Measurements of Surface Heat Flux Over Contrasting Surfaces

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In a multilaboratory field study held near Boardman in northeastern Oregon in June 1991 and described in greater detail elsewhere (Doran et al. 1991), various properties of the surface and lower atmospheric boundary layer over heavily irrigated cropland and adjacent desert steppe were investigated. The locale was selected because its disparate characteristics over various spatial scales stress the ability of general circulation models (GCMs) to describe lower boundary conditions, particularly across the discontinuity between desert (in which turbulent flux of heat must be primarily as sensible heat) and large irrigated tracts (in which turbulent flux of latent heat should be the larger term).

Objectives

This component of the initial Atmospheric Radiation Measurement (ARM) campaign seeks to increase knowledge through three critical activities: 1) determining the relationships between surface heat fluxes measured over multiple scales and the controlling surface parameters within each scale, 2) integrating local and nearly local heat flux estimates to produce estimates appropriate for GCM grid cells of 100- to 200-km horizontal dimension, and 3) characterizating the growth and development of the atmospheric boundary layer near transitions between surfaces with strongly contrasting moisture availabilities. The operational portion of the campaign took place very recently; thus, the results drawn to date must be regarded as very preliminary.

The initial effort of this particular project is being devoted to the determination of new methods for estimating areal averages of surface heat flux because much of the remote sensing technology necessary for the extension to scales on the order of a Cloud and Radiation Testbed (CART) site (100 to 200 km) is not available to us at this time. The results of these preliminary investigations will provide the springboard to the effective use of CART instrumentation for site characterization.

Approach

The approach taken toward the estimation of large area averages of surface heat flux, both within the overall design of our ARM project and in the initial field study in Oregon, has been to measure the surface heat flux at several different spatial scales. This implies the use of several different types of instrumentation, much of it involving remote sensors. Large-scale measurements and those at smaller scales nested within are compared and contrasted in order to determine inter-scale transfer functions. These transfer functions are expected to depend upon topography, land use, vegetation, stress, and meteorological conditions. At larger scales, "direct" measurements of heat flux will be replaced with measurements of atmospheric structure such as mixing layer height, capping inversion depth, and inversion strength; thermal plume dimensions will be used to infer heat flux over larger and larger scales.

During this field study, "direct" measurements of surface heat flux were made using point measurements of the correlation of vertical velocity (w) and temperature (T) (sonic anemometer-fine wire thermocouple), vertical profiles of the volume average of the temperature structure parameter (C_T^2) (sodar and minisodar), and line averages of C_T^2 (laser anemometer). Indirect measurements included tethersonde profiles of temperature, wet bulb temperature (T_w), wind speed (S) and wind direction (d), mixing height (z_i), and capping inversion depth and strength. These measurements were made on both sides of the interface between dry, unfarmed land (desert) and irrigated cropland (over crops of corn and potatoes).

Site Description and Sampling Locations

The agricultural fields, irrigated by linear sprinkling systems rotating around a central pivot, are circular and about 800 m in diameter. A typical rotation rate is about 12 deg/hr, but irrigation is not continuous, as the farming company makes daily decisions about sprinkling on the basis of crop stage and ambient conditions. Potatoes, alfalfa, corn, and wheat are the dominant crops. Each circular field is essentially a homogeneous surface except for a bare sand road about 3-m wide leading to the pivot; wider sand roads encircle each field. The offset "cookie-cutter" arrangement of the circular fields leaves concave triangular areas of unused land, which tend to have vegetation similar to that of the desert but somewhat taller because the desert is grazed in the early spring. Overall, about 10% of the agricultural area is uncultivated.

Surface and boundary layer properties over the desert and fields of corn and potatoes were intensively studied in the investigation component described here; the fields were located at the western or prevailing upwind edge of the farm. A layout of the intensive measurement area (known as site K in the overall experiment) is shown in Figure 1.

