J2.4 TURBULENCE AND HORIZONTAL ADVECTION ACROSS A CANOPY EDGE: MEASUREMENTS AND COMPARISON TO MODELED RESULTS

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1. INTRODUCTION

Standard micrometeorological methods rely upon the assumption of horizontal homogeneity. The surface of the earth is characterized by heterogeneity however, and efforts to measure the exchange between representative terrestrial ecosystems and the atmosphere require investigators to work in areas where measurements are compromised by poor fetch. A growing body of work addresses this problem and also provides guidance in biometeorological site selection.

Irvine et al. (1997) looked at changes in turbulence across a smooth to rough transition and developed equations using modeled and observed flow for the growth of the internal boundary layer at the top of the canopy, but they did not consider the effects of horizontal advection explicitly. Others (Bradley, 1968; Gash, 1986; Kaimal, 1994) have done similar work using both models and measurements of changing turbulent statistics at varying distances from a canopy edge, but again without attempting to measure or model changes in scalar concentrations and advection. Baldocchi and Rao (1995) measured scalar fluxes above an agricultural canopy at varying distances from the edge of a potato field. They found that fluxes became invariant with distance beyond a fetch to height ratio of 75 to 1. To our knowledge, no one has published measurements of advection near an edge in a field experiment.

Recent work in the field of footprint modeling also aids the researcher in site selection, but these models often rely upon unrealistic assumptions, require homogeneous turbulence and/or scalar fields, are more realistic for measurements taken well above the canopy, or do not consider the effects of horizontal advection explicitly. See Schmid (2002) for a comprehensive review of footprint modeling work.

Analysis of energy budget closure, turbulent quantities, and horizontal and vertical advection from a field campaign performed across a transition from bare ground to a crop canopy help elucidate the effects of inhomogeneity on surface-atmosphere exchange.

At the heart of this work is the two dimensional Reynolds averaged scalar budget (Paw U et al., 2000).

$$\frac{\partial \bar{c}}{\partial t} + \bar{u}\frac{\partial \bar{c}}{\partial x} + \bar{w}\frac{\partial \bar{c}}{\partial z} + \frac{\partial}{\partial x}(\overline{u'c'}) + \frac{\partial}{\partial z}(\overline{w'c'}) = \bar{S}$$

Equation (1)

The first term on the left is the storage term; the second term is horizontal advection; the third is vertical advection; the fourth is horizontal turbulent flux divergence; the last term on the left hand side of the equation is the vertical flux divergence term; and the term on the right hand side of the equation is the source term.

Ecosystem and micrometeorological investigators frequently estimate the net scalar exchange between the surface and the atmosphere by integrating the vertical flux divergence and the storage term from the ground up to the measurement height and they neglect the advection and horizontal flux divergence terms. Under ideal conditions, where the turbulence and the source are homogeneous in the horizontal directions, these other terms are negligible. In reality, however, the portion of the surface affecting the turbulence and scalar fields is never perfectly homogeneous. These neglected terms are difficult to measure because they require highly-accurate and spatially representative measurements of the momentum and scalar fields. Under controlled circumstances, however, using an agricultural canopy in an area with negligible topography, the magnitude of vertical and horizontal

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advection within the canopy is estimated here. This work provides future investigators with an estimate of the magnitude of horizontal advection present downwind of a change in surface characteristics, and the relative magnitude of advective terms and the vertical covariance term are looked at with respect to distance from the change in surface.

In addition, the field estimates of mean turbulent statistics, scalar concentrations and scalar fluxes are compared to the results of a higher-order closure model (Park, 2006). This work is still ongoing.

2. METHODS

2.1 SITE AND EXPERIMENT DESCRIPTION

On the UC Davis Campbell Tract field station, research staff planted a sorghum hybrid that grew to a height of approximately 1 m. The cultivated area measured 120 m wide in the east-west direction and 180 m long from north to south. To the south of the sorghum field there was over 100 m of bare soil. The terrain was both flat and level, and prevailing winds were from the south. The one-sided LAI of the mature sorghum crop was 4.

Using four three-dimensional sonic anemometers and four infrared gas analyzers (IRGAs) 10 Hz turbulence data including CO_2, H_2O, wind velocities, and sonic temperature were measured at a height of 1.2 m at x = -10 m, 5 m, 33 m, and 143 m from the southern edge of the field. With additional three-dimensional sonic anemometers also running at 10 Hz, wind speed and sonic temperature were measured at a height of 0.5 m within the canopy at x = 4.7 m, 33 m, and 143 m. For two weeks after the canopy had reached its full height, two additional sonic anemometers were mounted near the edge, at x = 1.0 m and 2.5 m, at a height of 1.2 m. Mean temperature and relative humidity (RH) sensors were mounted in aspirated radiation shelters at four heights and at five different distances from the edge along the same transect as the fast-response instruments. Please see the diagram in Figure (1). Net radiation and ground heat flux were also measured at three different locations within the canopy and over the bare soil upwind of the canopy.

Excluding cross-calibration periods before and after the field experiment, continuous turbulence and energy balance measurements were taken at the site from June 30, 2005 until October 31, 2005. The mean scalar measurements began on August 16, 2005, before the canopy reached its full height.

2.2 DATA SCREENING AND DATA PROCESSING

All results are screened for wind direction (within 14 deg of due S), z/L (between -0.4 and 0.4), and wind speed (above 1 m/s). For the turbulence statistics every 25 available consecutive half-hour estimates are averaged together. The number 25 was chosen in order to look at the results with reasonable temporal resolution, while also reducing some of the scatter in the results through averaging.

