# Local and Regional Components of Sensible Heat Advection[1]

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## ABSTRACT

Detailed knowledge of the advection of sensible heat is necessary to understand the energy balance of the evaporating surface in many parts of the world. Sensible heat advection can result from regional and/or local sources. The local and regional components of sensible heat advection ($A_{\rm loc}$ and $A_{\rm reg}$, respectively) are identified and their magnitudes in a semi-arid to sub-humid zone are established in the work reported here. Measurements of dry- and wet-bulb air temperature, wind speed and net radiation were made above an irrigated alfalfa field with relatively dry surroundings upwind at Mead, NE. A modified Bowen ratio-energy balance method which incorporates horizontal gradients of air temperature and vapor pressure was used to compute evapotranspiration (ET) rates.

Sensible heat advection at the furthest upwind location in the irrigated field contributed from 15 to 50% of the energy consumed in ET on a daily basis. $A_{\rm reg}$ was greatest on days with strong winds; $A_{\rm loc}$ was independent of wind speed. The dryer the air, the greater the advection of sensible heat.

## 1. Introduction

Energy consumed in evapotranspiration (ET) by a vegetated surface is provided mainly by net radiation ($Rn$) and, in certain areas, by the advection of sensible heat ($A$). Net radiation generally provides an upper limit for ET in humid regions. In sub-humid and semi-arid regions, however, ET by well-watered crops frequently exceeds the energy content of the net radiation by a factor of 2 or more (Rosenberg, 1969a,b; Rosenberg and Verma, 1978). In parts of Australia regional sensible heat advection has been reported to cause ET rates twice as great as the available net radiant flux density would permit (McIlroy and Angus, 1964).

Local advection occurs when wind blows across a surface which is discontinuous in temperature, humidity or roughness (as from a dry field to an adjacent wetter field). Rider *et al.* (1963), Dyer and Crawford (1965), Goltz and Pruitt (1970) and others have shown that local advection results in increased ET immediately downwind from a leading edge. As the distance from the leading edge (fetch) increases, the influence of local advection on ET decreases until, finally, horizontal homogeneity is established.

It is important to determine the relative magnitudes of the local and regional components of sensible heat advection (hereafter $A_{\rm loc}$ and $A_{\rm reg}$, respectively) in order to clearly understand the significance of sensible heat advection and its effects on the energy balance of a vegetated land surface. $A_{\rm loc}$ and $A_{\rm reg}$ may be quantified when the ET rates, the net radiation and soil heat flux are known for the surface under study.

The Bowen ratio-energy balance method (BREB) has been widely used to compute ET rates (Tanner, 1960; Pruitt and Lourence, 1968; Denmead and McIlroy, 1970). The BREB method does not, however, account for horizontal fluxes of sensible and latent heat. Use of this method has resulted in errors of 20–40% in ET estimation where $A_{\rm loc}$ is a factor (e.g., Hanks *et al.*, 1971).

Here we have incorporated, in a modified Bowen ratio method, horizontal gradients of air temperature and vapor pressure to more accurately estimate ET rates under conditions of local sensible heat advection. The magnitude of $A_{\rm loc}$ and $A_{\rm reg}$ is estimated for a few typical days of the 1976 growing season at Mead, NE. The modifications in air temperature and vapor pressure profiles downwind of the leading edge are also investigated.

## 2. Experimental details

The study was conducted during 1976 on 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 MSL). The field of Sharpsburg silty clay loam is

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approximately 1.9 ha in area and 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.

Crop height ranged from 40 to 60 cm during the observation period (9–25 June 1976). The field was irrigated with 42 mm of water on 4 June and with 82 mm on 19 June. Rain fell during this period on 23 June (14 mm) with lesser amounts on 10 June (2 mm) and 13 June (4 mm).

Measurements of dry- and wet-bulb temperatures above the canopy were made with self-checking, aspirated, shielded psychrometers (Rosenberg and Brown, 1974) at four stations (1, 2, 3 and 4; see Fig. 1 and Table 1 for locations). Measurements were made at four levels within the first meter above the crop at station 1 and at six levels within the first 2 m above the crop at stations 2, 3 and 4. The psychrometers provided a temperature resolution of 0.0125°C and 0.25°C when used as differential and absolute sensors, respectively. Horizontal temperature gradients are relatively small compared with vertical temperature gradients. Thermocouples at the lowest level of each psychrometer were wired to provide a measure of horizontal temperature difference with a resolution of 0.0125°C. Accuracy of the individual sensors in the differential configuration was checked by periodic immersion in ice baths. The circuitry was designed so that electrical malfunction in any one differential psychrometer was isolated from all other differential pairs.