Five sodars and minisodars were aligned across neighboring surface types characterized by different moisture availability and vegetative cover. The rover minisodar was designed for easy portability; its alternate locations are shown in the potato field and in the desert.

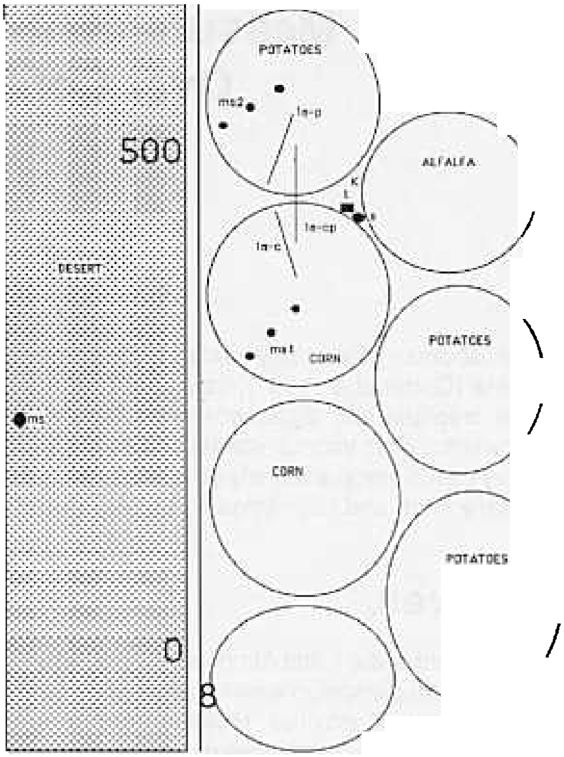

Figure 1. Configuration of ANL instrumentation during field study. Alternate positions are shown for the rover minisodar (ms) and the line of three vertically pointing minisodar antennae (ms1, ms2). Positions of the 12-m high eddy correlation tower (t) and sodar (s) are indicated by the solid square and circle. Laser anemometer paths across the potatoes (la-p), corn (la-c), and their interface (la-cp) are indicated by straight lines. The site K tethersonde was operated near the tower and desert tethersonde near the desert minisodar.

The desert in which the rover was sometimes located is not drawn to scale, as it was 6 to 7 km from the core operations. Alternate locations are also shown for a three-axis minisodar system that was operated as a row of three single-axis vertical minisodars in this ARM experiment. Three laser anemometers were operated essentially continuously in the potatoes and corn and across their junction, as shown in Figure 1. The paths are not precisely parallel because of the need to avoid a Bowen ratio station located in the potatoes and the desirability of orientation along radii from the sprinkler pivots to minimize down time as the sprinklers passed. The central path (cp) was about 20% longer than the other paths because the laser transmitter and receiver, each atop poles of about 2.5 m, had to be located where the tires and sprinkler heads of the rotating irrigation system would not contact the instruments and the supporting guy wires. The laser equipment was normally bagged for 1 to 2 hr to protect it from spray as the sprinklers passed. Other supporting instrument systems included three tethersondes aligned along the prevailing wind (WSW) at sites in the desert, about 800 m into the irrigated area, and in the middle of the irrigated area (site R, not shown) and a 12-m-high eddy correlation tower 800 m into the irrigated area.

Results

Meteorological conditions during the three weeks of the field study were less than ideal for the experimental goals and plans. Tethersonde sites and minisodars were aligned along the normally prevailing flow (WSW) and the laser anemometer paths were oriented approximately normal to the expected flow. However, the strong WSW flow tended to hamper tethersonde operations (Doran et al. 1991), particularly over the desert. In addition, extensive cloudiness, virga, and even light rain were more frequent than expected for a desert steppe; on those occasions, the reduction in heat loading to the surface by solar radiation reduced the contrasts in turbulent heat exchanges over different surfaces.