2.3 ADVECTION ESTIMATES

U is constrained at three heights (0 m, 0.5m, and 1.2m), two by measurements and one by the ground. The scalar profile is estimated from measurements at four heights, 0.25 m, 0.5 m, 1.0 m, and 1.2 m. Using linear shape functions we estimate the horizontal gradient of the scalar (T and e) from finite differences, and numerically integrate from the ground up to 1.2 m at three different distances from the edge of the canopy.

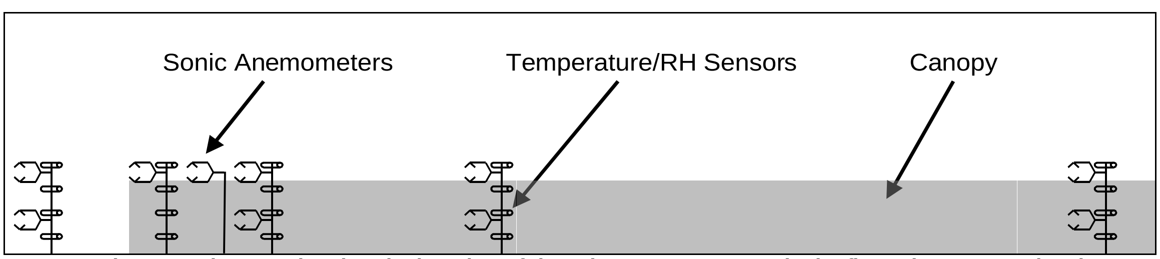

Figure 1, Diagram showing the location of the primary sensors used. The figure is not to scale. The mature canopy is 1.1 m tall, and the downwind measurements (at the right-hand side of the figure) are 144 m from the edge of the canopy.

$$\int_0^{z=1.2m} \overline{u} \cdot (\partial c / \partial x) \cdot dz \approx \sum_0^{z=1.2m} \overline{u} \cdot (\Delta c / \Delta x) \cdot \Delta z$$

Equation (2)

We estimate advection at x = 0.5 m, 2.95 m, 19 m, and 86 m. The measurements of advected quantities and the vertical eddy covariance fluxes are scaled by the net source at each location, which is estimated as the sum of all the advective and eddy covariance fluxes.

Temperature/RH measurements began when the canopy was 0.85m tall. Advection estimates are made from this time through the end of the campaign. This includes the period during which the crop grew to its full height (1.05 m), through the sorghum crop's maturity and well into its senescence.

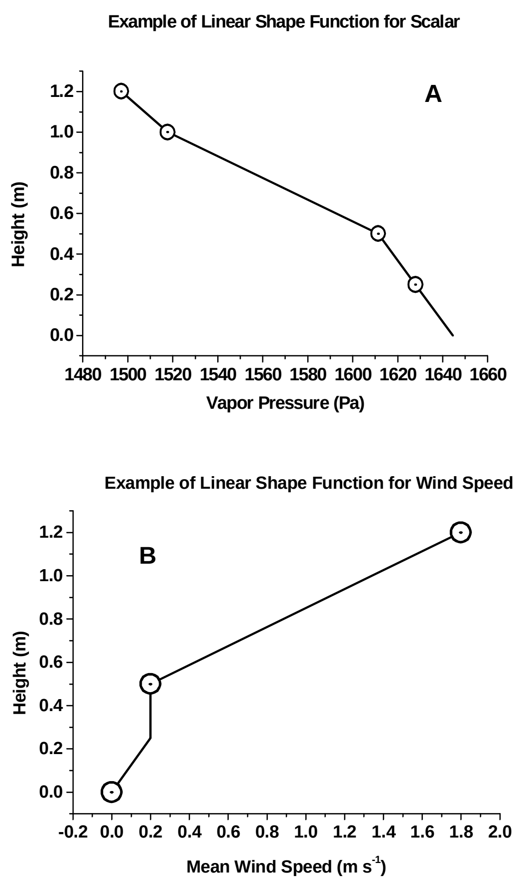

Figure 2, Linear shape functions used for advection calculations. Example scalar profile (A) and example wind speed profile (B).

Vertical advection is estimated using the assumed w profile from Lee (1998) and Finnigan (1999).

$$\partial \overline{w} / \partial z = \overline{w}_{z=1.2m} / z$$ ***Equation (3)***

Vertical advection below z = 1.2 m is estimated from

$$\Delta(x/h_c)^{-1} \int_{x/h_c}^{x/h_c+\Delta x/h_c} \overline{w}_{1.2} \left(\overline{c}_{1.2} - \frac{1}{z_{1.2}} \int_0^{z=1.2m} \overline{c} dz \right) dx/h_c$$

Equation (4)

where $\overline{w}_{1.2}$ is the vertical wind speed measured directly using carefully leveled sonic anemometers and the vertical scalar gradient is estimated from the shape function discussed above.

2.4 HIGHER-ORDER CLOSURE MODEL

Park's higher-order closure model is described in detail in (Park, 2006). Work using a K-theory model to investigate advection under similar conditions are also described in (Park and Paw U, 2004). The LAI profile of the model was changed to match the sorghum LAI profile. No additional tuning was performed on the model for the comparison. In the comparison of modeled to measured variables these variables are scaled by the upwind "reference" location corresponding to x = -10 m and z = 1.2 m. This is discussed in more detail in the results section.

