INTRA-FIELD VARIABILITY OF SCALAR FLUX DENSITIES ACROSS A TRANSITION BETWEEN A DESERT AND AN IRRIGATED POTATO FIELD

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(Received in final form 1 May, 1995)

Abstract. This paper reports on measurements of sensible and latent heat and CO_2 fluxes made over an irrigated potato field, growing next to a patch of desert. The study was conducted using two eddy correlation systems. One measurement system was located within the equilibrium boundary layer 800 m downwind from the edge of the potato field. The other measurement system was mobile and was placed at various downwind positions to probe the horizontal transition of vertical scalar fluxes. Latent (LE) and sensible (H) heat fluxes, measured at 4 m above the surface, exhibited marked variations with downwind distance over the field. Only after the fetch to height ratio exceeded 75 to 1 did LE and H become invariant with downwind distance. When latent and sensible heat fluxes were measured upwind of this threshold, significant advection of humidity-deficit occurred, causing a vertical flux divergence of H and LE.

The measured fluxes of momentum, heat, and moisture were compared with predictions from a second-order closure two-dimensional atmospheric boundary layer model. There is good agreement between measurements and model predictions. A soil-plant-atmosphere model was used to examine nonlinear feedbacks between humidity-deficits, stomatal conductance and evaporation. Data interpretation with this model revealed that the advection of hot dry air did not enhance surface evaporation rates near the upwind edge of the potato field, because of negative feedbacks among stomatal conductance, humidity-deficits, and LE. This finding is consistent with results from several recent studies.

1. Introduction

Numerical models are atmospheric scientists' chief tools for assessing the weather, climate, and air chemistry. While the models have many strengths, the parameterization of scalar fluxes at the earth's surface remains a persistent problem. Two key issues associated with the parameterization of surface fluxes are of particular interest to micrometeorologists: the first one concerns the fidelity of the submodels used to calculate scalar flux densities to and from a given patch of land (Shuttleworth, 1991; Vogel *et al.*, 1995). The second issue, and the focus of this paper, concerns the spatial variability of surface fluxes within and among constitutent patches of a landscape and the integration of these fluxes to the model-grid scale (see Klaassen, 1992; Avissar, 1992; Bonan *et al.*, 1993).

When modeling regional and global scale problems, atmospheric modelers divide the domain into multiple cells. The horizontal length scale of individual cells

Boundary-Layer Meteorology **76:** 109–136, 1995.

typically ranges between 1 km and 10 km on a side for mesoscale problems and 100 km and 500 km on a side for global problems. Landscapes, whose dimensions correspond to the grid size of a model, are rarely uniform. Typically, grid-size regions are comprised of a mosaic of land patches, each with a different potential to control or influence momentum, mass, and energy transfer.

Faced with the complexities of the real world, how does one proceed to parameterize surface scalar flux densities and evaluate them for an entire grid? The simplest scheme for parameterizing grid scale fluxes of mass and energy involves weighting scalar flux densities from constituent patches according to their relative area (Claussen, 1991). The accuracy of this assumption is subject to debate. When adjacent patches differ in their ability to provide moisture to the atmosphere, advection of heat and moisture can occur between fields (Rao *et al.*, 1974a; Philip, 1987; Naot and Mahrer, 1991; Klaassen, 1992; Kroon and de Bruin, 1993). The advection of hot dry air can enhance evaporation downwind, while the advection of cool moist air can suppress it (see e.g., McNaughton, 1976; McNaughton and Jarvis, 1983).

The magnitude of advective enhancement or repression of latent heat transfer depends, theoretically, on the constituent patch size and stomatal feedbacks to the advected humidity-deficit (Raupach, 1991; Klaassen, 1992; Kroon and de Bruin, 1993). Klaassen (1992) hypothesizes that the advective influence on latent heat transfer increases as the length scale of adjacent patches decreases. Whether or not this sensitivity of advection to patch size is significant can be debated. For one case, Klaassen showed that the advective enhancement of LE, where E is evaporation rate and L is latent heat of vaporization of water, is significant in relative terms (LE is enhanced by 5% to 20% as the length scale decreases from 10 km to 100 m). But in absolute terms, this evaporative enhancement may be considered trivial – Klaassen's calculations indicate that advective effects alter LE by less than 10 W m^{-2} for the case studied. In a study using an analytical advection model, Philip (1987) suggested that advection effects between a dry patch and a wet patch of land can persist for distances up to 1000 km. Raupach (1991), on the contrary, argued that interfield advection can be ignored if the horizontal size of landscape patches is much less than a horizontal length scale ($X = h\bar{U}/w_*$) of the convective boundary layer (CBL), where h is the CBL depth, $\bar{U}$ is horizontal velocity, and w_* is the convective velocity scale. Furthermore, the advection of dry air over actively transpiring vegetation may not necessarily increase evaporation if negative feedback causes stomatal closure (Philip, 1987; Kroon and deBruin, 1993; McAneney *et al.*, 1994; Brunet *et al.*, 1994).

Airplane-mounted flux systems are one means of acquiring data to evaluate parameterization schemes for spatially-averaged scalar fluxes (Desjardins *et al.*, 1992; Crawford *et al.*, 1993a). Yet, verifying the aircraft-measured flux densities for this task remains a problem. The conventional approach compares aircraft-based measurements against tower-based measurements. From an airplane's perspective, airplane and tower-based flux measurement systems need not agree; towers usually reside in the surface layer and are immersed in a fully-developed equilibrium boundary layer, while aircraft fly through multiple and evolving surface boundary layers (Schuepp *et al.*, 1990). Ironically, in order to verify aircraft flux measurements needed for addressing the advection problem at the regional and global model grid-scales, we must first investigate the advection of heat and moisture at the local scale.

Many researchers have conducted theoretical investigations on the influence of advection and the adjustment of surface fluxes between adjacent surfaces (Rao *et al.*, 1974a; McNaughton, 1976; Philip, 1987; Claussen, 1987; Naot and Mahrer, 1991; Klaassen, 1992; Kroon and de Bruin, 1993), but few have attacked the advection problem experimentally and with direct measurements. Rider *et al.* (1963), and Dyer and Crawford (1965) were among the first to measure advection, but they only examined the horizontal adjustment of mean temperature and humidity profiles. Lang *et al.* (1974), Brakke *et al.* (1978) and Naot and Mahrer (1991) quantified the adjustment of latent heat flux with distance from the leading edge between adjacent fields, but their studies suffered from reliance on the inferential flux-gradient method.

Eddy correlation instrumentation provides the modern experimenter with the capacity to measure the horizontal adjustment of surface fluxes between two different fields directly. Yet, few workers have taken this step. Gash (1986), for instance, used the eddy correlation method to investigate flow across the transition from a rough to smooth surface; however, he only measured momentum flux. De Bruin *et al.* (1991) conducted an advection experiment in southern France, but they have not disseminated their results. Cooper *et al.* (1992) used eddy correlation and lidar measurements to examine the spatial variability of latent heat transfer over an irrigated field. However, they did not directly measure how mass and energy flux densities evolved near the edge of the field, nor did they report on spatial variations of momentum, sensible heat, and CO_2 fluxes. Only Brunet *et al.* (1994) have conducted a thorough advection experiment across the transition between a dry surface and an evaporating surface.

Two factors led us to design and conduct an advection study. One was the paucity of direct flux measurements in environments influenced by advection effects. The other was a need to quantify the horizontal variability of surface fluxes to evaluate airplane flux measurements (e.g., Crawford *et al.*, 1993a) and model parameterizations (e.g., Rao *et al.*, 1974a; Kroon and de Bruin, 1993). Measurements of momentum, sensible and latent heat, and CO_2 flux densities were made over a potato field, located adjacent to a patch of desert. The study was conducted using two eddy correlation systems. One system was located 800 m downwind from the edge of surface transition from desert to farm. The other measurement system was mobile and was placed at various positions downwind from the transition to probe the horizontal variation of vertical flux densities of scalars.

In this paper, we examine how observed fluxes of momentum, heat, and moisture vary horizontally across a transition between a dry and an evaporating surface. The measurement, are compared to predictions from the second-order closure local advection model of Rao *et al.* (1974a), which has been modified to include the effects of vegetation canopy on surface energy and moisture budgets. We also use a soil-plant-atmosphere model to examine the mechanisms that control the fluxes of water vapor across the surface transition.