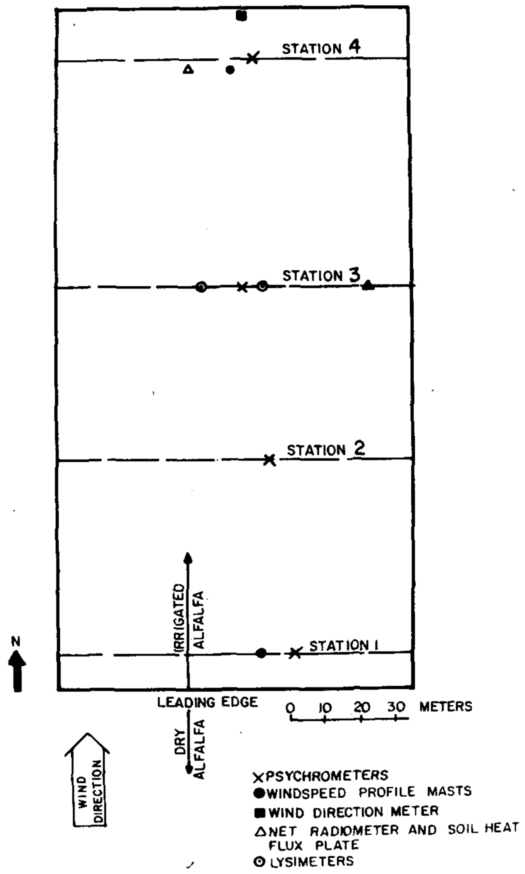

FIG. 1. Instrument locations in the experimental field.

TABLE 1. Psychrometer stations and locations for modified Bowen ratio-energy balance calculations (June 1976).

| Psychrometer station | Location for MBREB calculations | Distance from leading edge (m) |
|---|---|---|
| 1 | — | 10 |
| — | A | 38 |
| 2 | — | 65 |
| — | B | 89 |
| 3 | — | 113 |
| — | C | 146 |
| 4 | — | 180 |

Profiles of wind speed were measured at seven levels above the crop at station 4 with three-cup light-chopping Casella anemometers [model 442(2)].[3] Net radiation was measured with Swissteco net radiometers (type S-1).[4] 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) were located about 120 m from the southern boundary of the field.

Wind direction was measured with a wind vane coupled to a variable resistor and recorded on a strip chart. The data presented in this paper were selected from those periods when the winds were primarily from the southeast to southwest quadrant.

Dry- and wet-bulb temperatures, net radiation and soil heat flux were measured every 7 min. Wind speed and lysimetric weight change were integrated over 15 min periods. The data were logged on a Datex meteorological recording system. 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 min periods.

A modified Bowen ratio-energy balance (MBREB) method incorporating measurements of the horizontal gradients of temperature and vapor pressure (see next section) was used to compute ET rates. Thus, from the four psychrometers used, ET values were computed for three locations (A, B and C; see Table 1).

## 3. Theoretical details

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

$$LE_0 = -(Rn+S+A_0), \tag{1}$$

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

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

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

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where $L$ is the latent heat of vaporization of water and $E_0$, $Rn$, $S$ and $A_0$ are, respectively, the flux densities of water vapor, net radiation, soil heat and sensible heat at the surface.[6] The divergence in sensible heat flux between the surface and some level above it is given by

$$A_1 - A_0 = \rho c_p \int_0^{z_1} U \frac{\partial T}{\partial x} dz, \qquad (2)$$

where $A_1$ is the vertical sensible heat flux at a height $z_1$, $\rho$ the air density, $c_p$ the specific heat of air, $U$ the wind speed, $T$ the temperature and $x$ distance in the downwind direction. Similarly, for the latent heat flux we write

$$LE_1 - LE_0 = \frac{\rho L\epsilon}{P} \int_0^{z_1} U \frac{\partial e}{\partial x} dz, \qquad (3)$$

where $P$ is the atmospheric pressure, $\epsilon$ the ratio of the molecular weights of water vapor to dry air, and $e$ the partial pressure of water vapor in air (hereafter, the vapor pressure). Eqs. (1), (2) and (3) may be combined with the Bowen ratio at a height $z_1$

$$\beta_1 = \frac{A_1}{LE_1} = \frac{\rho C_p K_H \partial T/\partial z}{(\rho L\epsilon/P) K_W \partial e/\partial z} \approx \frac{P c_p}{L\epsilon} \frac{\partial T/\partial z}{\partial e/\partial z}\bigg|_{z_1} \qquad (4)$$

to yield the latent heat flux at the surface, i.e.,

$$LE_0 = \frac{-(Rn+S)}{1+\beta_1} - \frac{\rho}{1+\beta_1} \int_0^{z_1} U \left(\beta_1 \frac{L\epsilon}{P} \frac{\partial e}{\partial x} - c_p \frac{\partial T}{\partial x}\right) dz. \qquad (5)$$

Eq. (5) gives the latent heat flux by what we have called the modified Bowen ratio-energy balance method (MBREB). This modification of the BREB method is similar to that reported by Lang (1973).

The wind direction is considered in the MBREB method by replacing $U$ in Eq. (5) with $U \cos\theta$, where $\theta$ is the angle between the wind direction and a line perpendicular to the leading edge of the field. Wind speed is assumed to be zero at $z = z_0 + d$, where $z_0$ is the roughness parameter and $d$ the zero plane displacement. Eq. (5) thus transforms to

$$LE_0 = LE(\text{MBREB}) = \frac{-(Rn+S)}{1+\beta_1} - \frac{\rho}{1+\beta_1} \times \int_{z_0+d}^{z_1} U \cos\theta \left(\beta_1 \frac{L\epsilon}{P} \frac{\partial e}{\partial x} - c_p \frac{\partial T}{\partial x}\right) dz. \qquad (6)$$