For the purposes of comparing wind speeds and Reynolds Stresses, measurements from a location upwind of the canopy, at h = 1.2 m, x = -10 m (the reference point) are used to scale these variables measured downwind of the edge linearly. Only independent points are compared. During the period when the canopy is actively growing, every 20 available consecutive measurements are averaged together. Only measurements taken when the measured reference wind velocities are within +/-14 degrees of due south and +/-0.5 m s^{-1} of 2.45 m s^{-1} are used (corresponding to the reference wind speed from one run of the model). As the canopy grows, the heights of the turbulence measurements (z = 1.2 m and 0.5 m) and the distances from the edge (z = -10 m, 4.8 m, 33 m, and 144 m) change with respect to the canopy height ($z\ h_c^{-1}$ and $x\ h_c^{-1}$) and thus correspond to different points within the modeled domain. Using only data when the canopy is full grown (h_c = 1.1 m) for example, our measurements correspond to the modeled domain locations of (-9.4 h_c, 0.5 h_c), (4.9 h_c, 1.1 h_c), (4.9 h_c, 0.5 h_c), (31.1 h_c, 1.1 h_c), and (31.1 h_c, 0.5 h_c). Data recorded while the canopy changes in height provides more points to include in the comparison.

3. RESULTS AND DISCUSSION

3.1 ADVECTION AND ENERGY BUDGET ANALYSIS

The volume between x = 1.0 and 4.9 m. experiences large gradients in the scalar field and significant vertical advection. For one additional week, two carefully leveled sonic anemometers were mounted at a height of 1.2 m, two sonic anemometers were also located z = 0.5 m and at z = 1.2 m (at x = 4.9 m), and scalar (T/RH) measurements were made at four heights at both x = 1.0 m and at x = 4.9 m. Within this region horizontal advection of LE is often quite large and the vertical advection of H and LE play important roles in the energy budget as well. During the measurement campaign there are times when the net loss of water near the edge is much larger than it is further downwind.

Although we cannot estimate horizontal flux divergence from our measurements, we can assume that the horizontal flux divergence of water has a negative value near the edge, and given constant source strength, would supply more water vapor to be transported horizontally. This could be balanced in part by a positive horizontal flux divergence of sensible heat (H) when dT/dx is negative, but the magnitude of the horizontal flux divergence of H would be less than that of LE if the magnitude of H and LE advection can be taken as indicative of the energy gradients within the canopy that would fuel horizontal flux divergence. Park's (2006) higher-order closure results show that near the edge, due to flux divergence and vertical advection, horizontal advection exceeds the source strength by approximately 25%. Our results do demonstrate that a significant portion of the horizontal advection of LE is supplied by vertical advection, but the net source of LE near the edge still appears to be approximately double the value of LE at x/h_c = 130 (fig. 3). For this reason, we scale all flux estimates by the *local* net source estimated from the sum of advective and vertical turbulent fluxes.

Sensible heat near the edge shows considerable more scatter than LE when compared to downwind fluxes (fig. 4). Horizontal gradients of H near the edge change from positive to negative, and the resulting advection estimates vary accordingly. The downwind eddy covariance fluxes of H are also occasionally negative during the day due to evaporative cooling driven by what some would describe as non-local advection. Latent energy fluxes, by contrast, are always positive during the day and are negligible at night. Small changes in the relatively large LE budget have a large impact on the sensible heat fluxes, which are often within a few hundred W m^{-2} of zero.

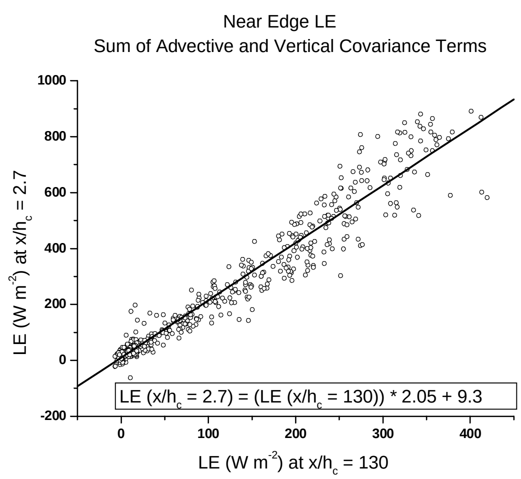

Figure 3, The net source of LE is estimated from the sum of horizontal advection, vertical advection, and vertical eddy covariance. LE near the edge is approximately double the value of the downwind (at x/hc = 130 m) LE. R^2 = 0.95.