2. Experimental Methods

2.1. Site and Crop Characteristics

The field experiment was a component of the 1992 Boardman ARM Regional Flux Experiment (BARFEX; Doran *et al.*, 1992). The study was performed on a 4500 ha farm near Boardman, OR (lat. 45° 40′ N; long. 119° 40′ W).

Environmental and scalar flux measurements were conducted over a potato (*Solanum tuberosum*) field between June 3 (Day 154) and June 13 (Day 164), 1992. The crop was planted in 0.91 m wide rows on a circular (800 m diameter) plot, with an area of approximately 64 ha. The crop was positioned next to a triangular patch of desert. Other adjacent and upwind fields were planted with alfalfa (see Figure 1). Over the course of the experiment, the potato crop grew from 0.30 m to 0.50 m and its row coverage increased from 50% to 75%. At the midpoint of the experiment (Day 160), leaf area index (LAI: area of leaves per unit ground area) was 2.2. The aerodynamic surface roughness was estimated as 0.05 m.

The soil was sandy (Quincy soil series mixed, mesic, xeric, Torripsamments) and contained negligible soil organic matter (<0.5%). Its bulk density was 1.18 g cm^{-3}. The crop was irrigated every one to three days. Measurements of soil moisture were made every other day using the gravimetric method. These measurements reveal that the water content ranged between 0.088 and 0.15 cm^3 cm^{-3}, so the crop did not suffer from a deficit of water.

2.2. Instrumentation and Data Acquisition

Horizontal variations of vertical flux densities of momentum, energy, and CO_2 were evaluated using one stationary and one mobile flux measurement system. The stationary system was mounted on a mast that was located on the northeast side of the potato field. Measurement sensors were placed 4 m above the ground, so that adequate fetch (up to 800 m) was achieved when the wind direction was from the predominant southwesterly direction (Figure 1). The mobile measurement system was mounted on a mast placed on the bed of a small pickup truck. Instruments were situated 4 m above the ground and were oriented upwind from the body of the truck. This instrument height and position was chosen to correspond with placement of the stationary system and to minimize any flow distortion that could result from wind flow around and over the truck.

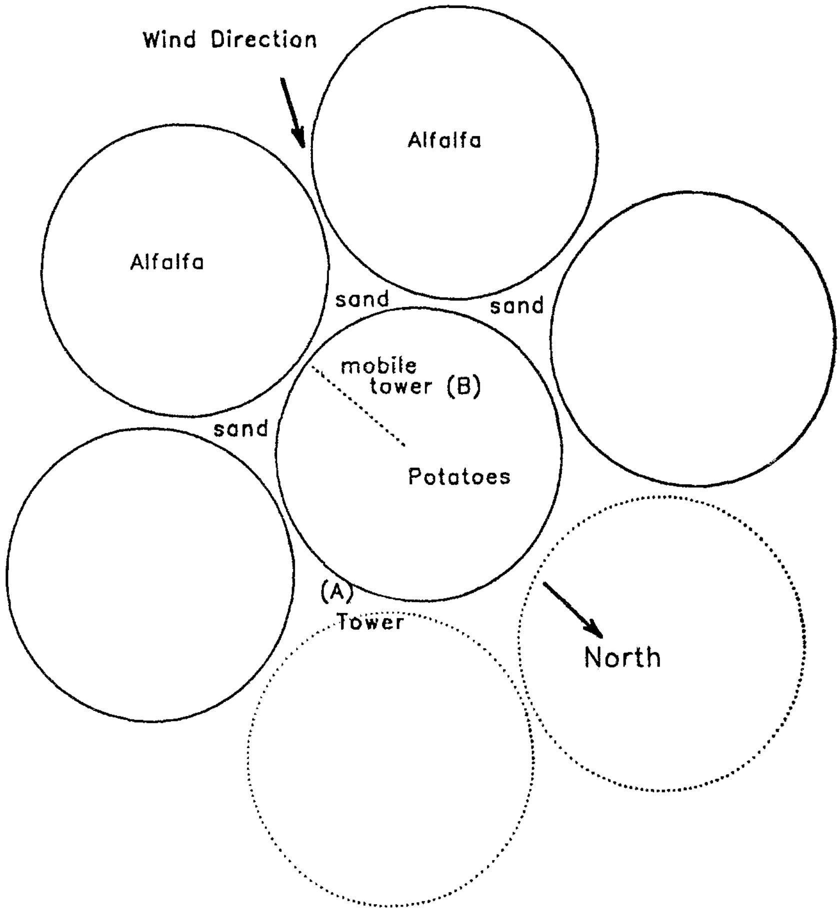


Fig. 1. Map of the experimental field site. The diameter of each irrigated circle was 800 m. The dashed line on the potato field indicates the access road where the mobile flux system was placed.

Three-dimensional orthogonal wind velocities (u, v, w) and virtual temperature (T_v) were measured with a sonic anemometer (Applied Technology, model SWS-211/3K). The pathlength between transducers was 0.15 m. Transducer shadowing effects were corrected using the sensor software.

Water vapor and CO_2 concentrations were measured with an open-path infrared absorption spectrometer (Auble and Meyers, 1992). Salient characteristics of this instrument are: the infrared beam is reflected three times between mirrors, creating a 0.80 m absorption path; and the response time of the sensor is less than 0.1 s and its noise level is less than 300 μg m^{-3}. CO_2 calibrations were performed with three standard gas mixtures with an accuracy of $\pm$ 1%. Calibration coefficients were found to be steady and varied less than 3% throughout the experiment. Water vapor calibration was referenced to a wet-bulb psychrometer. The infrared spectrometer measures fluctuations in scalar density, not mixing ratio. Consequently, CO_2 and water vapor fluxes were corrected for density fluctuations imposed by temperature and humidity fluctuations (Webb *et al.*, 1980).

Voltages from the sonic anemometer and infrared spectrometer were sampled and digitized at 10 Hz by an analog to digital converter. Digital signals were then transmitted from the field to a personal computer. The computer software transformed the data, calculated flux covariances, stored raw data, and displayed raw sensor signals on the video display for real-time quality control.

2.3. Ancillary Meteorological and Plant Measurements

Soil heat flux (G) was measured at each site. Three soil heat flux plates (REBS model HFT-3, Seattle, WA) were buried 0.08 m below the surface. Soil heat flux data were corrected for heat storage in the upper soil layer, which in turn was calculated from the Fourier equation for soil heat transfer as a function of the moisture content of the soil and the time rate of change of the soil mean temperature profile (measured with a thermocouple probe). Temperature sensors were placed logarithmically at depths of 0.02, 0.04, 0.08, 0.16 and 0.32 m below the surface.

Photosynthetic photon flux density and net radiation (R_n) were measured above the crop with a quantum sensor (LICOR model LI-190S) and a net radiometer (REBS model Q-6), respectively. An infrared radiometer (Everest Interscience model 4000), pointed downward at a 45° angle above the nadir, sensed the radiative temperature of the canopy. Air temperature and relative humidity were measured with appropriate sensors (Campbell Scientific model 207), while wind speed and direction were measured with a wind monitor (RM Young model 05701). Ancillary meteorological variables were sampled at 1 Hz with a data logger (Campbell Scientific model CR-21x) and the data were averaged for one-half hour periods. Stomatal resistance was periodically sampled to assess the water status of the vegetation. Measurements were made on upper sunlit leaves using a steady-state porometer (LICOR model LI-1600).

2.4. Eddy Flux Measurements

The eddy correlation method was used to measure fluxes of momentum, heat, water vapor, and CO_2. In theory, fluxes of mass and energy between a crop and the atmosphere are proportional to the mean covariance between vertical velocity (w') and scalar (c') fluctuations. For this experiment, CO_2 flux (F_c) measurements represent the net differences between gains from leaf photosynthesis and losses from leaf, root, and soil respiration. Water vapor exchange rates are the sum of soil evaporation and plant transpiration rates. Negative fluxes symbolize uptake or storage by the surface and positive values denote the loss of mass and energy by the crop.

In practice, several conditions must be met before the eddy correlation method can be applied to measure the fluxes of mass and energy over a crop canopy.

First, the site must be flat. Second, vertical velocity must be measured normal to the surface streamlines. Third, the crop should be homogeneous and extensive. Fourth, environmental conditions must be steady in time. Finally, no intermediate or advective sources or sinks should exist for the scalar under investigation (see Baldocchi *et al.*, 1988).