Evapotranspiration rates (in terms of $LE$) were computed using Eq. (6). The values of $LE$ (MBREB) at the far downwind location (C) were compared with lysimetrically measured fluxes [$LE$(LYS)] as is shown in Fig. 2. $LE$(MBREB) underestimates $LE$(LYS) by 10–40%. This error is due, primarily, to the assumption of equality of the exchange coefficients for heat ($K_H$) and water vapor ($K_W$) used in the MBREB method. Recent investigations under conditions of sensible heat advection (Blad and Rosenberg, 1974; Verma *et al.*, 1978) indicate that $K_H$ is generally greater than $K_W$. To correct for the underestimation in $LE$ by the MBREB method, we use an expression for $K_H/K_W$ derived by Verma *et al.* (1978), i.e.,

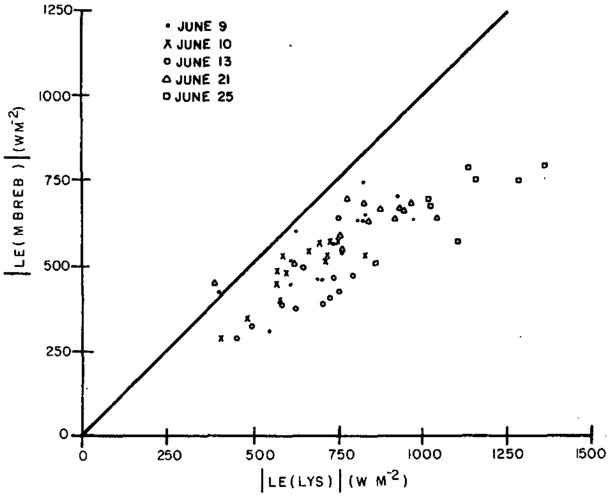

FIG. 2. $LE$ estimated by the MBREB (modified Bowen ratio-energy balance) method compared with $LE$ measured lysimetrically over irrigated alfalfa at Mead, NE.

$$K_H/K_W = 2.95 + 3.72(\Delta T/\Delta e) + 1.72(\Delta T/\Delta e)^2, \quad -0.1 < \Delta T/\Delta e < -0.8, \qquad (7)$$

where $\Delta T$ and $\Delta e$ are the vertical gradients of temperature and vapor pressure, respectively. Eq. (7) was derived for use under conditions of regional sensible heat advection such as prevailed at stations 3 and 4. In this paper, however, we have applied Eq. (7) to correct $LE$(MBREB) values determined for all the stations.

Eq. (7) was used to calculate a new Bowen ratio $\beta_c$ from Eq. (4):[7]

$$\beta_c \approx (P c_p/L\epsilon)[2.95 + 3.72(\Delta T/\Delta e) + 1.72(\Delta T/\Delta e)^2]\Delta T/\Delta e. \qquad (8)$$

Calculated values of $\beta_c$ were then applied to (6) to create a "modified modified" Bowen ratio-energy balance method (M2BREB) for calculating the latent heat flux [$LE$(M2BREB)].

$$LE_0 = LE(\text{M2BREB}) = \frac{-(Rn+S)}{1+\beta_c} - \frac{\rho}{1+\beta_c} \times \int_{z_0+d}^{z_1} U \cos\theta \left(\beta_c \frac{L\epsilon}{P} \frac{\partial e}{\partial x} - c_p \frac{\partial T}{\partial x}\right) dz. \qquad (9)$$

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[6] Fluxes to the surface are positive in sign.

[7] For details of this procedure, see Verma and Rosenberg, 1978.

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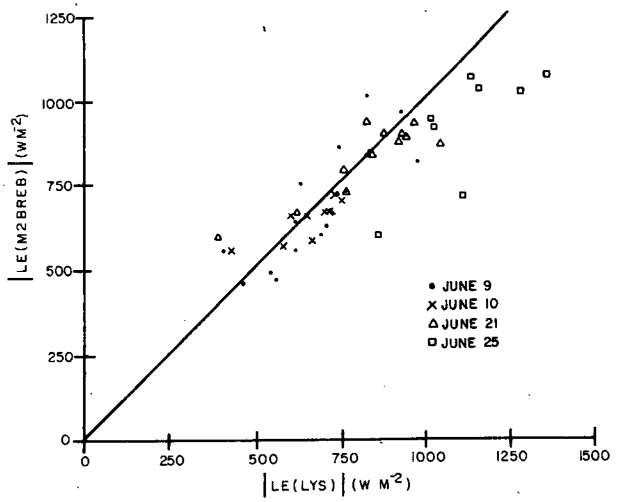

FIG. 3. *LE* estimated by the M2BREB ("modified modified" Bowen ratio-energy balance) method compared with *LE* measured lysimetrically over irrigated alfalfa at Mead, NE.

The resulting values of *LE*(M2BREB) values are scattered on both sides of a line representing 1:1 agreement (Fig. 3) but at high evaporation rates still underestimate the lysimetric evaporation. The agreement with *LE*(LYS) is significantly improved: therefore the M2BREB method is used below to compute latent heat flux, except where otherwise noted.

Using values of $LE_0$ calculated from Eq. (9) and measurements of *Rn* and *S*, the surface sensible heat flux ($A_0$) may be calculated from the energy balance of Eq. (1).