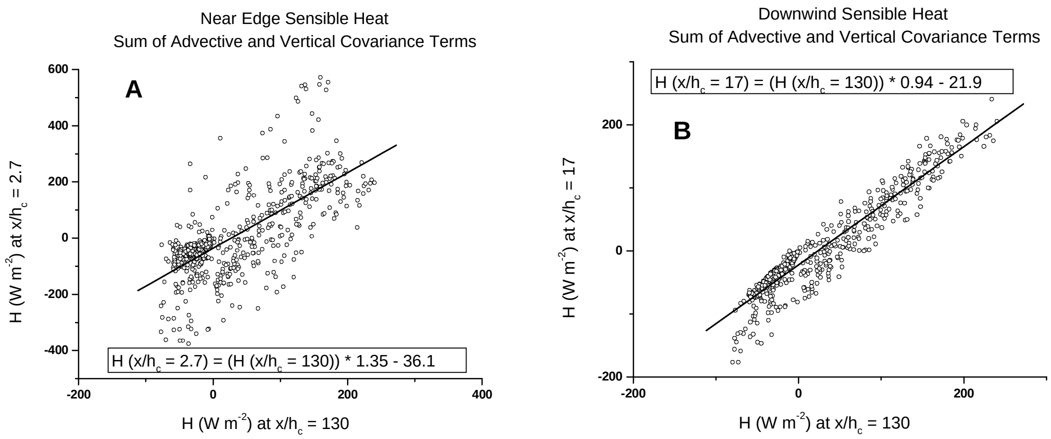

Figure 4, The net exchange of sensible heat is estimated from the sum of vertical advection, horizontal advection, and vertical eddy covariance of sensible heat. Sensible heat at x/h_c = 2.7 (A) is highly variable, and poorly correlated with sensible heat further downwind. Sensible heat from x = 19 m (B) compares more closely to the far-downwind sensible heat measurements (R^2 = 0.90).

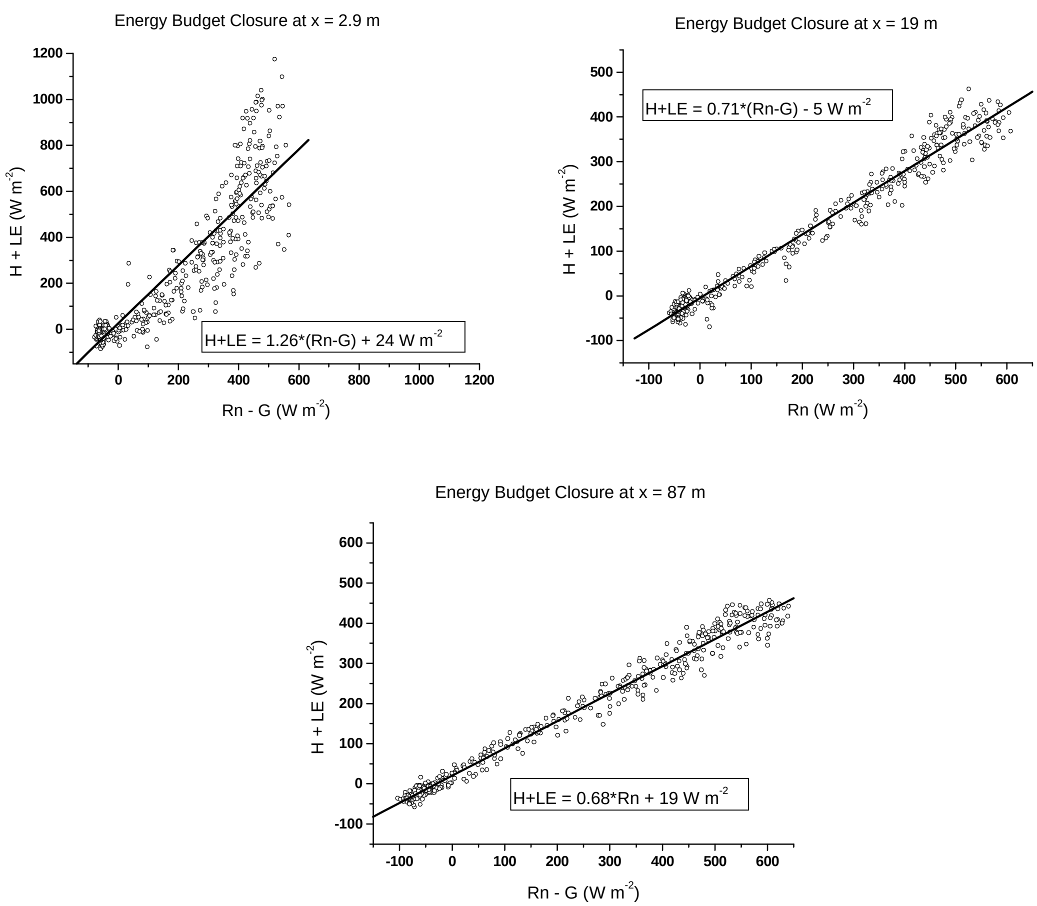

Figure 5, Energy budget closure including vertical and horizontal advection at varying distances from the edge.