One of the revealing descriptors of the effects of contrasting surface characteristics is the vertical profile of the temperature structure parameter. This profile is a function of the surface sensible heat flux (H) and the height above the surface in unstable conditions; with increasing stability, it becomes dependent upon stress. The vertical profiles of C_T^2 derived from analysis of the acoustic signals reveal boundary layer growth and development, temporally through their individual evolutions and spatially along the vertical cross section produced from the aligned profiles. The near-surface portion of the profile is characteristic of H on the local scale, while higher portions of the profile reflect H over increasingly larger areas. We hope that averaging H over surfaces with very different typical values of H will produce a unique profile that will provide insight into the averaging process.

Figure 2 shows the sodar intensity profiles on the morning of 18 June. Although this day was not ideal in terms of wind direction (NE) and cloud cover (cloudy), conditions served to limit boundary layer growth so that the minisodar could delineate spatial features for much of the day.

The increased amount of structure at heights 50 m above the potato field is apparent. Because the wind is from the NE, the minisodar "sees" near-surface profiles representative of potatoes and irrigated fields nearby. The portion of the profile in the elevated layer above 80 m is apparently representative of the desert to the east of the irrigated fields rather than to the west. If that is so, then the profile above 80 m or so may result from air that was originally representative of desert and has been modified during its passage above the irrigated fields. The "sudden" change in slope of the profile immediately above the near-surface

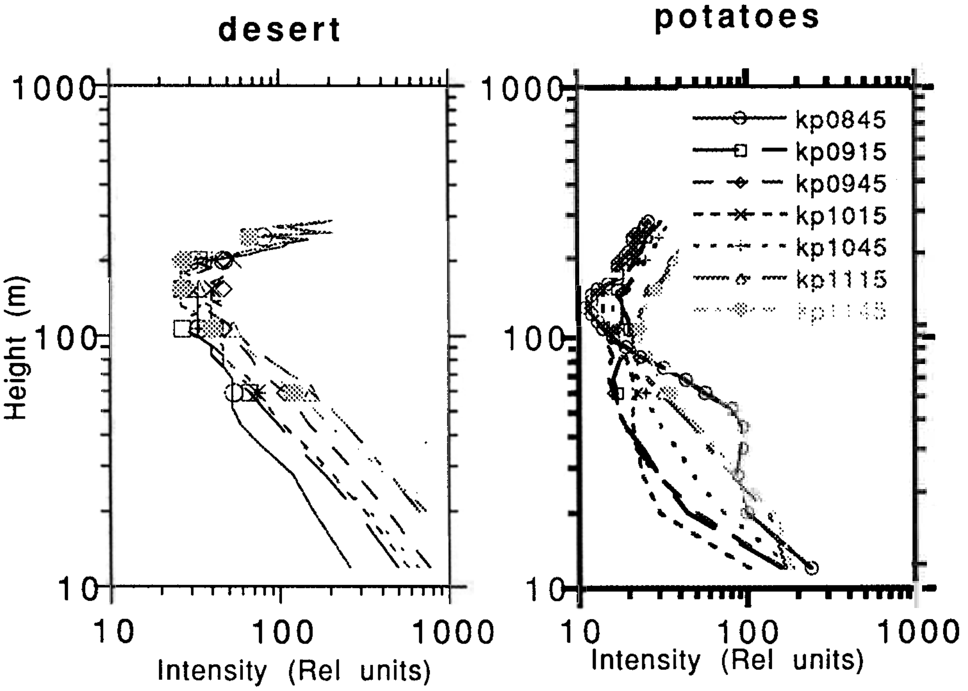

Figure 2. Vertical profiles of sodar intensity (uncalibrated) from desert and K sites. Profiles are from identical time periods. The same line style sequence is used in both plots.

layer represents the interfacial, or matching, layer between the two sections. Since the slopes of the profile below and above the matching zone are nearly the same and are characteristic of unstable conditions [dlog(C_T^2)/dlog(z) = -4/3], one can calculate a value for surface heat flux that is representative of those two air masses. In comparison, the profiles from the desert site are relatively free of structure, with -4/3 slope well above 100 m because of the more vigorous mixing over the desert.