Fig. 4 illustrates, schematically, the way in which $A_0$ (the sum of the local and regional sensible heat fluxes) decreases rapidly with distance downwind of the leading edge. $A_0$ reaches an asymtotic value ($A_{\mathrm{reg}}$) far downwind, where the local sensible heat flux ($A_{\mathrm{loc}}$) becomes negligible. At any distance downwind of the leading edge the regional ($A_{\mathrm{reg}}$) and local ($A_{\mathrm{loc}}$) sensible heat flux components can thus be separated, i.e.,

$$A_{\mathrm{loc}} = A_0 - A_{\mathrm{reg}}. \tag{10}$$

| SYMBOL | FLUX DENSITY |
|---|---|
| LE₀ | LATENT HEAT |
| Areg | SENSIBLE HEAT ADVECTION, REGIONAL |
| Aloc | SENSIBLE HEAT ADVECTION, LOCAL |
| Rn | NET RADIATION |
| S | SOIL HEAT |

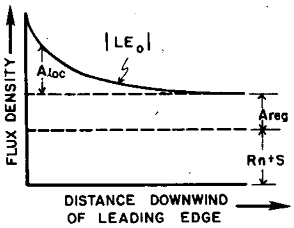

FIG. 4. Variations in energy balance of an irrigated alfalfa field with distance from the leading edge.

## 4. Results and discussion

### a. *Temperature and vapor pressure profiles under conditions of sensible heat advection*

Temperature profiles, measured at four stations downwind of the leading edge at various times on a typical day, are shown in Fig. 5. These inverted temperature profiles indicate that the flux of sensible heat was directed toward the surface. Air temperature was greatest near the leading edge and decreased with increasing fetch. Horizontal temperature differences were

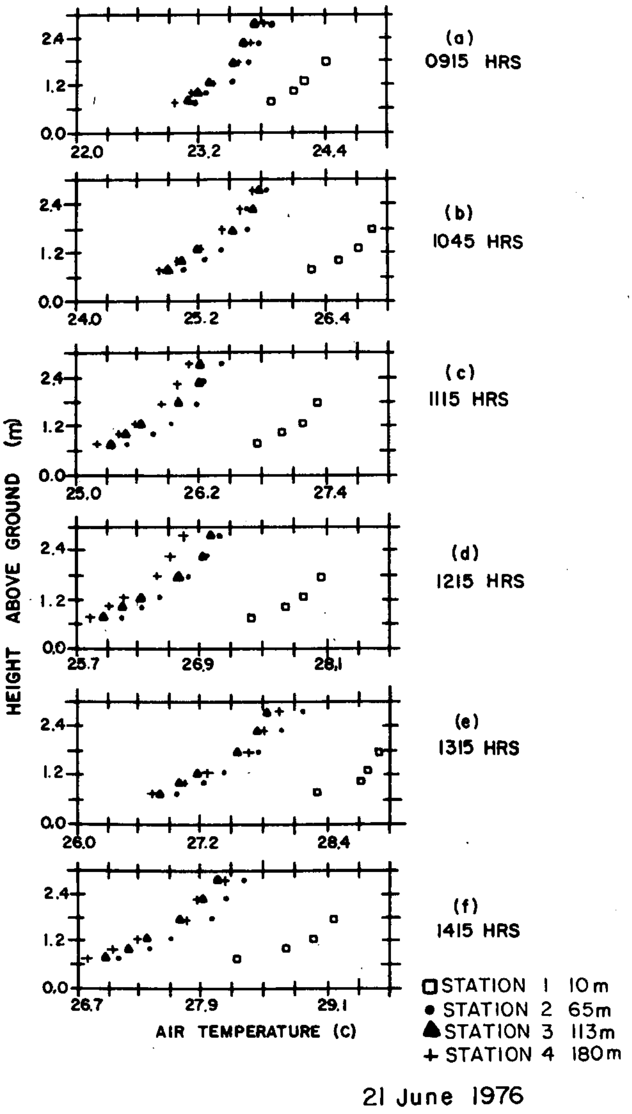

FIG. 5. Temperature profiles at varying distances from the leading edge of an irrigated alfalfa field at Mead, NE, 21 June 1976.

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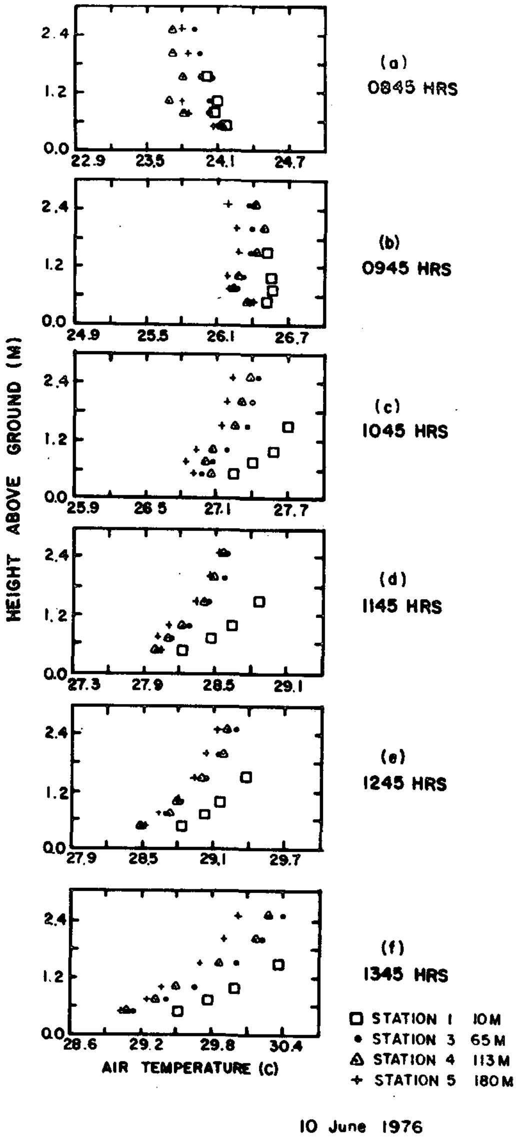

