Exchange Coefficients Under Sensible Heat Advection Determined by Eddy Correlation

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EXCHANGE COEFFICIENTS UNDER SENSIBLE HEAT ADVECTION DETERMINED BY EDDY CORRELATION*

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ABSTRACT

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Results of eddy correlation measurements of exchange coefficients for sensible heat (K_H) and water vapor (K_W) made over alfalfa under conditions of regional sensible heat advection are presented. K_H was found to be generally greater than K_W under moderate to strong advection. The inequality of K_H and K_W under advective conditions was inferred by Blad and Rosenberg (1974) and has been demonstrated with other micrometeorological methods by Verma et al. (1978). The inequality of K_H and K_W is particularly significant with respect to the Bowen ratio-energy balance method of evapotranspiration estimation, which is based on the assumption that $K_H = K_W$. Use of this assumption results in consistent underestimation of evapotranspiration under advective conditions.

INTRODUCTION

The vertical flux densities of sensible heat (H) and water vapor (LE) in the atmospheric surface layer can be expressed by:

$$H = \rho C_p K_H \frac{\partial T}{\partial z} \tag{1}$$

and

$$LE = \frac{L\epsilon}{P} \rho K_W \frac{\partial e}{\partial z} \tag{2}$$

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where ρ is the air density, C_p is the specific heat at constant pressure, L is the latent heat of vaporization of water, E is the evapotranspiration rate and LE is the latent heat flux. ϵ is the ratio of molecular weights of water (M_w) to dry air (M_a) and P is the atmospheric pressure. K_H and K_W are the turbulent exchange coefficients for heat and water vapor.

Several studies (e.g., Dyer, 1967; Swinbank and Dyer, 1967) have shown that, under lapse conditions, K_H is equal to K_W. Other investigators (e.g. Webb, 1970; Oke, 1970) have shown that K_H and K_W are nearly equal under nocturnal inversion conditions.

Because of the inadequate performance of Bowen ratio-energy balance methods, which depend upon the assumption $K_H = K_W$, in semi-arid areas Blad and Rosenberg (1974) questioned whether the equality of K_H and K_W remains valid under conditions of sensible heat advection (for a detailed discussion of sensible heat advection see Rosenberg, 1974; Brakke et al. 1978). Based on his theoretical analysis Warhaft (1976) indicated that K_H/K_W may indeed depart from unity when the gradients of temperature and humidity are of opposite sign. Under advective conditions the temperature and humidity gradients have opposing signs since the sensible heat flux is directed toward the crop or other evaporating surface. Verma et al. (1978) determined values for K_W and K_H from lysimetric measurements of LE and energy balance measurements of H over alfalfa and soybeans. K_H was shown to be generally greater than K_W under advective conditions.

Eddy correlation measurements of water vapor and sensible heat over an alfalfa crop under conditions of sensible heat advection provide an alternate method for determination of K_H and K_W. The efficiency of turbulent transport of sensible heat and water vapor is also examined to explain the inequality in exchange coefficients which is supported by these measurements.

METHODS

Measurements of the turbulent transport of sensible heat and water vapor were made over a well-watered alfalfa field at the University of Nebraska Agricultural Meteorology Research Laboratory at Mead, Nebraska (41° 09′N; 96° 30′W; 354 m above m.s.l.) during June and July 1977. Three dimensional Gill (UVW) propeller anemometers*[1] were used for wind component measurements. Microbead thermistors*[2] and fine wire dry- and wet-bulb thermocouples (Tillman, 1973) were used for air temperature and vapor pressure measurements. The sensors were mounted 4.45 meters above the ground at the north end of an alfalfa field approximately 400 m in the N—S direction by 105 m in the E—W direction. Observations were made only when the wind direction ranged from southeast to southwest. Concurrently, air temperature and vapor pressure profiles were measured at elevations up to 5.4 m with the "self-

*[1] R. M. Young Co., Traverse City, Michigan (Model No. 27103).
*[2] Victory Engineering Co., Springfield, New Jersey (VECO No. 51A401C).

checking" thermocouple psychrometers of Rosenberg and Brown (1974). A computer controlled data acquisition system consisting of a mini-computer, analog to digital converters and a magnetic tape drive was employed for sampling and recording all data. The fast-response turbulence signals were sampled thirteen times per second (13 Hz) while the slow-response signals were sampled three times per minute. The fast-response signals were passed through a 5 Hz RC low-pass filter.

The propeller anemometers were individually calibrated in a wind tunnel.* These calibrations were used to correct the anemometer data for its deviation from perfect cosine response. An iteration procedure similar to that of Horst (1973) was used for this purpose. Instantaneous covariances of vertical velocity and temperature or vapor pressure were averaged over 45 minute periods and appropriate constants were applied to yield estimates of sensible heat and water vapor fluxes:

$$H = \rho C_p \overline{W'T'} \tag{3}$$

$$LE = \frac{L\epsilon}{P} \rho \overline{W'e'} \tag{4}$$

where W is the vertical wind component, T is the air temperature and e is the vapor pressure. The bar denotes a time average and the prime denotes an instantaneous deviation from the time-averaged quantity.

