Areally Averaged Estimates of Surface Heat Flux from Field Studies for the Atmospheric Radiation Measurement Program

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Introduction

The determination of areally averaged surface fluxes is a problem of fundamental interest to the Atmospheric Radiation Measurement (ARM) Program. The Cloud and Radiation Testbed (CART) sites central to the ARM Program will provide high-quality data for input to and verification of general circulation models (GCMs). The extension of several point measurements of surface fluxes within the heterogeneous CART sites to an accurate representation of the areally averaged surface fluxes is not straightforward. As the CART sites become fully operational, several different types of measurements, including vertical profiles of meteorological variables, can potentially be used synergistically with point measurements to provide reliable estimates of surface fluxes averaged over large areas.

To investigate these problems, ARM science team members conducted two field studies near Boardman, Oregon, during June of 1991 and 1992. The site was chosen to provide strong contrasts in surface moisture while minimizing the differences in topography. The region, described in detail by Doran et al. (1992), consists of a substantial dry steppe (desert) upwind of an extensive area of heavily irrigated farm land, 15 km in width and divided into 800-m-diameter circular fields in a close packed array, in which wheat, alfalfa, corn, or potatoes were grown (Figure 1). A full rotation of the irrigation arm was completed approximately once every 28 or 35 h during the growing season. This region provides marked contrasts, not only on the scale of farm-desert (10-20 km) but also within the farm (0.1-1 km) because different crops transpire at different rates, and the pivoting irrigation arms

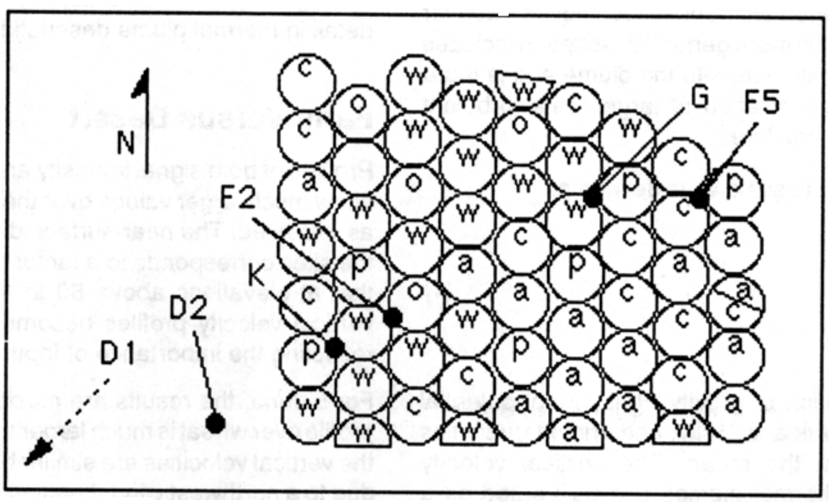

Figure 1. Farm crop locations and instrument locations (solid dots) in 1992. Field types are w (wheat), a (alfalfa), c (corn), or p (potatoes). With prevailing wind from the southwest, the crop sampled is to the southwest of instrument site. The D1 location, not to scale, is 8 km west of the farm. Site G is the location of the permanent minisodar. Capital D and F stand for desert and farm, respectively.

provide an ever-changing pattern of heavy surface moisture throughout the farm area. This paper primarily discusses results from the 1992 field study.

Thermal Plumes

Convection is the principal mechanism by which the atmosphere transports energy from the surface layer throughout the mixed layer. Thermal plumes, large regions of buoyant, rising air whose maximum height is limited by the top of the mixed layer, dominate the convective boundary layer. They scale with the height of the mixed layer (z_i), are the large-scale source of energy input to the turbulence spectrum (Stull 1989), and provide the mechanism for transferring energy from the surface through the mixed layer and into the capping inversion. When conditions are appropriate, fair-weather cumulus clouds develop at the top of the thermal plumes. In this sense, small cumulus clouds provide a visual description of the size, location, and lifetime of mature, active thermal plumes in a deep mixed layer. Traveling with the mean wind, thermal plumes act as a conduit for heat and moisture between the surface and lower troposphere.

We can define thermal plumes either as organized regions of rising air or more generally as organized regions of enhanced "thermal turbulence" that can be depicted by large values of the temperature structure parameter C_T^2, which can be evaluated with sodar techniques (Coulter and Wesely 1980). This more general description includes some regions of entrainment into the plume and is more descriptive of the organization of large scale turbulent transfer of heat and moisture.