FIG. 6. As in Fig. 5 except for 10 June 1976.

largest near the leading edge, on the order of 0.2–0.3°C between stations 1 and 2 (at an elevation of 0.75 m above ground). Between stations 2 and 3, and stations 3 and 4, the temperature differences were substantially smaller, ranging from near zero to 0.2°C at 0.75 m above ground. The decrease in the rate of cooling with increasing distance downwind from the leading edge indicates that local sensible heat advection was greatest near the leading edge and decreased with increasing distance into the irrigated field.

On 10 June, by way of contrast, temperature profiles were lapse in the early morning. Inversions did not occur until later in the day (Fig. 6). By 1345 local time (Fig. 6f) all temperature profiles were inverted. Air temperature decreased systematically from stations 1–4, in a manner similar to that on most other days. The increasing influence of local sensible heat advection as the day progressed is indicated by the increased temperature difference between station 1 and the other stations.

A typical set of vapor pressure profiles measured at four locations downwind from the leading edge is shown in Fig. 7. Vapor pressure increased from station 1 to 2 and from station 2 to 3, but decreased from station 3 to 4. The possibility that this observation was due to experimental error was eliminated by the periodic ice bath calibrations described above. The transport processes occurring at the locations where decreased vapor pressure was observed must have been such that more vapor was being transported vertically than was being supplied by ET from the surface. The vapor pressure would thus decrease downwind. Other investigators (e.g., Wiersma, 1968; Crawford and Dyer, 1962) have observed similar occurrences. A more complete explanation is not yet available. The relatively large vapor pressure increase from station 1 to 2 is another indication that the local sensible heat advection component was greatest near the leading edge.

### *b. Local and regional components of sensible heat advection*

Fig. 8 shows the influence of fetch on *LE* flux during a typical day. *LE* flux decreases as the impact of the local sensible heat advection diminishes with increasing fetch. At the far downwind location *LE* reaches an asymptotic value but still exceeds $Rn+S$, indicating the occurrence of regional sensible heat advection.

Daily values of the latent heat flux (*LE*), sensible heat fluxes ($A_0$, $A_{\mathrm{reg}}$, $A_{\mathrm{loc}}$), and the sensible heat fluxes as fractions of the latent heat flux are presented in Table 2 for the five days in June. Sensible heat advection was strong on 25 June. Fifty percent of the latent heat flux at location *A* was due to sensible heat advection. Thirty-eight percent of the latent heat flux was due to regional sensible heat advection ($A_{\mathrm{reg}}$) and 12% was due to the local sensible heat advection ($A_{\mathrm{loc}}$).

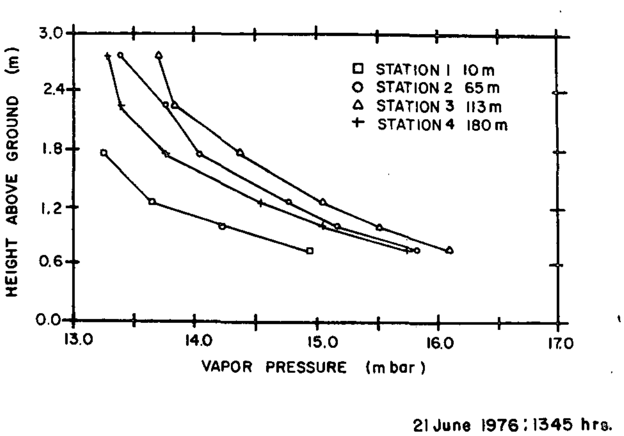

FIG. 7. Typical vapor pressure profiles downwind from a leading edge above irrigated alfalfa at Mead, NE (1345 LT 21 June 1976).