The cited prerequisites for proper application of the eddy correlation method were met for the reference tower (system A) through proper site selection, experimental design, and data processing. For example, the data processing system was designed to ensure that the eddy flux measurement system captured most of the flux-containing eddies. This goal was accomplished by sampling the sensors rapidly and by averaging velocity-scalar fluctuation products for thirty minutes; this averaging period was sufficient for second moments, based on criteria established by Sreenivasan *et al.* (1978). Turbulent fluctuations were computed as the difference between instantaneous and mean quantities. Mean values were determined in real-time using a digital recursive filter with a 400 s time constant. The coordinate system of the three orthogonal wind vectors was rotated to obtain a mean vertical velocity of zero and to orient the longitudinal component ($\bar{U}$) along the mean wind. Scalar flux covariances were computed in reference to the new coordinate system. Finally, data were rejected when winds were not coming from the potato field, when it was raining, or when the irrigation system passed through the upwind fetch.

Closure of the surface energy balance is the ultimate test of the eddy correlation method. Figure 2 shows a test of surface energy balance closure made with the reference eddy flux system A, which was positioned well within the equilibrium boundary layer. Measured energy balance components (sensible, latent, and soil heat fluxes) matched the net radiation flux satisfactorily.

Flux measurements at the variable upwind site, B, were made outside the equilibrium boundary layer over the potato field. This location places flux system B in an advective condition. Consequently, flux divergence is expected, so that the fluxes measured at 4 m are not necessarily the fluxes sensed by the crop at the ground. Flux divergences were estimated by using a physically and physiologically-based soil-plant-atmosphere model (CANPOT) to assess the rates of mass and energy exchange at the interface between the vegetation and the atmosphere. The model, discussed in Section 2.6, is validated with field flux measurements. The issue of flux divergence is examined and discussed further in Sections 3 and 4.

When conducting any difference or comparison study, bias errors between two measurement systems must be documented. Side by side studies were conducted to investigate if the truck, on which the mobile flux system was mounted, disrupted the air flow and caused an undesirable bias error. Figure 3 shows the comparison between the two flux measurement systems for sensible and latent heat transfer. The agreement between the two systems is good and reveals little bias. Additional statistical information is presented in Tables I and II. In summary, Student's t-test statistics for independent mean differences indicated that no significant differences (at the 5% probability level) were detected between systems A and B for the mea-

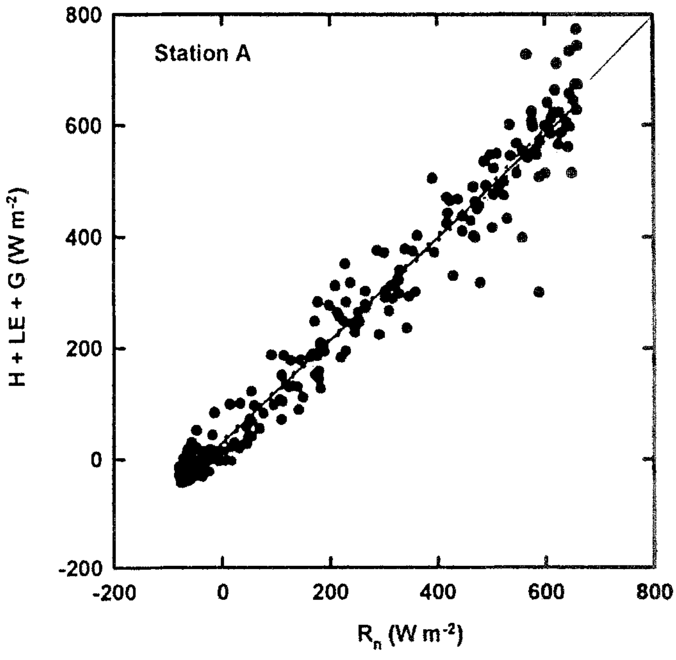


Fig. 2. Demonstration of the surface energy balance closure at the stationary reference site. The slope of the regression of $LE + H + S$ on R_n is 0.95, the intercept is 14 W m^{-2}, and $r^2 = 0.93$.

surements of u_*, LE, H and F_c. Paired t-tests revealed that significant differences between flux systems A and B occurred only for the measurement of sensible heat flux. Even in this case, the mean paired difference was only 7.35 W m^{-2} and the standard error of this mean was 3.25 W m^{-2}. Thus, we can conclude from Tables I and II that the distortion of the mean wind flow by the truck had only a minor influence on the measurement of momentum, energy, and mass transfer by system B.

2.5. Experimental execution

To investigate the horizontal variation in vertical turbulent fluxes, experiments were performed by placing the mobile eddy flux system (B) at various distances from the upwind edge of the potato field (see Figure 1) for extended periods. To compensate for geophysical variability of environmental conditions, these data were referenced to simultaneous measurements made by the stationary system (A) which was positioned within the equilibrium boundary layer over the potato field. The mobile system was placed at nominal distances of 0, 20, 40, 58, 200 and 800 m from the upwind edge; the actual distance wind travelled from the upwind edge, for each half-hour experimental run, was calculated using the measured wind direction and trigonometric relationships.

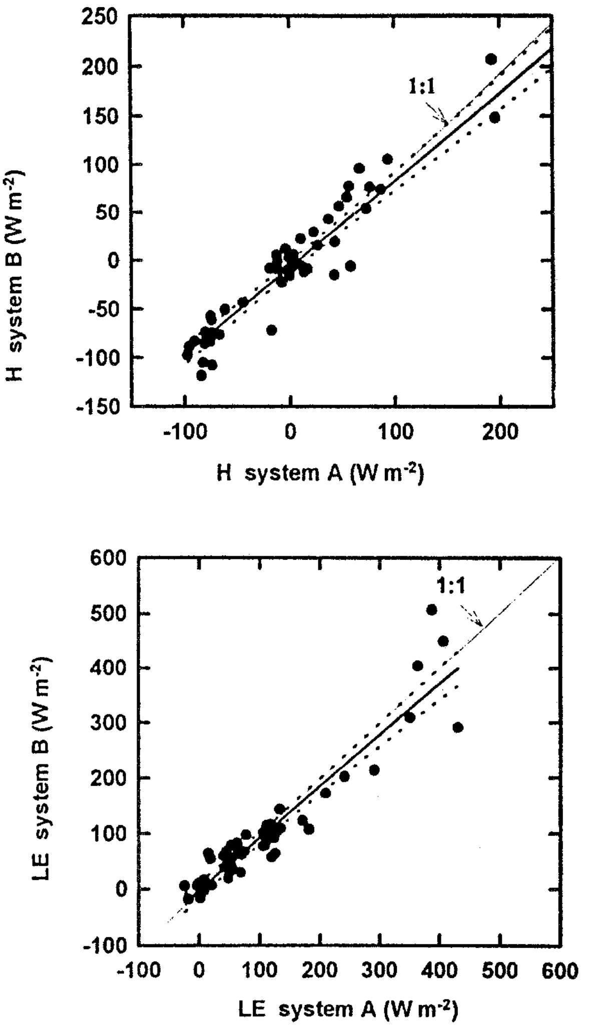


Fig. 3. Side by side comparison of sensible and latent heat fluxes measured by the stationary tower A and the mobile system B that was mounted on the back of a small truck. Both eddy flux systems were located 4 m above the ground. These data were obtained over alfalfa and potato fields.

For the ensuing analysis, data were selected only when the wind direction was between 220° and 240°. Under these conditions, winds were oriented along the long axis of the desert triangle. This constraint allowed the wind to run over hot dry sand and short dead grass for fetches up to 230 m (see Figure 1). Based on relationships developed from this experiment, this fetch was long enough for parcels of air to adjust to the underlying surface. Since experiments were conducted over sequential days, data used in this analysis were restricted to a narrow range of meteorological conditions. Data were selected from periods when the net radiation flux exceeded

TABLE I

Mean and regression statistics for side by side comparisons of flux systems A and B; system B was mounted on the back of a small pickup truck. These data were obtained over potato and alfalfa crops. 51 degrees of freedom are associated with these statistical tests. For the regression, flux measured by system A is the independent variable and flux measured by system B is the dependent variable

Variable	Mean	Std. error	Intercept	Slope	r^2
$(u_*)_A$ (m s^{-1})	0.278	0.23	−0.023	1.11	0.98
$(u_*)_B$ (m s^{-1})	0.253	0.016			
$(LE)_A$ (W m^{-2})	106.4	15.7	−0.76	1.04	0.86
$(LE)_B$ (W m^{-2})	97.3	15.6			
$(H)_A$ (W m^{-2})	2.57	10.9	−7.09	0.91	0.90
$(H)_B$ (W m^{-2})	−4.77	10.3			
$(F_c)_A$ (mg m^{-2} s^{-1})	−0.11	0.056	−0.033	0.98	0.89
$(F_c)_B$ (mg m^{-2} s^{-1})	−0.059				

500 W m^{-2}. Mean meteorological conditions encountered during the experiment are presented in Table III.

2.6. The Theoretical Interpretation

The two models utilized in this study are briefly described below.