K_H and K_W values were computed by substituting the turbulent fluxes of sensible heat and water vapor (eqs. 3 and 4) and gradients of air temperature and vapor pressure in eqs. 1 and 2. The gradients of temperature and vapor pressure were evaluated using finite differences in a manner suggested by Panofsky (1965). The gradient of variable x with respect to height z is given by:

$$\frac{\partial x}{\partial z} = \frac{x_2 - x_1}{(z_1 z_2)^{\frac{1}{2}} \ln(z_2/z_1)} \tag{5}$$

where the subscripts indicate level above the ground (z_1 = 3.9 m and z_2 = 4.9 m in this study). All data associated with $|\partial T/\partial z| < 0.1°C\ m^{-1}$ and $|\partial e/\partial z| <$ $0.1\ mb\ m^{-1}$ were excluded from the analysis to ensure meaningful computations. The data was also carefully scrutinized for consistency over several runs to ensure stationarity of conditions.

We recognize that the propeller anemometer responds inadequately to high frequency fluctuations resulting in some loss (about 10%) of flux for both sensible heat and water vapor measurements. This limitation should not, however, invalidate our conclusion on the ratio, K_H/K_W because both K_H and K_W computations are expected to be affected similarly.

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RESULTS AND DISCUSSION

Values of the ratio of the exchange coefficients for sensible heat and water vapor (K_H/K_W) were computed from measurements made under advective conditions of July 13, July 18 and July 19, 1977. Mostly clear skies with moderate to strong south winds prevailed on these days (general crop and meteorological conditions for these three days are presented in Table I).

TABLE I

General crop and meteorological conditions of July 13, 18 and 19, 1977

Date	LAI*	Plant height (m)	Average windspeed ($m\ sec^{-1}$)	Wind direction	Average temperature (°C)	Average vapor pressure (mb)	Average net radiation ($ly\ min^{-1}$)
July 13	1.7	0.25	6.09	S	33.3	23.8	0.68
July 18	2.5	0.45	7.00	S	34.1	17.7	0.61
July 19	2.5	0.45	7.45	SSW	32.4	21.6	0.52

* LAI = leaf area index.

Windspeed was measured at 4,0 m and net radiation was measured at 2.0 m. Air temperature and vapor pressure were measured at 2.75 m.

Temperature inversions extended to at least 16 m, the height of an adjacent mast. This indicates that advection of sensible heat was regional in nature (for details see Verma et al., 1978; Brakke et al., 1978). Results plotted in Fig.1 indicate that K_H was generally greater than K_W under conditions of sensible heat advection. This result agrees with other data reported by Verma et al. (1978) using an alternative micrometeorological method.

Diurnal variations of K_H/K_W are examined for the three days in Fig.2A. Figure 2A shows an increase in the value of K_H/K_W during the afternoons. Moderate to strong sensible heat advection occurred during these afternoon hours. The intensity of advection can be gauged by the magnitude and direction of heat flux. The fluxes* of sensible heat and water vapor are plotted as a function of time of day in Fig.3 for July 13, 18 and 19. The greatest fluxes of sensible heat toward the crop occur in the afternoon which suggests that advection is most intense during these hours. In addition to the net radiant energy, advected sensible heat is consumed in the evapotranspiration process. The net radiant energy decreases after solar noon while the proportion of energy supplied to the crop by sensible heat advection increases in the afternoon. We conclude, therefore, that the ratio K_H/K_W is greater than unity under conditions of moderate to strong sensible heat advection.

* The sign convention employed here is such that all energy streams toward the crop or ground surface are positive and all away from the surface are negative.

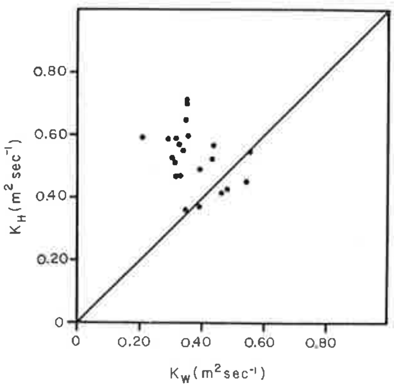

Fig.1. The exchange coefficient for sensible heat (K_H) compared with the exchange coefficient for water vapor (K_W) for three days, July 13, 18 and 19, 1977 over the well-watered alfalfa crop.