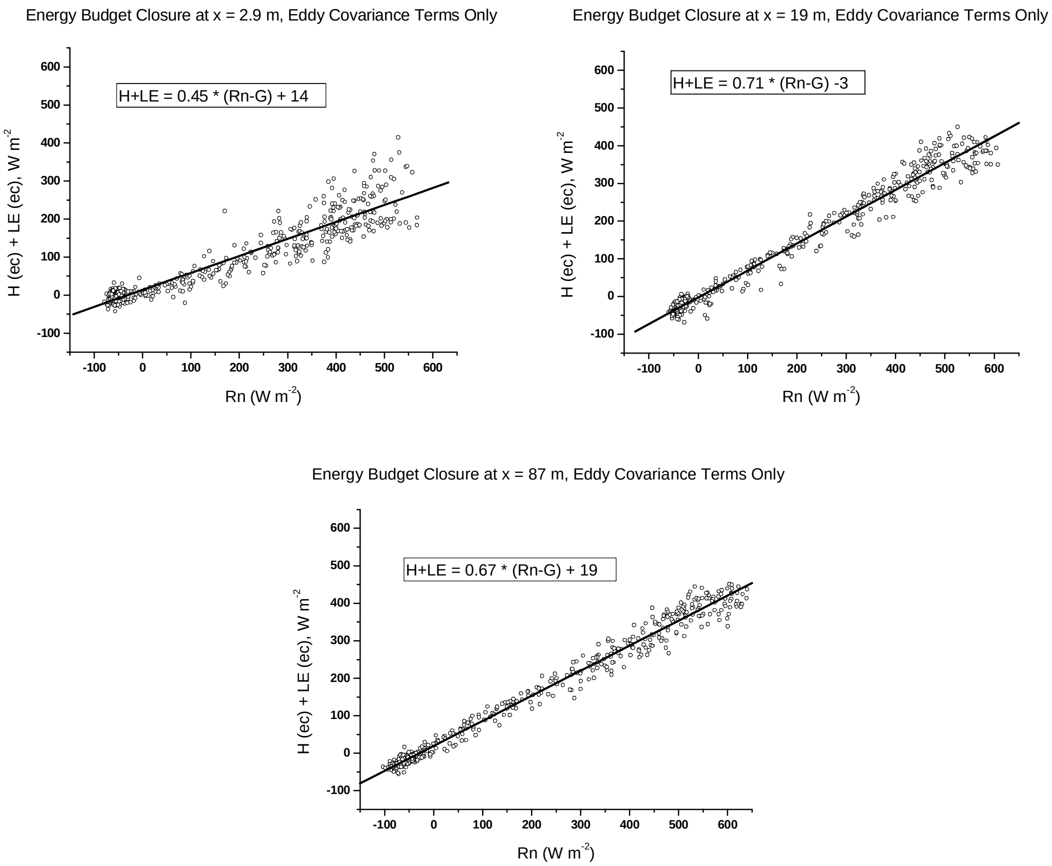

Figure 6, Energy budget closure, excluding advection terms, at varying distances from the edge.

The effect of advection on the energy balance can be negligible when the magnitude of advected sensible heat and latent energy are equal and opposite. Neglecting the advection estimates at x = 19 m, for example, has very little effect on the energy budget even though the magnitude of advected LE and H is significant.

As shown in Fig. (7), advected latent energy and sensible heat can balance each other. Horizontally advected evapotranspiration fuels the horizontal advection of sensible heat at x = 19 m. The negligible magnitude of vertical advection here makes the energy budget less complex. At x = 2.9 m however, the horizontal advection of H is much smaller than the horizontal advection of LE. Examination of the scalar budget suggests that this is because of the vertical wind velocities within this region. The often-negative and significant magnitude of vertical advection estimated from our measurements at x = 2.9 m confirm this. One can infer from this that in the special case such as at x = 19 m, where the momentum field within the canopy is fairly homogeneous, advection does not play a large role in the energy budget within the canopy. The cautious reader should

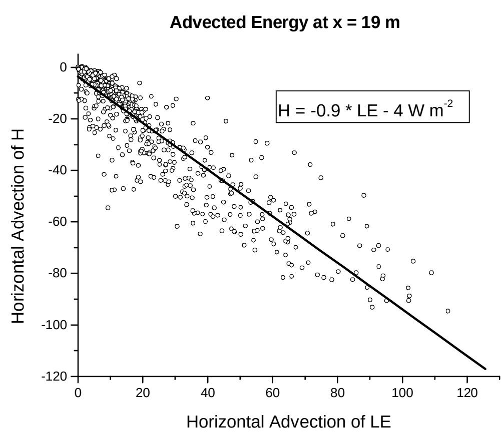

Figure 7: Advected sensible heat regressed against advected LE. R^2 = 0.84

note that these fluxes are estimated from the ground up to a height of approximately 1.1 canopy heights, and the distance downwind from a change in surface over which advection becomes negligible will be much greater when the measurement height is well above the canopy.

We estimate the local source of LE by summing advected LE with LE transported by vertical eddy covariance. The locally measured advection and eddy covariance terms are normalized by this local source, and we compare the relative importance of these transport mechanisms below in Fig. (8).

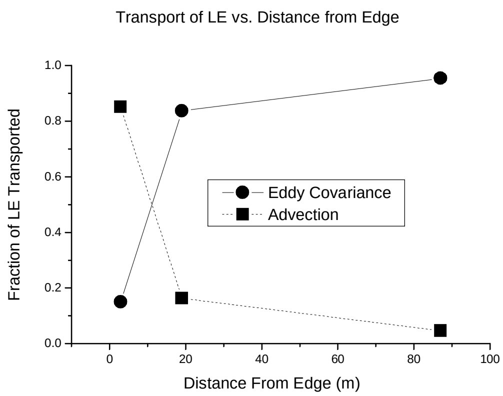

Figure 8: The sum of the vertical and horizontal advection of LE/source (dashed line with squares) and the vertical eddy covariance/source (solid line with circles). The source is estimated as the local sum of the vertical advection, horizontal advection, and vertical eddy covariance terms. Eddy covariance measurements are taken at a height of 1.2 m, and advection is estimated from the ground up to 1.2 m.

As expected, advection becomes less important further from the edge. Despite the fact that we are only estimating advection within 1.1 canopy heights of the ground, the magnitude of advection is still considerable (5.0%) at over 80 m (approximately 80 canopy heights) downwind of the change in surface.

3.2 TURBULENT STATISTICS

While the canopy is growing, every 25 points that are available after filtering for wind direction are averaged together. Near the edge (at x = 4.9 m, z = 0.5 m) we see the magnitude of the Reynolds stress increase and then decline as the canopy grows.