2.6.1. *Soil-Plant-Atmosphere Model*

A soil-plant-atmosphere model (CANPOT) was used to calculate water vapor and CO_2 flux densities over the vegetation and to assess nonlinear feedbacks between humidity-deficits, stomatal conductance, and evaporation. Computations of mass and energy exchange were made by combining a Lagrangian random-walk turbulent diffusion model, a spherical Poisson radiative transfer model, a C_3 photosynthesis model, a photosynthesis-dependent stomatal conductance model, and a leaf energy balance model. The model is one-dimensional and assumes steady-state conditions. The original model was developed for a soybean canopy (Baldocchi, 1992), and has been modified for wheat canopy (Baldocchi, 1994a, b); see references cited within these papers for additional details on the model. In this application, the model was modified by changing input structural variables and by applying photosynthetic parameters for a potato canopy, as reported in Wullschleger (1993). Figure 4 shows that the model was able to calculate the

TABLE II

Student's t test statistics for side by side comparisons of flux systems A and B. These flux data were obtained over potato and alfalfa crops. 51 degrees of freedom are associated with these statistical tests. p is the probability, and p@0.05 denotes the null hypothesis test at 5% level of significance

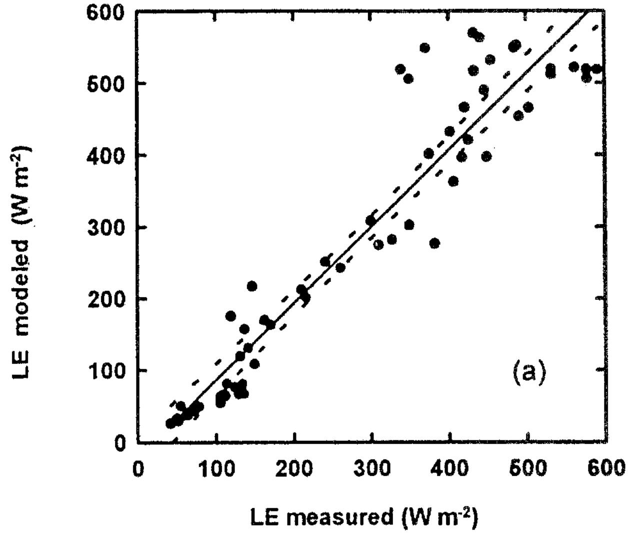
	t-paired	Measurement	t-independent
		u_*	
t	0.87		0.90
p	0.40		0.38
p@0.05	$(u_*)_A = (u_*)_B$		$(u_*)_A = (u_*)_B$
		H	
t	2.27		0.49
p	0.027		0.067
p@0.05	$(H)_A \neq (H)_B$		$(H)_A = (H)_B$
		LE	
t	1.72		0.41
p	0.091		0.067
p@0.05	$(LE)_A = (LE)_B$		$(LE)_A = (LE)_B$
		F_c	
t	1.63		0.39
p	0.107		0.69
p@0.05	$(F_c)_A = (F_c)_B$		$(F_c)_A = (F_c)_B$

TABLE III

Mean meteorological conditions over the Farm during the advection experiment

Variable	Mean	Standard deviation
R_n (W m^{-2})	582	60
LE (W m^{-2})	494	87
H (W m^{-2})	52.9	31
G (W m^{-2})	32	7.8
$\bar{U}$ (m s^{-1})	3.76	1.12
u_* (m s^{-1})	0.378	0.11
Wind dir. (deg)	232	16.8
T_a (C)	24.3	1.94
ρ_v (g m^{-3})	9.00	1.34
z/L_m	−0.004	

ρ_v = mean absolute humidity.
L_m = Obukhov length.



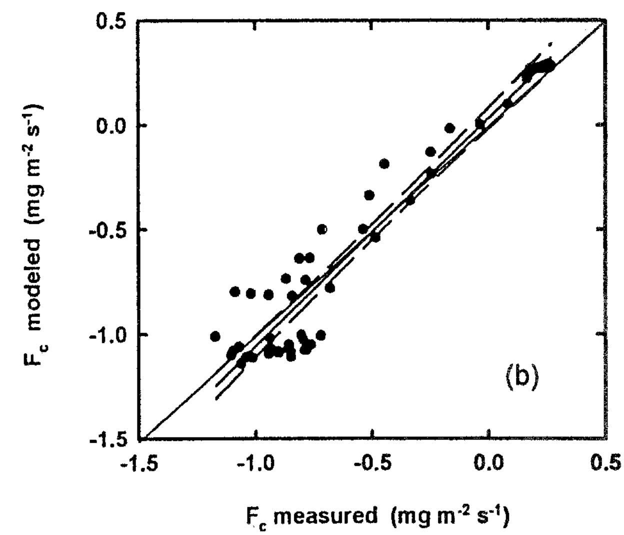


Fig. 4. Comparison of the canopy mass and energy exchange (CANPOT) model predictions against measurements of latent heat and CO_2 fluxes.

fluxes LE and F_c accurately and can be used with confidence as a diagnostic tool in the ensuing data analysis.

2.6.2. *Numerical Advection Model*

The two-dimensional second-order closure atmospheric boundary layer (ABL) advection model of Rao *et al.* (1974a) was used as a tool to diagnose and evaluate the flux measurements. The advection model carries full transport equations for turbulent fluxes. The unknown third moment terms in these equations are approximated in terms of second moments, means gradients, and a turbulence time scale which is proportional to the ratio of the turbulent kinetic energy to viscous dissipation rate. Since the model includes a dynamical equation for the dissipation rate, this time scale is determined by the model itself, and is not specified *a priori*. The original model of Rao *et al.* (1974a) has been modified, following an approach similar to that described by Kroon and de Bruin (1993), to include the effects of vegetation canopies on surface energy and moisture budgets. This is done by incorporating the Penman–Monteith 'big-leaf' equation (e.g., Thom, 1975; Vogel *et al.*, 1995) for estimating the latent heat flux LE at the surface:

$$LE = \frac{[\epsilon(R_n - G) + (L/R_a)\rho D]}{[\epsilon + 1 + R_s/R_a]}. \tag{1}$$

Here, $D = \{Q_s(T_1) - Q(T_1)\}$ is the mean specific humidity-deficit of air at a reference height $z = z_1$ above the surface, $Q_s(T_1)$ is saturation specific humidity of air at temperature T_1 at the reference height, R_a is bulk aerodynamic resistance, R_s is bulk surface resistance, ρ is air density, $\epsilon = (L/c_p)S$, $S = \partial Q_s/\partial T$ is slope of saturation specific humidity versus temperature curve, and c_p is the specific heat of air at constant pressure. The value of ϵ is 2.66 at 25 °C. The bulk aerodynamic resistance to the transfer of scalar properties such as heat and water vapor (see, e.g., Garratt, 1992) is calculated directly from the model as $R_a = \bar{U}(z_1)/u_*^2 + 1/(ku_*)\ln(z_0/z_{0T})$, where $\bar{U}(z_1)$ is the mean wind speed at height z_1, u_* is surface friction velocity, and z_0 and z_{0T} are aerodynamic surface roughnesses for momentum and heat (moisture) transfer, respectively.