The convective velocity scale w_* is defined as

$$w^* = \left[\frac{g z_i}{\theta_v} \overline{w' \theta_v'} \right]^{1/3} \quad (1)$$

where g is acceleration of gravity, θ_v is virtual potential temperature, w is vertical velocity, and primed quantities are deviations from the mean. The vertical velocity fluctuations within thermal plumes can be treated as a measure of w^*, which ties the surface heat flux and the mixed layer together precisely as does a thermal plume. Measurements have shown a positive difference in both temperature and moisture between plume and ambient air, as this definition of w^* implies.

The potential usefulness of thermal plumes in quantifying areal averages of surface heat flux results from the relatively long lifetime of a coherent structure that, in traveling with the mean wind, is representative of the integrated surface heat flux input from all the surfaces over which it has passed. A plume lifetime of 30 min with a mean wind speed of 5 m/s results in a 9-km path. One can also surmise that the relationship of the profile of either C_T^2 or w to surface forcing is height dependent; that is, the near-surface portion of the profile is closely identified with "nearby" surfaces, while the upper portion is an integrated sample of more distant surfaces.

Two minisodars were used in 1992 to sample relative heat flux contributions within the study area. One minisodar, permanently stationed upwind (most of the time) of an actively growing wheat field (site G) measured three components of the wind and C_T^2. The second, a portable, single-axis system, measured only vertical velocity and C_T^2 and was placed at various locations (solid dots in Figure 1) for periods ranging from several hours to a day or two. Thus, a benchmark was maintained at site G to facilitate intercomparisons among different fields. Averaging times varied from as long as 30 s (about 24 samples) to 0 s (every pulse recorded). The data reported here were not averaged prior to this analysis, permitting the maximum detail in thermal plume description.

Farm Versus Desert

Profiles of both signal intensity and w (Figure 2) on 4 June show much larger values over the desert than over wheat, as expected. The near-surface difference in C_T^2 between the sites corresponds to a factor of nine in heat flux. Note that at elevations above 80 to 100 m the intensity and vertical velocity profiles become more similar, perhaps reflecting the importance of input from larger scales.

For 5 June, the results are much different. The intensity profile over wheat is much larger than that over desert, and the vertical velocities are similar below 40 m. This result is due to a northwest wind direction at site G that apparently allows the desert-like boundary region between fields to dominate at very low levels. The steep fall-off of the

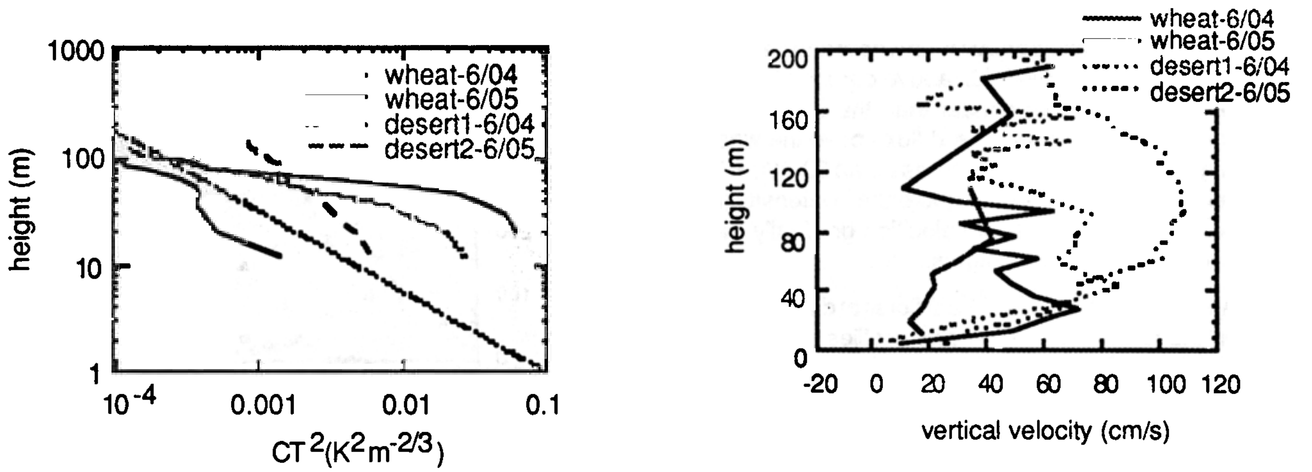

Figure 2. Signal intensity and vertical velocity profiles within plumes above wheat and two desert sites. The desert2 site was located about 0.5 km west of the farm. The dashed straight line is a reference line with slope proportional to $z^{-4/3}$.

intensity and velocities above 40 m corresponds to sampling of the wheat field to the northwest of site G. In addition, this desert site, unlike that on 4 June, was located very near the eastern edge of the desert and was under the influence of the easterly "farm breeze" during this averaging time. Hence, the low-level intensity profile is depressed; however, the upper levels reflect a steep increase in values, probably coinciding with wind direction reversal to southwesterly above the farm breeze.

