.92
7101107	24.95	24.29	23.85	23.22	22.89	22.58	25.06	24.39	23.95	23.36	22.94	22.65	33.54	33.62	33.62	33.66
7101122	24.34	23.75	23.32	22.68	22.31	22.03	24.82	24.10	23.67	23.04	22.60	22.31	33.71	33.84	33.82	33.86
7101137	24.38	23.79	23.34	22.63	22.10	21.84	24.63	23.86	23.51	22.91	22.52	22.25	33.82	33.96	33.89	33.91
7101207	24.76	24.08	23.56	25.01	24.70	24.21	24.71	23.91	23.50	22.87	22.47	22.19	34.30	34.46	34.41	34.43
7101222	25.09	24.37	23.83	23.17	22.84	22.36	25.32	24.49	24.03	23.38	22.96	22.65	34.59	34.73	34.73	34.78
7101237	24.68	24.02	23.52	21.27	20.69	20.41	24.81	24.05	23.58	22.97	22.53	22.27	34.79	34.91	34.98	35.01
7101307	25.03	24.29	23.75	25.05	24.83	24.25	24.96	24.15	23.68	23.06	22.63	22.31	35.22	35.38	35.46	35.50
7101322	24.53	23.87	23.53	24.59	24.37	23.73	24.85	24.01	23.54	22.91	22.47	22.14	35.34	35.49	35.55	35.61
7101337	24.52	23.83	23.31	24.40	23.92	23.56	25.05	24.11	23.70	22.98	22.56	22.27	35.38	35.53	35.60	35.65
7101407	25.24	24.58	24.08	23.52	23.22	22.70	25.33	24.40	23.96	23.25	22.83	22.51	35.48	35.62	35.69	35.76
7101422	25.33	24.70	24.22	23.70	23.46	22.93	25.27	24.35	23.97	23.33	22.98	22.73	35.51	35.70	35.78	35.85
7101437	25.52	24.85	24.29	23.66	23.34	22.86	25.79	24.87	24.43	23.75	23.37	23.02	35.56	35.74	35.82	35.93
7101507	25.38	24.69	24.16	23.57	23.39	22.85	25.34	24.42	24.01	23.39	23.06	22.74	35.40	35.63	35.72	35.83

Table A-10. Air temperature at Stations 2, 3 and 4 for July 10, 1976.

Date	Air Temperature (C) Station 2 50 cm	75 cm	100 cm	150 cm	Station 3 50 cm	75 cm	100 cm	150 cm	200 cm	250 cm	Station 4 50 cm	75 cm	100 cm	150 cm	200 cm	250 cm
7101007	31.46	31.59	31.69	31.85	30.93	31.24	31.24	31.57	31.50	31.63	30.91	30.96	31.02	31.21	31.29	31.35
7101022	31.78	31.94	32.04	32.18	31.22	31.54	31.56	31.88	31.85	31.98	31.10	31.19	31.28	31.50	31.57	31.62
7101037	32.02	32.14	32.22	32.44	31.34	31.65	31.68	31.97	31.94	32.03	31.47	31.57	31.62	31.85	31.87	31.93
7101107	32.70	32.93	33.04	33.20	32.06	32.41	32.48	32.78	32.77	32.92	32.08	32.26	32.37	32.56	32.64	32.70
7101122	32.95	33.21	33.28	33.48	32.28	32.69	32.71	33.03	33.05	33.22	32.36	32.57	32.67	32.97	33.07	33.12
7101137	33.14	33.35	33.45	33.66	32.47	32.89	32.93	33.23	33.31	33.50	32.60	32.87	32.96	33.47	33.59	33.67
7101207	33.48	33.76	33.91	34.14	32.84	33.18	33.30	33.55	33.68	33.84	32.82	33.05	33.17	30.38	30.49	30.59
7101222	33.75	34.01	34.16	34.40	33.06	33.40	33.56	33.82	33.93	34.10	33.19	33.41	33.51	33.87	33.98	34.09
7101237	33.96	34.26	34.47	34.71	33.25	33.63	33.80	34.10	34.22	34.39	33.03	33.25	33.44	36.18	36.37	36.49
7101307	34.29	34.63	34.85	35.09	33.54	33.98	34.16	34.47	34.63	34.80	33.38	33.64	33.85	31.11	31.29	31.41
7101322	34.44	34.76	34.96	35.24	33.71	34.14	34.34	34.67	34.81	34.97	33.57	33.86	33.80	31.47	31.64	31.75
7101337	34.45	34.78	34.98	35.24	33.74	34.18	34.37	34.73	34.90	35.07	33.61	33.91	34.09	31.78	31.99	32.09
7101407	34.53	34.92	35.17	35.42	33.87	34.34	34.55	34.96	35.15	35.34	33.72	34.01	34.25	34.53	34.76	34.89
7101422	34.66	35.05	35.29	35.59	33.88	34.38	34.63	35.02	35.18	35.39	33.78	34.12	34.32	34.61	34.84	35.03
7101437	34.66	35.00	35.20	35.54	33.96	34.43	34.69	35.05	35.18	35.37	33.81	34.16	34.37	34.67	34.87	35.05
7101507	34.62	34.98	35.18	35.51	33.92	34.41	34.64	35.06	35.19	35.39	33.85	34.22	34.44	34.74	34.95	35.12