The bulk surface resistance R_s is required for modeling vegetation-atmosphere interactions at canopy and larger scales. This resistance strongly depends on stomatal resistance r_s and is a function of the humidity-deficit at the leaf surface (e.g., Kelliher *et al.*, 1994). Therefore, R_s is expected to decrease with increasing fetch, due to changes in saturation deficit resulting from the simultaneous increase in air humidity and decrease in temperature. Noilhan and Planton (1989) formulated R_s as

$$R_s = \frac{R_{s,\min}F_1}{LAI\,F_2F_3F_4}, \tag{2a}$$

where the factors F_1 and F_2, respectively, account for the influence of photosynthetically active radiation and soil water availability, and the factors F_3 and F_4 represent the influence of humidity and temperature of air, respectively, on the canopy system. Kroon and de Bruin (1993) simplified this equation by assuming that F_1 and F_2 are constant over the irrigated field downwind at a given time, though these constant values are different from their values over the upwind surface. If LAI is also assumed to be constant, this equation reduces to

$$R_s = \frac{R_{\min}}{F_3F_4}, \tag{2b}$$

where $R_{min} = R_{s,min}F_1/(LAIF_2)$. R_{min} characterizes the minimum surface resistance of a vegetated surface under conditions of adequate light, ample soil water, low humidity-deficit, and optimal temperature. A R_{min} value of 20 s m^{-1} is usually recommended for well-watered agricultural crops, and is adopted in this study. This value is supported by measurements in the Boardman experiment (Vogel *et al.*, 1995), and gives R_s values of about 60 s m^{-1} from Equation (2b). This R_s value has also been inferred from the BARFEX data.

Following Kroon and de Bruin (1993), the factor F_3 is specified as

$$F_3 = 1 - \alpha D(x), \tag{2c}$$

for small $D(x)$, where $D(x)$ is the humidity-deficit at downwind distance x, and $\alpha = 40$ kg kg^{-1} for short vegetation (Noilhan and Planton, 1989). F_4 is parameterized as

$$F_4 = 1 - 0.0016[25 - T_1]^2, \tag{2d}$$

for $0 < T_1 < 50°$ C. McAneney *et al.* (1994) also parameterized R_s as shown in Equations (2b) and (2c) in a study of downwind evolution of transpiration by two irrigated crops under conditions of local advection; however, they set $F_4 = 1$, a reasonable assumption for air temperatures close to 25 °C. With R_{min} and α values as given above, the latent heat fluxes calculated from their parameterizations are close to the measured values in the present study.

The governing equations of the model together with the specified initial and boundary conditions were integrated on a personal computer using a Dufort-Frankel explicit finite difference scheme. A logarithmic transformation of the vertical coordinate was used to obtain a fine computational mesh near the ground. The lowest level z_1 in the domain was taken as 1 m to save computational time; the conditions at this level are related to their surface values through the equilibrium flux-profile relations based on the local similarity assumption. The z_0 values over the desert and the field respectively were taken as 0.005 m and 0.05 m. The surface roughness for heat and moisture (z_{0T}) was assumed to be $z_0/5$ (Thom, 1975). Model calculations were based on the mean meteorological conditions shown in Table III. Consequently, we specified $R_n - G = 550$ W m^{-2} over the downwind surface. Differences in surface temperature and albedo caused the total energy available for partition between sensible and latent heat fluxes to be about 100 W m^{-2} larger over the irrigated crop field than over the upwind surface. Using this information, and values for Bowen ratios over desert surfaces, the surface sensible and latent heat fluxes over the desert were specified to be 350 and 100 W m^{-2}, respectively.

3. Results

3.1. Momentum Transfer

Advection studies in the literature fall into two classes. The first class investigated the transition between aerodynamically smooth and rough surfaces (e.g., Bradley, 1968; Rao *et al.*, 1974b). The second class of problems dealt with the transition between two different source or sink strength regions (e.g., Rao *et al.*, 1974a; Kroon and de Bruin, 1993; Brunet *et al.*, 1994). Here, we studied flow across an abrupt surface transition from a bare dry soil to a short transpiring crop. Surface friction velocity reacts to the sudden increase in roughness by overshooting and then rapidly returning to a new equilibrium value, which is larger than the corresponding value over the upwind surface. Most of the surface stress ($\tau_0 = \rho u_*^2$) variation occurs within a short distance from the discontinuity in roughness (see Figure 5); there was a 28% drop in surface stress within the first 75 m of the surface transition, and then a more gradual adjustment to the new equilibrium value. Overall, the horizontal variation of friction velocity was small because the transition in surface roughness was not extreme; crop height ranged between 0.30 m and 0.50 m over the course of the experiment, and the estimated aerodynamic roughness lengths over the desert and the crop were about 0.005 m and 0.05 m, respectively.

Except for the first two points very close to the surface discontinuity, the measured values in Figure 5 agree reasonably well with the predictions from Rao *et al.*'s (1974b) second-order closure ABL model. The measured overshoot and subsequent adjustment of momentum transfer shown in Figure 5 is consistent with available data and model results presented by many authors for transitions between smooth and rough surfaces (see Garratt, 1990). Kaimal and Finnigan (1994) explain this phenomenon as follows: "In the smooth-to-rough case an airstream, traveling relatively rapidly over the smooth surface, generates a high stress on first encountering the roughness. As the new and rougher surface absorbs momentum from the air layers above it and this region of decelerated flow thickens into an internal boundary layer, the velocity of the air layer in contact with the enhanced roughness falls and so does the resulting surface stress."

3.2. Latent and Sensible Heat Transfer

The variation of measured and calculated latent heat flux densities across the potato field are shown in Figure 6. Two points can be drawn from this figure. First, there is excellent agreement between measured and calculated LE values. From these data it can be inferred that the temperature and humidity-deficit functions in Equation (2) incorporated into the Rao *et al.* (1974) advection model were satisfactory. Second, the magnitude of LE increases hyperbolically with distance over the irrigated field. At the upwind edge of the potato field, LE was about 45% of the flux measured at reference station A. By $x = 300$ m, latent heat flux measured at 4 m had adjusted to the value measured at the reference station A at the opposite end of the field.

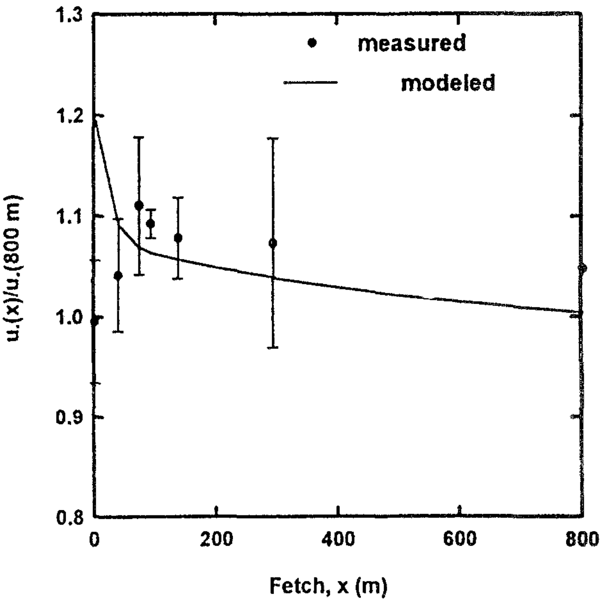


Fig. 5. Variation of friction velocity measured at 4 m above the ground with fetch over the potato field. The values are normalized with measurements made at tower A, which was in the equilibrium boundary layer at about 800 m from the leading edge of the field. The solid line shows the prediction from the second-order closure ABL model of Rao *et al.* (1974b). The datum at $x = 800$ m was determined using the linear regression derived from the flux system intercomparison study and the mean friction velocity measured during the horizontal transect studies.

The distance at which full flux adjustment occurred corresponds to a 75 to 1 fetch-to-height ratio. While this ratio is less than the classical recommendation of 100 to 1 (Dyer, 1963), it is consistent with other observations and calculations (Munro and Oke, 1975; Schuepp *et al.*, 1990).

The distance at which horizontal variation of LE, measured at 4 m, becomes very small corresponds with the theoretical development of the equilibrium boundary layer, which is defined as 10% of the internal boundary layer (Rao *et al.*, 1974b; Garratt, 1990). Following Kaimal and Finnigan (1994), the depth δ of this equilibrium or constant flux layer can be computed from

$$\delta/z_0 = 0.075(x/z_0)^{0.8}. \tag{3}$$

Figure 7 shows that the theoretical depth of the constant flux layer reached 4 m after a horizontal transition of 320 m, near the location where measured flux densities became constant.