Farm Versus Farm

Comparisons of wheat (at G), potatoes and corn are shown in Figure 3. Near-surface values of intensity and w over wheat and potatoes are similar; however, even though the vertical velocities become very similar at larger altitudes, the intensities at larger altitudes above potatoes rapidly become very small. This is surprising, because the desert is upwind of the potato field.

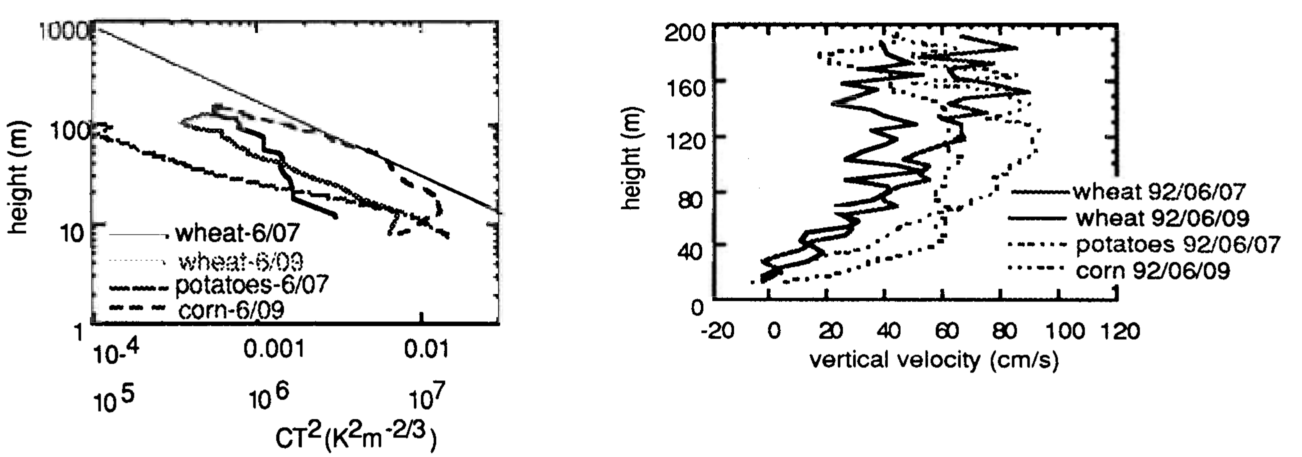

Figure 3. Signal intensity and vertical velocities within plumes above wheat, potatoes, and corn.

Well-behaved profiles above both wheat and corn translate to about 70% more heat flux above corn than wheat. The wheat crop was much denser than the corn; preliminary eddy correlation values of heat flux above the wheat field were quite small, usually much less than 50 W/m^2. Profiles well above both crops tend to increase in intensity (relative to the $z^{-4/3}$ slope). Vertical velocities gradually merge to similar values at larger heights.

Comparison between two wheat fields at different locations within the farm (Figure 1) shows profiles of both intensity and vertical velocity (not plotted) that are almost identical; slightly smaller near-surface values and similar velocities and slightly larger intensities above 100 m appear at site G, but these differences may not be significant.

Estimates of the ratio of w^* values at the control site to values at the other locations are given in Table 1. The values of w^* were determined by taking the maximum values within the profiles.

These values probably underestimate the maximum values within the thermal plumes because the limits of the plumes were determined by large values of intensity rather than by large w. Actual values of w^* will be larger than those calculated from these data.