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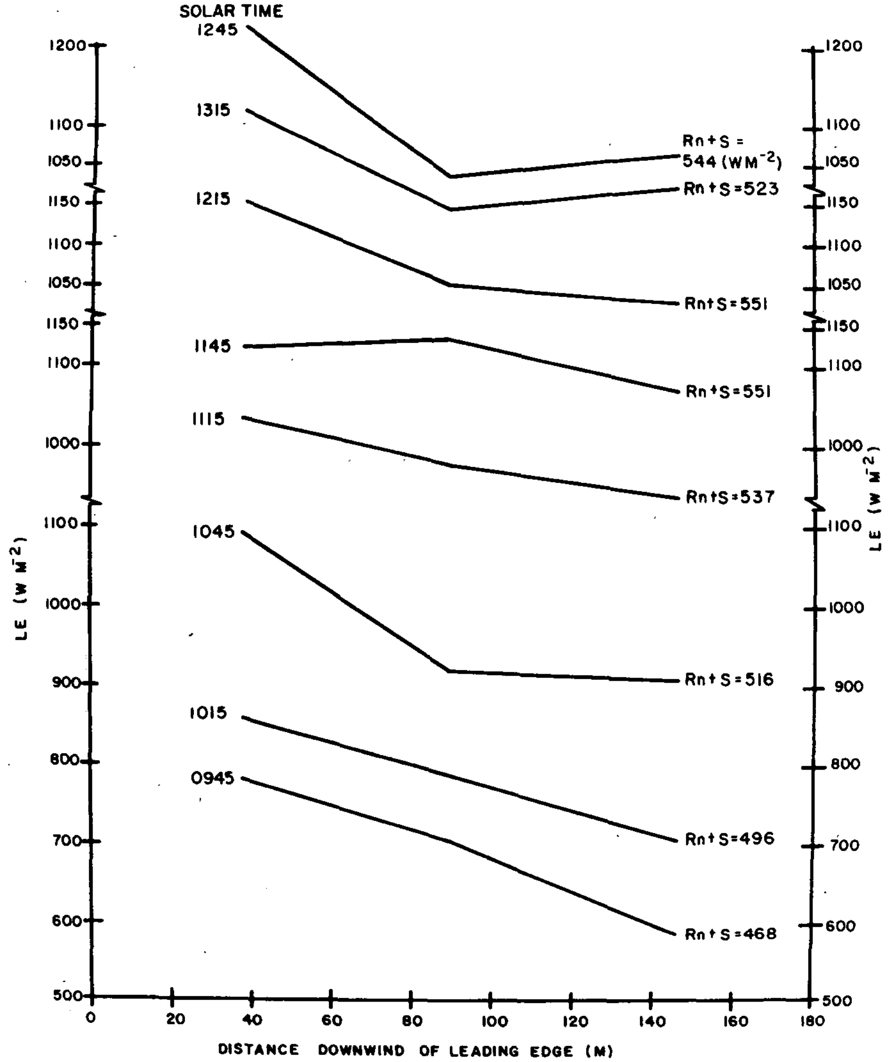

FIG. 8. Variation in latent heat flux over irrigated alfalfa at Mead, NE (25 June 1976). Locations A, B and C are 38, 89 and 146 m downwind from the leading edge, respectively.

On 9 June $A_{\text{reg}}$ was again quite significant (40%) but $A_{\text{loc}}$ (at location A) contributed only 1%. The regional components on 10 and 21 June were smaller (10 and 26%, respectively) and the local components were slightly larger (5 and 10%, respectively) than on 9 June. $A_{\text{reg}}$ was not always greater than $A_{\text{loc}}$, however. On 13 June, $A_{\text{loc}}$ contributed 14% of the energy used in $LE$ as compared to 7% from $A_{\text{reg}}$.

The daily course of $A_{\text{reg}}$ and $A_{\text{loc}}$ are shown for a typical day in Fig. 9. Windspeed, air temperature, vapor pressure and the sum of net radiation plus soil heat flux are also shown. $A_{\text{loc}}$ was generally greater near the leading edge (location A) than downwind at location B. $A_{\text{reg}}$ generally increased in the afternoon.

Relatively strong regional sensible heat advection was measured on 9, 21 and 25 June (Table 2). Wind speeds ranged around 5–6 m s$^{-1}$ during most of the time on these days. On 10 and 13 June, when regional sensible heat advection was smaller, winds were lighter (3–4 m s$^{-1}$). Regional sensible heat advection and wind speed appear to be positively related in an approximately linear fashion (Fig. 10). Multiple regression of $A_{\text{reg}}$ as a function of $Rn+S$, $e$, $U$ and $T$ (5 days data) provided the expression

$$A_{\text{reg}} = -1010.6 + 56.53(Rn+S) - 36.99e + 108.18U + 60.02T. \quad (11)$$

The multiple correlation coefficient was 0.82. The individual independent variables in order of significance were $U(r=0.74)$, $Rn+S(r=0.20)$, $e(r=-0.53)$ and $T(r=0.01)$.

No relationship between regional sensible heat advection and cloudiness was evident in the data. Strong regional sensible heat advection occurred on a cloudy day (9 June) as well as on clear days (21 and 25 June).