The canopy creates more drag as it grows, but then momentum flux decreases near the edge as the sink of much of the momentum moves above z = 0.5 m, remaining in the canopy which has grown above the sensor. In addition, momentum advected into the near edge region near the ground, beneath the bulk of the canopy, causes u'w' to be less negative. During some half hours $\overline{u'w'}$ is actually positive as the canopy absorbs momentum from the fast moving air below it, which has been injected from the edge. The sink of momentum at z = 1.2 m, x = 4.9 m, however, increases as the canopy grows. In addition to the growing canopy sinking more momentum, the source of this sink moves closer to the sonic anemometer mounted at z = 1.2 m as the canopy grows, and the anemometer therefore "sees" more of the signal generated in the 4.9 m of canopy upwind of it. One can see this is in the initial lack of response to the growing canopy near the edge in the Reynolds stress (Fig (9A), blue with upside-down triangles). Advection of momentum, or the effect of the upwind bare ground on the footprint at this near-edge location, plays a smaller role as the canopy grows. When the canopy is quite small, by contrast, at x = 4.9 m the magnitude of $\overline{u'w'}$ is similar to that of $\overline{u'w'}$ upwind of the canopy (at x = -10 m). For the same reason, when the canopy is less than 0.5 m tall $\overline{u'w'}$ from z = 0.5 m, x = 4.9 m increases much faster with the growth of the canopy than $\overline{u'w'}$ from z = 1.2 m, x = 4.9 m.

We expect $\overline{u'w'}$ to be equal at all heights upwind of the canopy, over this extensive area of bare ground, but the $\overline{u'w'}$ estimates from the measurements taken at z = 0.5 m are less negative than the $\overline{u'w'}$ estimates from a height of 1.2 m. The vertical divergence of $\overline{u'w'}$ upwind of the canopy may be due partly to spectral and path averaging errors effecting the sonic closest to the ground.

$$\overline{u'w'}(z = 0.5m) = 0.89 \cdot \left[\overline{u'w'}(z = 1.2m)\right],$$
$$R^2 = 0.98$$

We also look at changes in turbulent kinetic energy (TKE) by location and canopy height in Fig. (9B). As momentum is absorbed by the canopy, both mean and turbulent kinetic energy are absorbed. Although the canopy increases the momentum flux, it decreases the magnitude of TKE. Further