Conditional sampling of minisodar data was used to produce vertical velocity profiles within thermals that were extrapolated to the middle of the mixed layer in order to produce estimates of the mean vertical velocity in the thermal plume. These estimates were then used as measures of w^* along with estimates of the capping inversion height determined from airsonde releases to produce estimates of H from (1). We note (Figure 4) that

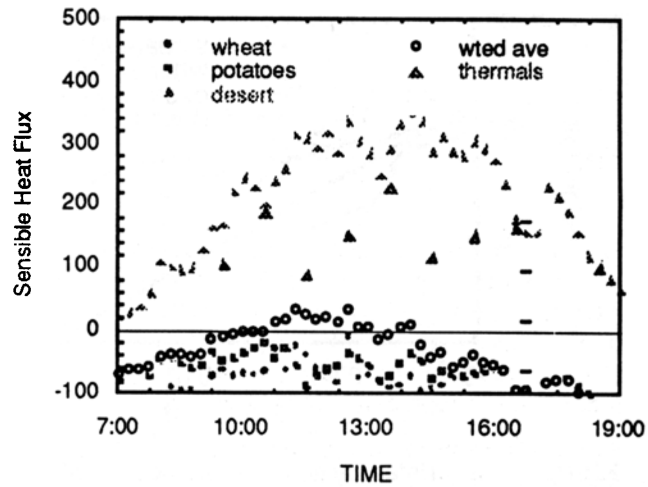

Figure 4. A comparison of heat fluxes via direct, local measurements 4 m above wheat, potatoes and desert on 7 June 1992, with an areally weighted average from the farm and values derived from thermal plumes representative of the mixed layer located approximately 1 km from the farm-desert interface.

the coherent structure values are again representative of an average of the underlying surfaces. The values from coherent structures are very appealing as a measurement tool because they are derived from structures that have a definite lifetime, during which they travel with the mean wind over a significant distance. The conditional sampling procedure concentrates the analysis within those portions of the atmosphere most responsible for vertical transport and mixing.

Table 1. Estimated ratios of convective velocity scale and heat flux at selected sites to those at the permanent wheat site G. 1991 estimates are from eddy correlation values.

	Desert1	Desert2	Potatoes	Corn
$w^*/(w_*)_w$	1.67	1.83	1.36	1.44
H/H_w	4.66	6.13	2.52	3.01
H/H_w 1991	4-5		1.5-2	1.8-2

Transfer Functions

If one assumes, for the farm-steppe system, an exponential form for the relative downward influence of horizontally separated surface inputs and assumes that the horizontal sampling of a measurement at height z is limited to a distance 10z, a relationship for the surface heat flux "seen" at height z is

$$H(z) = \frac{1}{\int_0^L e^{-gx/z}} \left(H_f \int_0^d e^{-gx/z} + H_d \int_d^L e^{-gx/z} \right) \qquad (2)$$

which becomes

$$H(z) = \frac{H_f\left(1 - e^{-\frac{gd}{z}}\right) + H_d\left(e^{-\frac{gd}{z}} - e^{-gm}\right)}{1 - e^{-gm}} \quad (3)$$

where H_f and H_d are the average values across the farm and desert, respectively; g is a distance constant determining the relative horizontal importance with height; and L = mz is the horizontal integration distance. Indeed, H_f could be calculated by using a similar expression with more terms to represent each irrigation plot.

Figure 5 illustrates how this type of transfer function would appear over the farm portion of the study region in the case where the farm is downwind of the desert. The plotted points are "average" values determined from coherent structures over farm locations at different distances from the farm-desert interface (not on the same day). The farm has an apparent effect on desert values just upwind of the interface. This may be due to effects of the local farm breeze circulation prevalent on the day of these measurements. This effect would not be accounted for with this transfer function, because it assumes the farm is downwind of the desert.

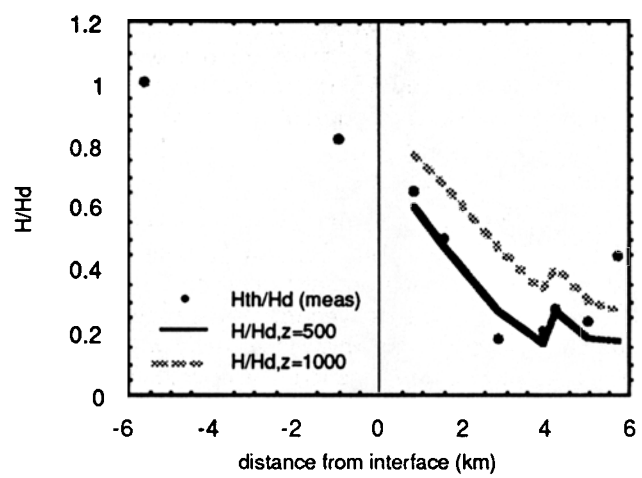

Figure 5. Variation of H measured from thermal plumes (Hth) normalized by measured heat flux over the desert and H/Hd calculated from Equation (3) with different assumptions of effective measurement height. The values of Hf/Hd used in Equation (3) are those determined from measured values over desert and farm.

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References

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