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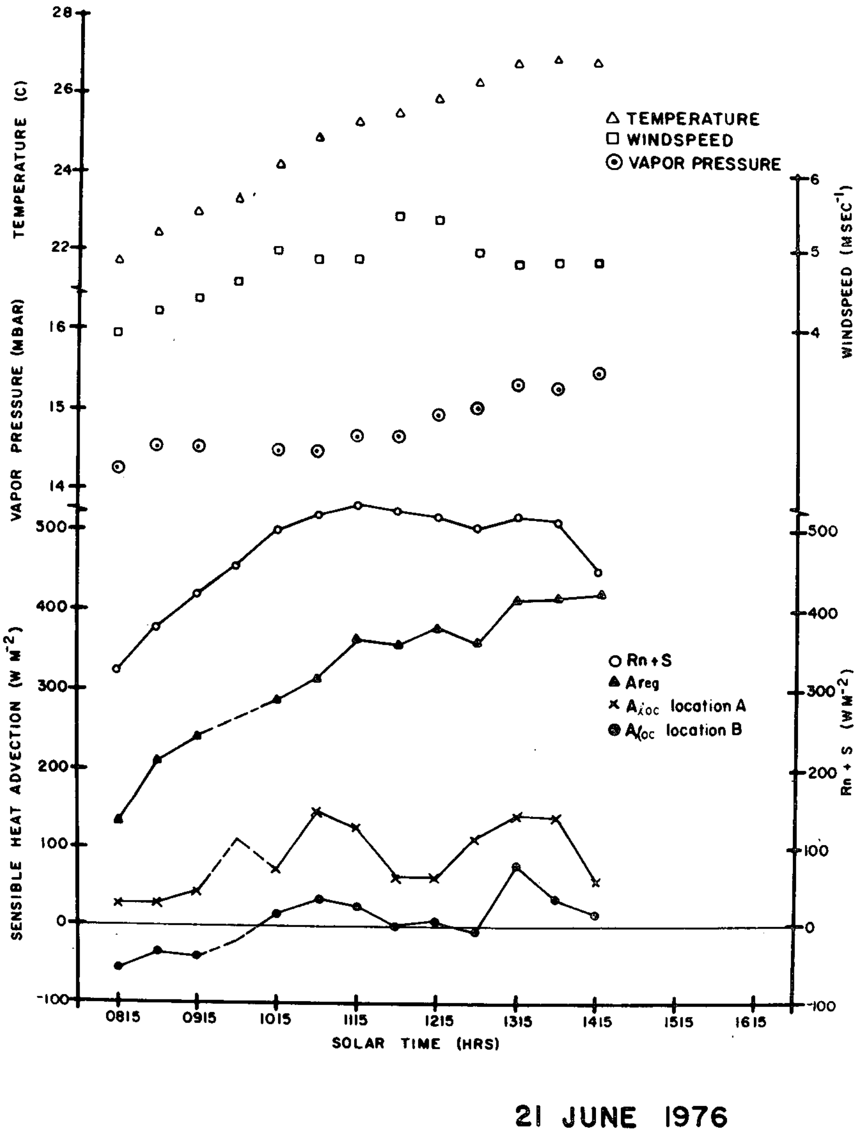

Fig. 9. Local ($A_{\mathrm{loc}}$) and regional ($A_{\mathrm{reg}}$) components of sensible heat advection over irrigated alfalfa at Mead, NE (21 June 1976). Daily patterns of $Rn+S$, $U$ (1.5 m, station 5), $T$ (0.75 m, station 5) and $e$ (0.75 m, station 5) are also shown.

Local sensible heat advection (at location A) was strong on 13, 21 and 25 June; the latter two days were windy and clear, while the former was cloudy and relatively calm. Local sensible heat advection and wind speed did not appear to be clearly related.

On days when both local and regional sensible heat advection components were strong (21 and 25 June), vapor pressure was relatively low (14–18 mb) as compared to conditions on three other days (9, 10 and 13 June) when vapor pressures >20 mb were measured (Table 2). Dryness of the air is associated with strong sensible heat advection. When the air is dry sensible heat advection results in strong latent heat flux.

## 5. Summary and conclusions

Profiles of air temperature and vapor pressure were measured at a number of locations in an irrigated alfalfa field bordered upwind by a relatively dry alfalfa field. Wind speed and net radiation were also measured. The transfer of sensible heat downward 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. Profiles of vapor pressure were lapse. Vapor pressure above the crop generally increased downwind from the leading edge. A slight decrease in vapor pressure was observed at a distance of ~180 m downwind on several occasions.

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TABLE 2. Daily values of the latent heat flux ($LE$), total sensible heat flux ($A_0$), regional sensible heat flux ($A_{\mathrm{reg}}$) and local sensible heat flux ($A_{\mathrm{loc}}$) above irrigated alfalfa at locations A, B and C.

| | Location A | | | | | | Location B | | | | | Location C | | Average values | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date & time | $A_{\mathrm{reg}}$ ($10^4$ J m$^{-2}$) | $LE$ ($10^4$ J m$^{-2}$) | $A_{\mathrm{loc}}$ ($10^4$ J m$^{-2}$) | $\frac{A_{\mathrm{loc}}}{LE}$ | $\frac{A_{\mathrm{reg}}}{LE}$ | $\frac{A_0}{LE}$ | $LE$ ($10^4$ J m$^{-2}$) | $A_{\mathrm{loc}}$ ($10^4$ J m$^{-2}$) | $\frac{A_{\mathrm{loc}}}{LE}$ | $\frac{A_{\mathrm{reg}}}{LE}$ | $\frac{A_0}{LE}$ | $LE$ | $\frac{A_{\mathrm{reg}}}{LE}$ | $Rn$ (W m$^{-2}$) | $U$ (m s$^{-1}$) | $T$ (°C) | $e$ (mb) | $S$ (W m$^{-2}$) |
| 9 June 1976 0845–1645 | 812 | 2044 | 13 | <0.01 | 0.40 | 0.40 | 2023 | −4 | 0.00 | 0.40 | 0.40 | 2031 | 0.40 | 454 | 5.8 | 26.5 | 20.5 | −35 |
| 10 June 1976 0845–1645* | 142 | 1491 | 75 | 0.05 | 0.10 | 0.15 | 1461 | 46 | 0.03 | 0.10 | 0.13 | 1415 | 0.10 | 489 | 3.7 | 27.9 | 24.3 | −42 |
| 13 June 1976 0845–1345* | 63 | 900 | 126 | 0.14 | 0.07 | 0.21 | 833 | 21 | 0.03 | 0.08 | 0.11 | 775 | 0.08 | 426 | 3.0 | 27.9 | 24.0 | −49 |
| 21 June 1976 0815–1415 | 695 | 1922 | 197 | 0.10 | 0.36 | 0.46 | 1729 | 13 | 0.01 | 0.40 | 0.41 | 1729 | 0.40 | 523 | 4.8 | 24.8 | 14.8 | −49 |
| 25 June 1976 0945–1315** | 506 | 1336 | 168 | 0.12 | 0.38 | 0.50 | 1214 | 42 | 0.04 | 0.42 | 0.45 | 1173 | 0.43 | 579 | 5.9 | 25.6 | 17.2 | −56 |