Table A-11. Air temperature and windspeed at Station 5 for July 10, 1976. Net radiation (Rn), soil heat flux (S) and wind direction (θ) are also shown.

Date	Air Temperature (C) Station 5 50 cm	75 cm	100 cm	150 cm	200 cm	250 cm	Windspeed (m sec^{-1}) Station 5 50 cm	75 cm	100 cm	125 cm	150 cm	200 cm	250 cm	Rn (ly/min)	S (ly/min)	θ (degrees)
7101007	30.74	30.91	30.94	31.11	31.15	31.18	3.58	4.23	4.63	4.93	5.26	5.67	5.80	0.81	-0.11	10.00
7101022	30.98	31.16	31.19	31.38	31.44	31.47	3.52	4.22	4.60	4.92	5.21	5.65	5.72	0.83	-0.12	10.00
7101037	31.29	31.49	31.53	31.71	31.79	31.82	3.51	4.14	4.52	4.83	5.07	5.44	5.57	0.85	-0.13	999.99
7101107	31.90	32.14	32.23	32.44	32.54	32.59	3.90	4.68	5.04	5.46	5.74	6.21	6.22	0.89	-0.17	10.00
7101122	32.23	32.49	32.57	32.82	32.93	33.01	3.87	4.68	5.01	5.51	5.73	6.28	6.29	0.90	-0.17	10.00
7101137	32.47	32.75	32.84	33.09	33.20	33.29	4.00	4.79	5.17	5.64	5.88	6.43	6.41	0.90	-0.18	10.00
7101207	32.62	32.91	33.01	33.28	33.39	33.48	4.05	4.83	5.31	5.67	6.02	6.47	6.52	0.90	-0.19	10.00
7101222	32.93	33.22	33.33	33.62	33.72	33.81	3.56	4.27	4.60	5.00	5.24	5.70	5.77	0.90	-0.18	10.00
7101237	32.79	33.11	33.22	33.49	33.68	33.77	4.09	4.87	5.34	5.71	6.06	6.52	6.58	0.89	-0.17	10.00
7101307	33.31	33.65	33.78	34.06	34.23	34.34	3.93	4.73	5.12	5.55	5.82	6.33	6.32	0.87	-0.16	10.00
7101322	33.29	33.65	33.81	34.13	34.31	34.41	3.87	4.68	5.08	5.50	5.80	6.32	6.39	0.86	-0.15	10.00
7101337	33.39	33.79	34.00	34.34	34.51	34.62	4.22	5.03	5.48	5.92	6.22	6.75	6.73	0.83	-0.14	10.00
7101407	33.54	33.91	34.10	34.42	34.60	34.71	4.26	5.17	5.61	6.10	6.41	6.98	6.91	0.78	-0.12	10.00
7101422	33.52	33.93	34.16	34.51	34.68	34.79	4.24	5.18	5.61	6.12	6.40	7.02	6.91	0.76	-0.11	999.99
7101437	33.61	34.00	34.23	34.57	34.71	34.83	3.93	4.72	5.13	5.53	5.81	6.28	6.36	0.72	-0.10	10.00
7101507	33.66	34.07	34.32	34.65	34.81	34.92	3.88	4.68	5.04	5.46	5.71	6.17	6.19	0.65	-0.08	10.00