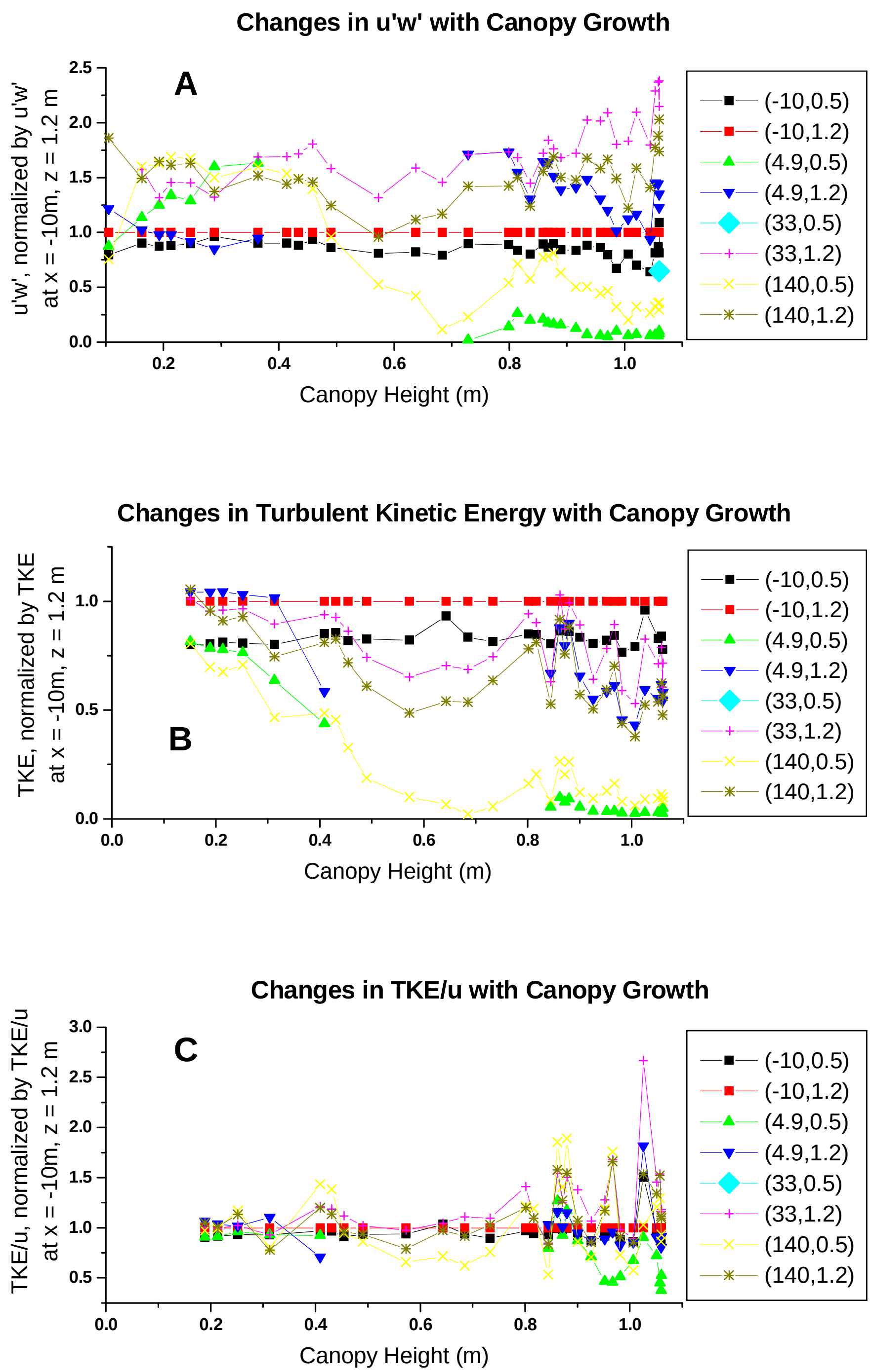

Figure 9, Changes in u'w' (A), TKE (B), and TKE/u (C) by measurement location throughout the season. Values are averaged and scaled by the upwind reference value.

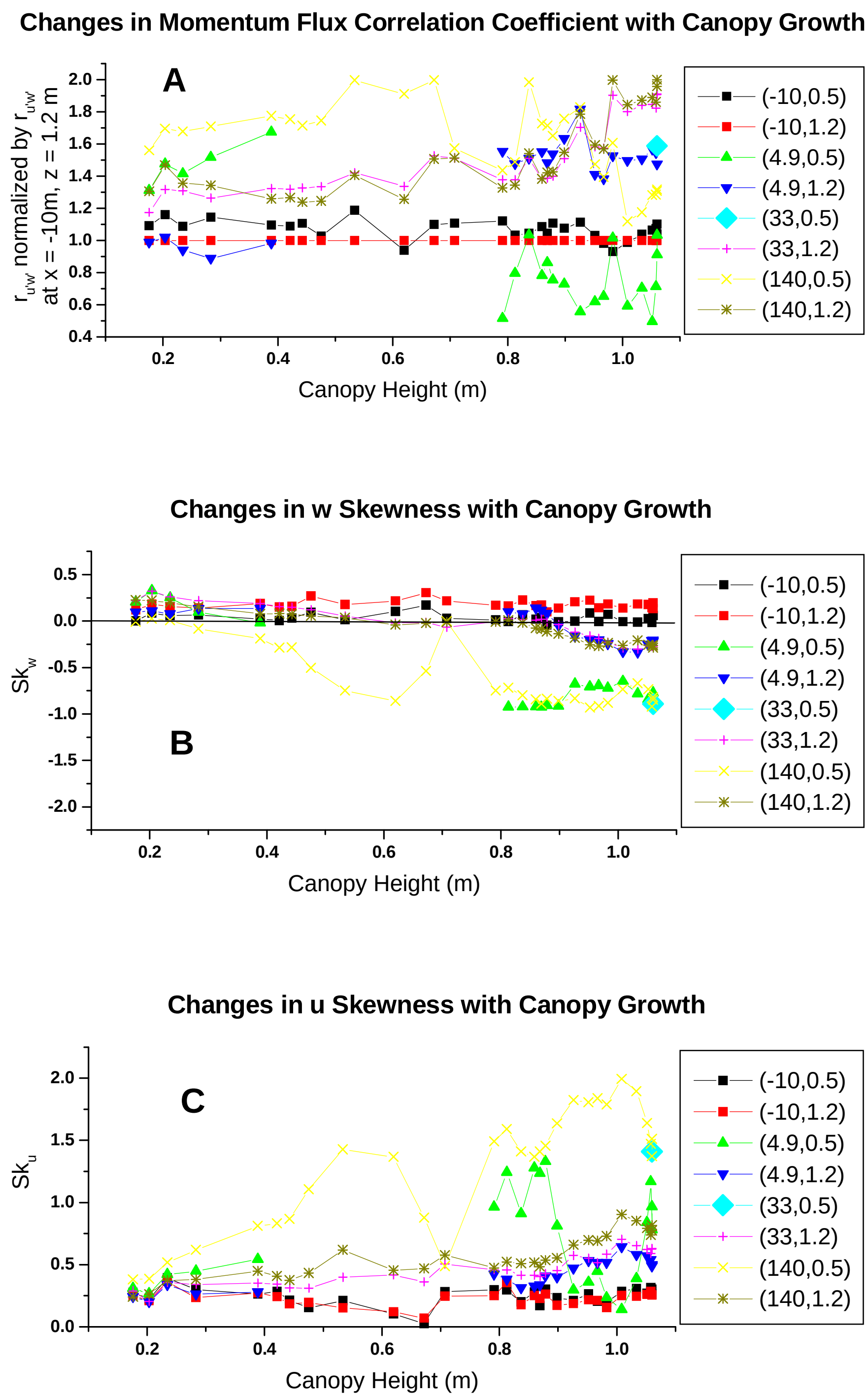

Figure 10, Changes in correlation coefficients of u'w' scaled by the upwind reference value (A), w skewnesses (B), and u skewnesses (C) by measurement location throughout the season.

downwind of the canopy edge TKE is lower, and as the canopy grows TKE diverges from the upwind bare ground TKE. TKE scaled by the mean wind speed ($TKE/\overline{u}$) however, resembles more closely the changes in momentum flux (Fig. (9C)). Some of the variability in $TKE/\overline{u}$ may be caused by the changing magnitude of the mean wind speed between averaged values.