The horizontal variation of measured and calculated sensible heat flux densities is shown in Figure 8. At the upwind edge of the field, the measured and normalized sensible heat flux, $H(x)/R_n$, was about 20% greater than the normalized sensible heat flux measured within the equilibrium boundary layer. As the fetch increased, the differences between normalized heat flux values diminished and $H(x)$ adjusted

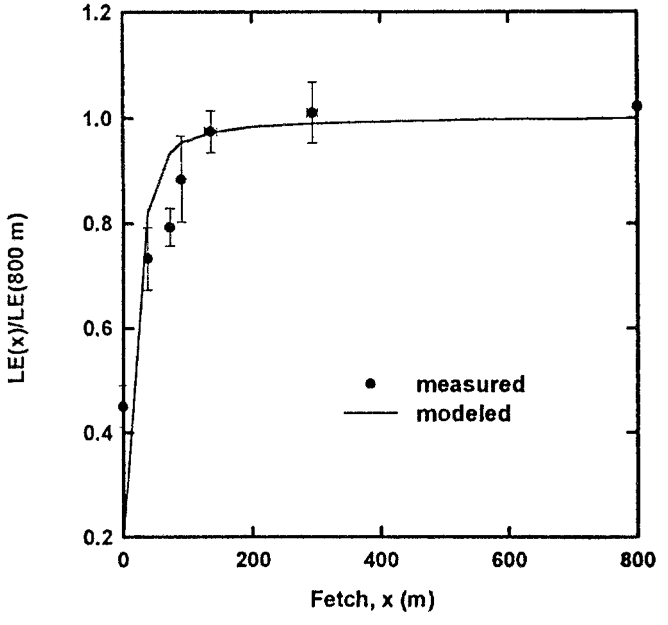


Fig. 6. Variation of latent heat flux measured at 4 m above the ground with fetch over the irrigated field. The values of $LE(x)$ are normalized with measurements made at tower A. The solid line shows the prediction from the modified advection model of Rao *et al.* (1974a), which has been modified for this study. The data are restricted to periods when R_n exceeded 500 W m^{-2}. The datum at 800 m was determined using the linear regression derived from the flux system intercomparison study and the mean latent heat flux measured during the horizontal transect studies.

to the value of its reference measurement, H (800 m), by about $x = 300$ m. The agreement between the measured values and the advection model predictions is also good. Consequently, it is justified to use the Rao *et al.* (1974a) advection model to investigate some boundary-layer properties over the landscape.

Since there were no mean profile measurements over either the desert or the potato field during the 1992 BARFEX advection experiment, we used the advection model to investigate variation of temperature and humidity profiles over the field. The evolution of the calculated mean potential temperature (Θ) profiles is shown in Figure 9(a). The temperature profile changes from strongly superadiabatic over the desert to a positive stratification near the surface over the field, due to the presence of moisture and the resulting loss of energy by evaporation. Near the surface transition, the surface inversion strengthens with increasing fetch. Eventually, the feedbacks between humidity-deficits, stomatal resistance, latent heat flux, and the turbulent mixing reduce the temperature gradient near the surface. The corresponding mean humidity profiles presented in Figure 9(b) show the transition from well-mixed upwind conditions to a strong negative vertical gradient (vertical humidity flux directed upwards) near the surface, as the humidity of air increases with fetch.

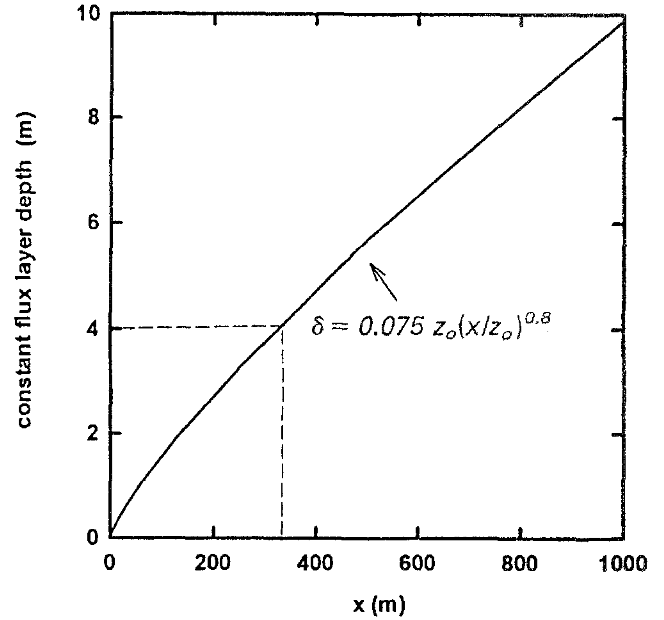


Fig. 7. Variation of the depth (δ) of the constant flux layer with fetch (x) over the potato field. The equation for δ is from Kaimal and Finnigan (1994).

3.3. CO_2 TRANSFER

The horizontal variation of CO_2 flux is presented in Figure 10. At the upwind edge of the potato field, CO_2 fluxes were about one-half of the value sensed within the equilibrium boundary layer over the crop at station A. Small flux densities occurred at the upwind edge of the potato field, because the upwind surface consisted of dry sand and dead grass, which was not photosynthesizing. CO_2 flux densities measured over the potato field increased rapidly with increasing fetch. In fact, variation of F_c over the potato field differed considerably from the evolution of LE and H (Figures 6 and 8). By $x = 30$ m, F_c values were on par with measurements at station A. Further downwind, F_c values exceeded measurements made at the reference station. For example, CO_2 fluxes at 300 m into the field were 20% higher than fluxes measured at the far end of the field. Rapid horizontal adjustment of F_c occurred because the horizontal advection of CO_2 concentration was small compared to the advection of moisture and heat; Crawford *et al.* (1993b) report that the horizontal differences between CO_2 concentration measured over the Boardman farm and the adjacent steppe (+10 km) typically ranged between 1 and 3 ppm at 10 m above the surface.

The CO_2 exchange rates over a partial canopy are very sensitive to variations in leaf area index (Baldocchi, 1994a). In this study, the observed spatial variability of LAI was great, ranging between 1.5 and 3.08 over the field. Consequently, it is

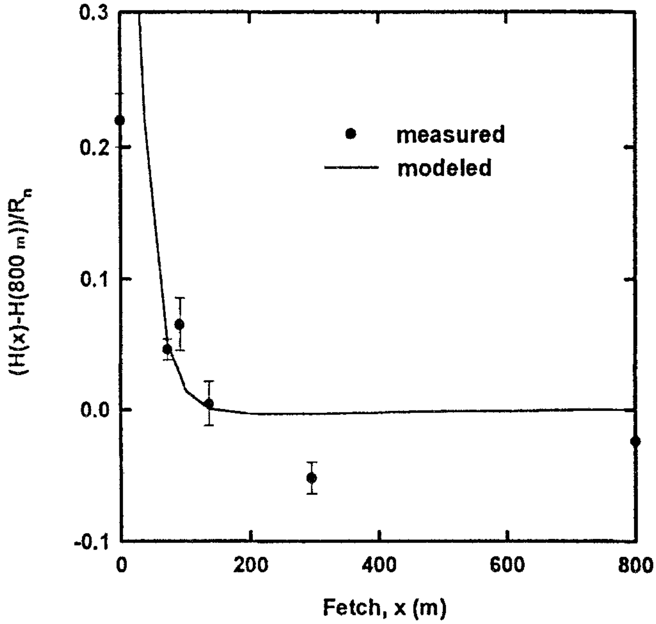


Fig. 8. Variation of sensible heat flux measured at 4 m above the ground with fetch over the irrigated field. The values of $H(x)$ are compared against measurements made at tower A, and the differences are normalized with the net radiation flux. The solid line shows the prediction from the modified advection model used in this study. The data are restricted to periods when R_n exceeded 500 W m^{-2}. R_n was used for normalization, because observed sensible heat fluxes at tower A were often near zero. The datum at 800 m was determined using the linear regression derived from the flux system intercomparison study and the mean sensible heat flux measured during the horizontal transect studies.

plausible that the observed horizontal variation of F_c was mostly due to intra-field variations of leaf area index.