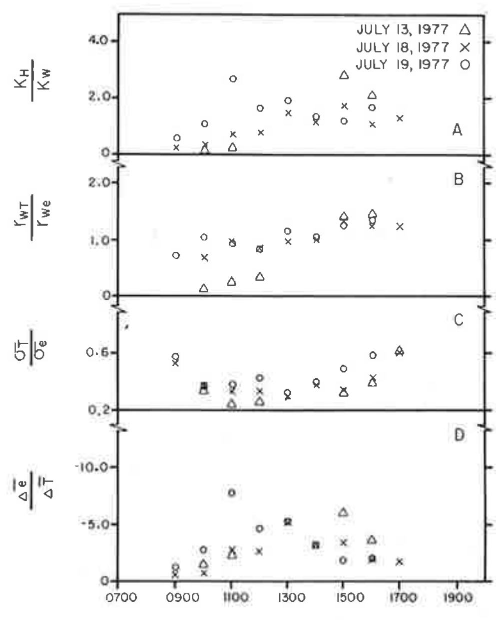

Fig.2. The ratios of A. exchange coefficients for sensible heat and water vapor, K_H/K_W; B. correlation coefficients of sensible heat and water vapor, r_{WT}/r_{We}; C. standard deviations of temperature and vapor pressure, σ_T/σ_e; and D. gradients of vapor pressure and air temperature as functions of time of day for July 13, 18 and 19, 1977.

The ratio of exchange coefficients can also be represented as:

$$\frac{K_H}{K_W} = \frac{L\epsilon}{C_p P}\frac{H}{LE}\frac{\partial e/\partial z}{\partial T/\partial z} = \frac{r_{WT}}{r_{We}}\frac{\sigma_T}{\sigma_e}\frac{\Delta e}{\Delta T} \tag{6}$$

where $r_{WT} = H/(\rho C_p \sigma_W \sigma_T)$ is the correlation coefficient for sensible heat and $r_{We} = LE/(L\epsilon/P\rho\sigma_W\sigma_e)$ is the correlation coefficient for water vapor. σ_T and σ_e are standard deviations of temperature and vapor pressure fluctuations, respectively. Δe and ΔT are the gradients of vapor pressure and air temperature.

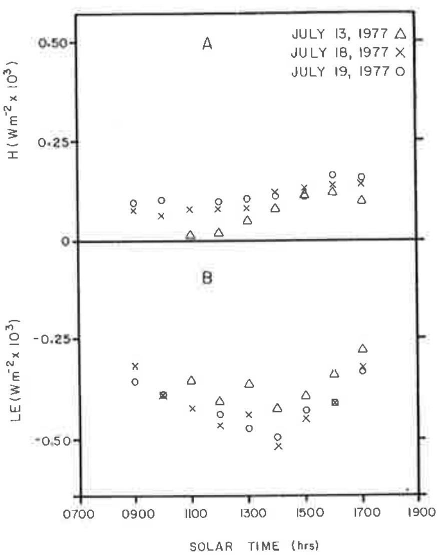

Fig.3. Daily patterns of A. sensible heat flux, and B. water vapor flux over a well-watered alfalfa crop as a function of time of day for July 13, 18 and 19, 1977.

It is interesting to examine the diurnal variations of the components of K_H/K_W in eq. 6. The correlation coefficients r_{WT} and r_{We} represent measures of transfer efficiency of sensible heat and water vapor. The ratio, r_{WT}/r_{We}, shown in Fig.2B, increases in the afternoon hours after 1200 hrs. This implies that the transfer efficiency of sensible heat becomes greater than that of water vapor when advection is moderate to strong.

The ratio of standard deviations, σ_T/σ_e, (Fig.2C) decreases as the morning progresses, levels off near midday and then begins to increase. Motha et al. (1979) found that σ_e decreased during the afternoon in direct proportion to LE, but σ_T did not decrease until late afternoon. Thus the increase in σ_T/σ_e during the afternoon is the result of both the decrease in σ_e and the sustained high value of σ_T under advective conditions. The ratio of vapor pressure and temperature gradients, $\Delta e/\Delta T$, is presented in Fig.2D. Some degree of variability is observed in $\Delta e/\Delta T$ over the three days.

The following points can be made from examination of Fig.2. The ratio K_H/K_W becomes greater than unity during the afternoon hours when advection of sensible heat is moderate to strong. Then both r_{WT}/r_{We} and σ_T/σ_e increase as well, indicating that sensible heat transfer is more efficient than water vapor transfer.

SUMMARY AND CONCLUSIONS

Turbulence measurements made over an alfalfa crop indicate that the exchange coefficient for sensible heat is greater than that for water vapor under conditions of strong sensible heat advection. This finding supports earlier inferential evidence presented by Blad and Rosenberg (1974) and earlier observations by other micrometeorological methods by Verma et al. (1978). Our analysis indicates, at least qualitatively, that under these strongly advective conditions the transfer efficiency of sensible heat is greater than that for water vapor.

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