The sensible heat flux terms are also expressed as fractions of the latent heat flux. Average values of net radiation $Rn$, windspeed $U$ (150 cm, station 4), air temperature $T$ (75 cm, station 4), vapor pressure $e$, (75 cm, station 4) and soil heat flux $S$ are shown.

* Modified Bowen ratio-energy balance (MBREB) method values rather than the "modified modified" Bowen ratio-energy balance (M2BREB) method values are used because Eq. (9) is not applicable due to relatively small regional sensible heat advection occurring on the indicated days.

** $LE$ and $A_{\mathrm{reg}}$ might be underestimated on this day due to an underestimation by the model at high ET rates.

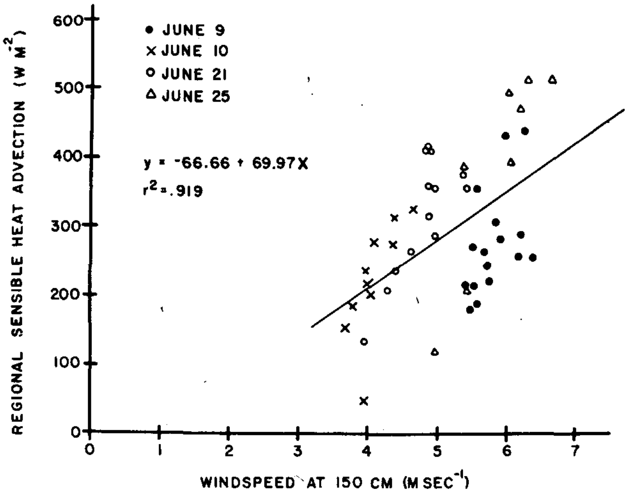

FIG. 10. Dependence of regional sensible heat advection on wind speed above irrigated alfalfa at Mead, NE.

Horizontal gradients of temperature and vapor pressure were incorporated in a modified form of the Bowen ratio-energy balance method to improve the estimation of evapotranspiration under conditions of local sensible heat advection. The local and regional components of sensible heat advection were separated and quantified.

On a daily basis regional sensible heat advection supplied from 7 to 40% and local sensible heat advection supplied from 1 to 14% of the energy consumed as latent heat in the evapotranspiration process. Together the advective components provided 15–50% of the total energy consumed in evapotranspiration at location A. Thus the high ET rates characteristic of the Great Plains region can be primarily attributed (where fields are large) to the regional scale advection of sensible heat.

Regional sensible heat advection was greatest on days with strong winds. Local sensible heat advection did not appear related to wind speed. Neither local nor regional sensible heat advection were affected by the appearance of clouds. The contribution of sensible heat advection to ET increased as the dryness of the air increased.

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## APPENDIX

### Nomenclature

| Symbol | Definition | Units |
|---|---|---|
| $A$ | sensible heat flux (subscripts 0 and $z$ refer to the surface and a height $z$, respectively) | W m$^{-2}$ |
| $A_{\mathrm{loc}}$ | local sensible heat advection | W m$^{-2}$ |
| $A_{\mathrm{reg}}$ | regional sensible heat advection | W m$^{-2}$ |
| $A_0$ | total (local and regional) sensible heat advection | W m$^{-2}$ |
| $c_p$ | specific heat of air at constant pressure | J kg$^{-1}$ °C$^{-1}$ |
| $d$ | zero plane displacement | m |
| $e$ | vapor pressure of water in air | mb |
| $E$ | water vapor flux | m$^{-2}$ s$^{-1}$ |
| $K_H$ | exchange coefficient for sensible heat | m$^2$ s$^{-1}$ |
| $K_W$ | exchange coefficient for water vapor | m$^2$ s$^{-1}$ |
| $L$ | heat of vaporization of water | J kg$^{-1}$ |
| $LE$ | latent heat flux (subscripts 0 and $z$ refer to the surface and a height $z$, respectively) | W m$^{-2}$ |
| $P$ | air pressure | mb |
| $Rn$ | net radiation | W m$^{-2}$ |
| $S$ | soil heat flux | W m$^{-2}$ |
| $T$ | temperature | °C |
| $U$ | mean wind speed in $x$ direction | m s$^{-1}$ |
| $x$ | downwind distance from leading edge | m |
| $z$ | vertical distance | m |
| $z_0$ | roughness parameter | m |
| $z_1$ | upper limit of integration in Eq. (6) | m |
| $\beta$ | Bowen ratio | |
| $\beta_1$ | Bowen ratio at a height $z_1$ | |
| $\beta_c$ | corrected Bowen ratio [Eq. (8)] | |
| $\epsilon$ | ratio of molecular weights of water vapor to air | |
| $\theta$ | wind direction | deg (0° = due south) |
| $\rho$ | air density | kg m$^{-3}$ |

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