4. Discussion

Classical analysis of the steady-state conservation of mass equation reveals that a vertical flux divergence ($\partial F/\partial z$) occurs when the horizontal transport of scalar ($\bar{U}\partial C/\partial x$) is non-zero. When studying the transition of latent heat transfer between a dry surface and a moist field, it is not sufficient to consider the horizontal advection of moisture ($\bar{U}\partial Q/\partial x$) independently of heat ($\rho c_p \bar{U}\partial \Theta/\partial x$). For example, a vertical divergence of latent heat flux may not occur if the advection of moisture and heat offset each other and cause the advection of the atmosphere's humidity-deficit D to be zero (see McNaughton, 1976; McNaughton and Jarvis, 1983). Because moisture and heat transfer are coupled, McNaughton (1976) and Raupach (1991) argue that it is preferable to examine advective enhancement of suppression of evaporation in terms of D. From the conservation budget for D, we observe

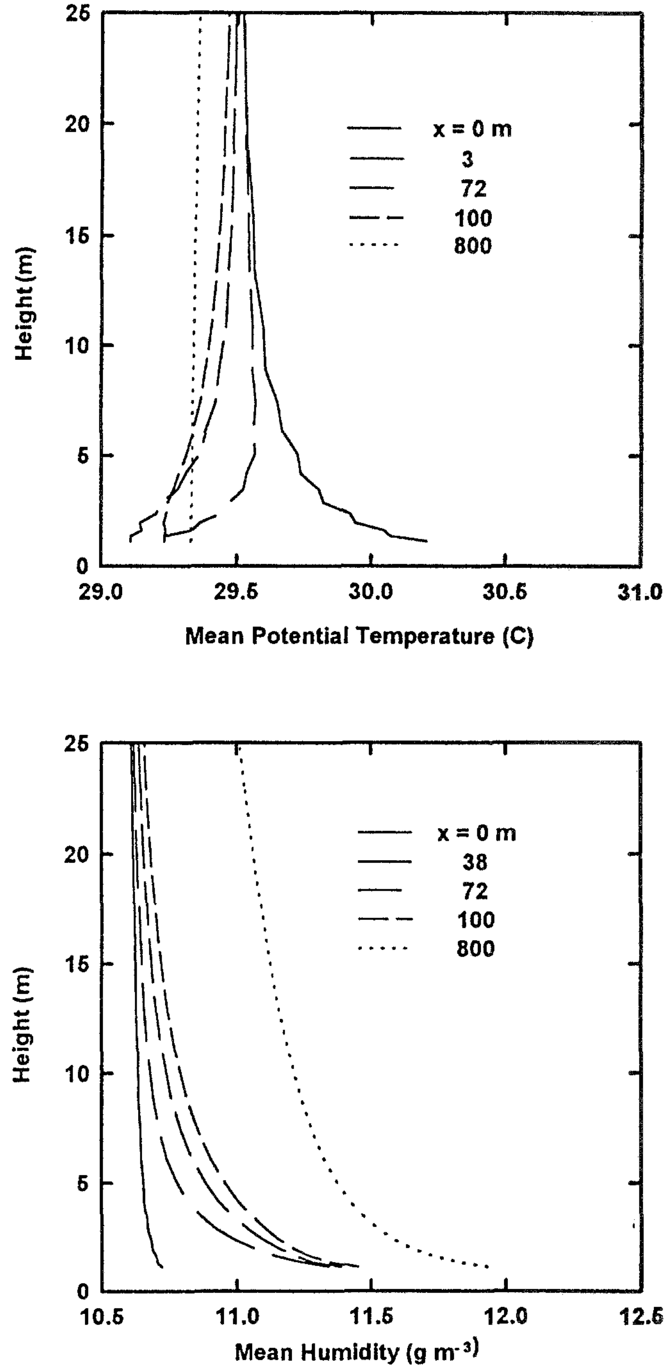


Fig. 9. Evolution of the vertical profiles of mean quantities over the irrigated field, calculated by the modified advection model of Rao *et al.* (1974a): (a) mean potential temperature, and (b) means absolute humidity. There were no observed profiles.

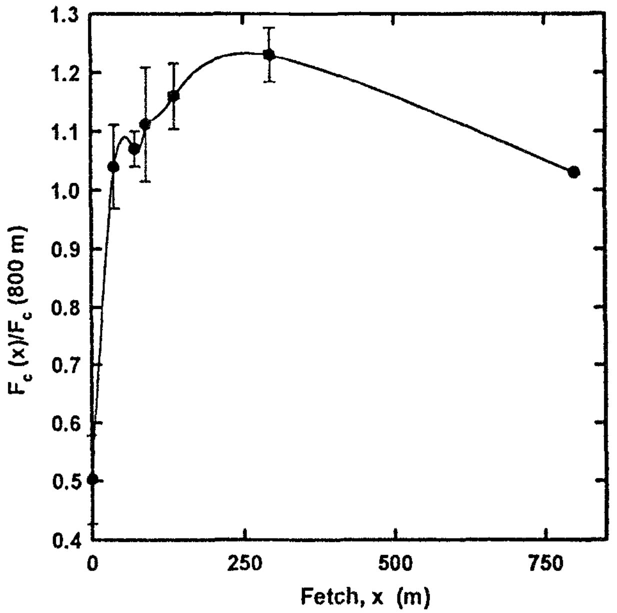


Fig. 10. Variation of CO_2 flux measured at 4 m above the ground with fetch over the potato field. The values are normalized with measurements made at tower A. The datum at 800 m was determined using the linear regression derived from the flux system intercomparison study and the mean CO_2 flux measured during the horizontal transect studies.

that the advection of humidity-deficit can cause the flux divergence of the energy balance components H and LE to be non-zero:

$$\rho L\bar{U}\frac{\partial D}{\partial x} = -\frac{\partial}{\partial z}(\epsilon H - LE). \tag{4}$$

Figure 11 presents the horizontal evolution of the normalized atmospheric humidity-deficit across the potato field. The ABL model predictions reproduce the trend of observed variation, through not the magnitude. At the upwind edge, hot air is advected over the potato field. As these parcels of dry air travel over the irrigated field, they become humidified by evapotranspiration at the surface and their humidity-deficit is diminished. By $x = 300$ m, the vapor-pressure deficit of air at 4 m has adjusted to the value measured at reference station A. These data resemble systematic patterns of humidity that has been detected with a lidar system across an irrigated alfalfa field by Cooper *et al.* (1992).

As Equation (4) indicates, advection of humidity-deficit will cause the vertical flux of LE to vary with height. To evaluate the consequence of the horizontal variation in D, shown in Figure 11, we evaluated the flux divergence of LE between the 4 m measurement height and the surface (Figure 12). The coupled micrometeorological/physiological mass and energy exchange model, CANPOT, was used to estimate the latent heat flux at the surface by forcing it with the measured

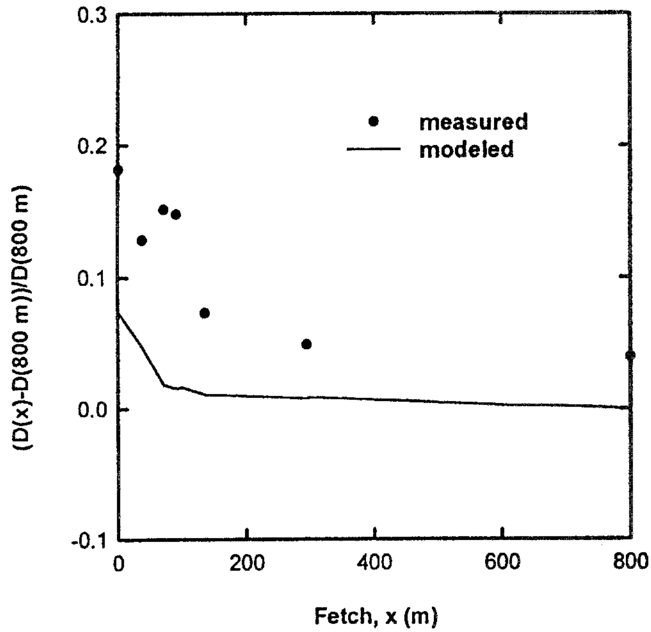


Fig. 11. Variation of the humidity-deficit of air measured at 4 m above the ground with fetch over the irrigated field. The values are compared and normalized with measurements made at tower A. The solid line shows the prediction by the modified advection model. These data are restricted to periods when R_n exceeded 500 W m^{-2}.

atmospheric humidity-deficit, wind speed, friction velocity, and available energy. We also evaluated the flux divergence of LE using the modified advection model of Rao *et al.* (1974a). The measurement-derived estimates of LE flux divergence decreased from 68 to about 19 W m^{-3} as the fetch increased from 0 to 60 m. Flux divergences estimated with the advection model show that the advection effect is concentrated within 200 m of the edge of the field.

In Figure 6 we observe how LE varied across the potato field – the latent heat flux measured at 4 m height increased with fetch. But what happened at the surface? If there was no humidity induced stomatal closure, latent heat fluxes near the upwind edge of evaporating surface theoretically should have exceeded the downwind value (Rao *et al.*, 1974a; Philip, 1987). If stomatal resistance responds to horizontal variations in humidity and temperature, negative feedbacks will occur and cause the horizontal change of LE to be small for a dry-to-wet transition under warm conditions (Kroon and de Bruin, 1993; McAneney *et al.*, 1994).