Correlation coefficients of u'w' ($r_{u'w'}$) are scaled by the value of $r_{u'w'}$ at the reference location. Above the canopy, they increase with as the canopy grows and accordingly becomes rougher. $r_{u'w'}$ above the canopy also increases with distance downwind of the edge.

Within the canopy, at z = 0.5 m, 140 m downwind of the edge (yellow with cross hatches) for example, $r_{u'w'}$ initially increases with canopy growth, reaches a maximum when it is near the top of the canopy, and then decreases once the canopy grows well above it.

The turbulence becomes less Gaussian as the canopy grows, with u Skewnesses (Sk_u = $\overline{u'u'u'}/\sigma_u^3$) increasing as the canopy grows, and w Skewnesses (Sk_w = $\overline{w'w'w'}/\sigma_w^3$) becoming more negative as the canopy grows (Fig. 10B and 10C). These trends are more pronounced well downwind of the edge than near the edge. As expected, these values measured upwind of the edge and at different distances downwind from the edge diverge from each other as the roughness of the plant canopy increases. Sk_u and Sk_w demonstrate the increase in the relative speed and strength of sweeps vs. ejections within the canopy and near the top of the canopy as both the canopy and the internal boundary layer of the canopy grow.

3.3 COMPARISON TO HIGHER-ORDER CLOSURE RESULTS

In the figures above (Fig. 11A, 11B) the results of Park's (2006) higher-order-closure model are compared to selected results from the field experiment.

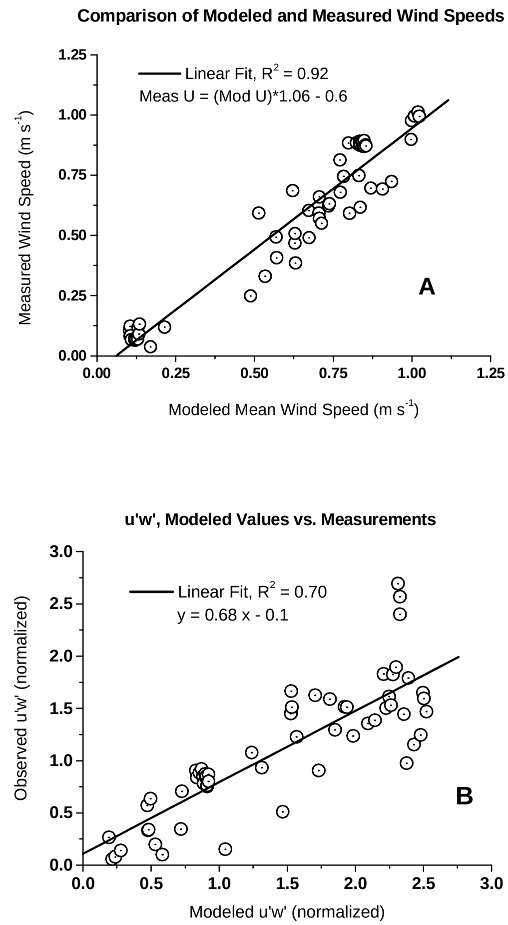

Figure 11, Mean wind speed (A), and u'w' (B) normalized by the upwind value at h = 1.2 m.

Using the same screening, scaling, and averaging techniques as for the mean wind speed data, u'w' data is compared to the modeled data in Fig. (11B). The magnitude of the observed momentum flux is smaller than the modeled momentum flux, but qualitatively the modeled and observed Reynolds stress match well.

4. CONCLUSIONS

Horizontal advection dominates the scalar transport near the edge, with a portion of the vertical transport also accounted for by vertical advection very close to the edge. Further downwind from the edge (10-15 canopy heights) vertical advection quickly becomes negligible as the vertical velocity approaches zero; horizontal advection decreases; and vertical turbulent transport becomes the dominant transport term.

Advection is important not only in the scalar budget but also in the energy budget. This is particularly true in areas where vertical advection may occur, and horizontal advection of LE may not be balanced by the horizontal advection of H. We suggest that one test for the presence of non-turbulent vertical transport or horizontal flux divergence in areas where horizontal advection is significant would be to search for inequalities between the magnitude of horizontal advection of H and LE.

It is interesting to note that despite the apparent edge-enhanced levels of ET, no visible heterogeneity in the canopy was observed during the experiment. The entire field began senescing at the same time, and the sorghum plants at the upwind edge of the field appeared to be as green, as tall, and as vigorous as the plants throughout the rest of the field. Irrigation of the field was conducted carefully by researchers and UC Davis agricultural staff with the goal of applying water to the field as homogenously as possible, and there is no reason to suggest that the downwind edge received more water than the rest of the field. Sorghum plants are known to have deep root systems however; because of this and because our irrigation strategy was to keep the plants well watered in order to avoid the possible effects of heterogeneous irrigation, it is possible that within the clay soils at the site there was sufficient water for the plants near the edge to experience enhanced transpiration without suffering from a lack of soil moisture.

The turbulent statistics demonstrate known phenomena about plant canopy turbulence, with momentum flux increasing with canopy height and the importance of sweeps becoming more prevalent (Finnigan, 2000; Raupach and Thom, 1981). In addition to having the opportunity to look at changes in turbulence as the canopy develops, we see how the turbulence develops as a function of the distance from the change in roughness. The growth of the internal boundary layer is apparent in all of the turbulence statistics analyzed. Near the edge of the canopy where momentum is injected into the canopy near the ground, evidence of highly non-classical behavior is apparent in the mean wind speed, momentum flux, and other turbulent statistics.

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