To investigate the role of feedbacks among humidity-deficit and stomatal conductance on transpiration, we used the CANPOT model to examine the horizontal variation of LE at the surface (Figure 13a). These calculations, which adjusted the surface conductance for differences in humidity-deficit, reveal an interesting pattern. Contrary to conventional wisdom, surface latent heat flux densities at the

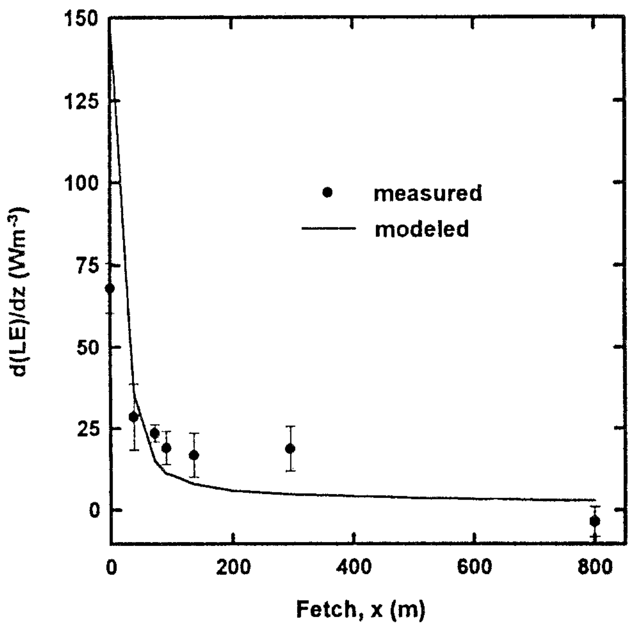


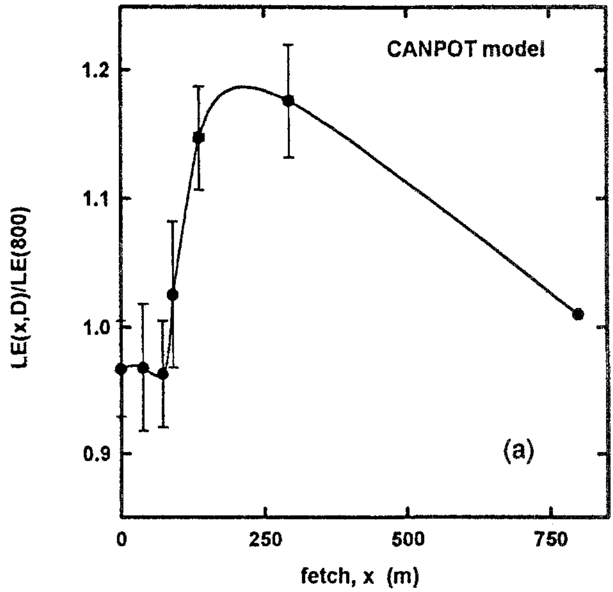
Fig. 12. Variation of latent heat flux divergence with fetch over the irrigated field. This quantity is estimated as the finite difference between LE measured with system B and LE estimated at the canopy surface with the CANPOT model. The solid line shows the prediction from the modified advection model.

edge of the potato field were not enhanced (e.g., Philip, 1987). Instead, they were less than measurements made within the equilibrium boundary layer and at the opposite end of the field.

Figure 13(b) helps explain why there was not an advective enhancement of LE at the upwind edge of the potato field. Model calculations suggest that the advection of hot dry air caused the integrated canopy stomatal conductance (G_c) to decrease relative to values calculated at the far end of the field. In other words, negative feedback occurred among D, G_c, and LE to minimize and negate the potential advective enhancement of LE at the upwind edge of the field. This result is also supported by the data analysis of McAneney *et al.* (1994).

In Figure 13(a), LE values at x = 250 m were about 18% greater than measurements at the far end of the field; this relative difference corresponds to a 75 W m^{-2} absolute difference in LE. Such intra-field variations are consistent with data reported in the literature. Cooper *et al.* (1992) used kriging to derive a map of latent heat flux across an irrigated alfalfa field in Arizona, and reported that LE values ranged between 340 W m^{-2} and 460 W m^{-2} across a 400 m domain. They attributed their observed spatial variability of LE to spatial variations in soil texture and soil hydraulic conductivity.

Finally, how do spatial variations of latent heat flux impact upon parameterization of LE for a landscape patch? The simplest landscape integration scheme would



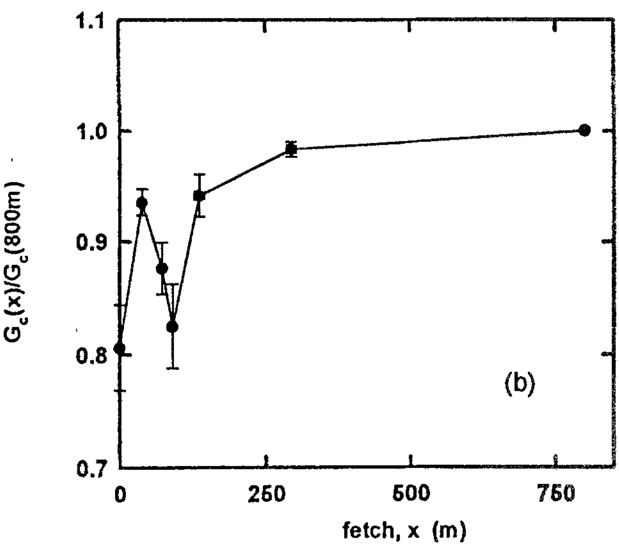


Fig. 13. (a) The estimated spatial variability of latent heat flux at the surface over the potato field. The LE values, estimated from the CANPOT model by forcing with measurements of humidity-deficit, availabe energy, wind speed, and friction velocity, are normalized with LE measured at reference station A. (b) The estimated spatial variability of canopy stomatal conductance (G_c). Stomatal conductances are estimated from the CANPOT model.

assume that the flux density over a landscape patch is horizontally-uniform. Comparing the normalized and spatially averaged LE shown in Figure 13(a) against the horizontally homogeneous value that equals the measurement made at tower A yields an 8% difference between the two schemes (1.082 vs 1.000). While this relative difference is small, it represents a 36 W m^{-2} difference from the mean LE measured at site A (494 W m^{-2}). On the other hand, the advection of hot dry air over the potato field did not greatly enhance LE near the edge of the field. Since this study was conducted in a location with strong local advection, these results suggest that intra-field variability effects may exceed advective effects. Feedbacks among turbulence, humidity-deficits, and evaporation seem to reduce the potential for advective enhancement at the field's leading edge, a conclusion that is supported by the model calculations presented here.

5. Conclusions

A field study was conducted to investigate the variability of turbulent mass, momentum and energy fluxes across an irrigated potato field located next to a patch of desert. Latent and sensible heat flux densities measured at 4 m above the surface exhibited marked horizontal variations with downwind ditance. Only after the fetch-to-height ratio exceeded 75 to 1 did LE and H become invariant with increasing distance. Significant advection of humidity-deficit occurred upwind of this threshold, causing vertical flux divergences in the measured H and LE. Consequently, the latent and sensible heat flux measurements within the advection zone must be adjusted by their local divergences to represent the latent and sensible heat fluxes at the surface. The latent heat flux at the surface was evaluated using a soil-plant-atmosphere model; a significant enhancement or suppression was not detected near the leading edge of the field from the advection of hot dry air. Friction velocity and CO_2 flux densities measured near the edge of the field adjusted rapidly to their measured values in the equilibrium boundary layer. These fluxes were relatively unaffected by the change from desert to irrigated crop, because horizontal roughness and CO_2 gradients across the farm and the desert were small. Variations of LAI within the field, however, led to intra-field variations of CO_2 flux density.

Acknowledgements

This project was a component Boardman Regional Flux Experiment in U.S. DOE's ARM Program. The first author thanks Mr. David Auble and Ms. Helen and Evo Baldocchi for field assistance, and Dr. Tilden Meyers for pre-experiment assistance. Mr. Frank Lamb of the Eastern Oregon Farming Company, provided access to his farm. Dr J. C. Doran and Pacific Northwest Laboratory organized the experiment, arranged logistical support through a DOE contract DE-AC06-76RLO 1830 and reviewed an early version of this manuscript. Additional internal review by Dr. C. A. Vogel of ATDD is gratefully acknowledged.

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