Figure 3 shows the calculated temperature and wet bulb temperature (T_w) profiles from site K and the desert site for the only time at which they were both operating.

Note that the profile from above the potatoes shows a marked transition from relatively moist, cool air to drier, warmer air about 180 m above the surface. Above this height, the temperature profile above the potatoes is more stable at 200 m, after which it is almost the same as that over the desert. This is indicative of the mixing and entrainment that take place well above the surface of contrasting land types. This structure is largely the result of differing sensible and latent heat over those same surfaces.

Figure 4 shows the result of calculating the heat flux from the minisodar profiles above and below 80 m. Note the much larger heat fluxes calculated over the desert than over the potatoes. Note also that the "elevated" profile above the potatoes represents some measure of heat flux that is representative of both sites. We cannot claim that this method is the best or most representative for this situation. It is, at present, one method under investigation for such calculations.

Line averages of index of refraction structure function C_N^2 over contrasting surfaces were produced through scintillation measurements with the laser anemometers over paths approximately 200-m long and 2- to 3-m high in corn, potatoes, and across the corn/potato interface. The variations in the path heights resulted from the slightly rolling surface of the fields. The principal component of C_N^2 is C_T^2, which can be related to heat flux in the same way as the sodar measured values (Wyngaard and Clifford 1978). In

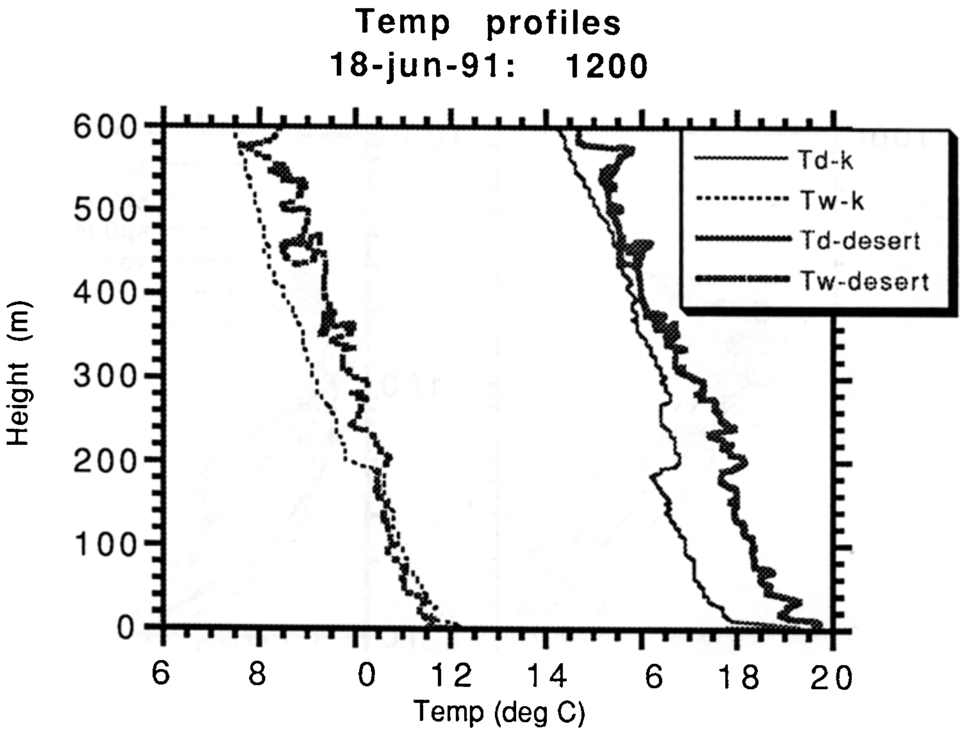

Figure 3. Temperature profiles from simultaneous tethersonde flights above desert and K sites. The absolute accuracy of wet bulb temperatures is no better than 3°C; thus potato and desert T_w quite possibly agree above 180 m.

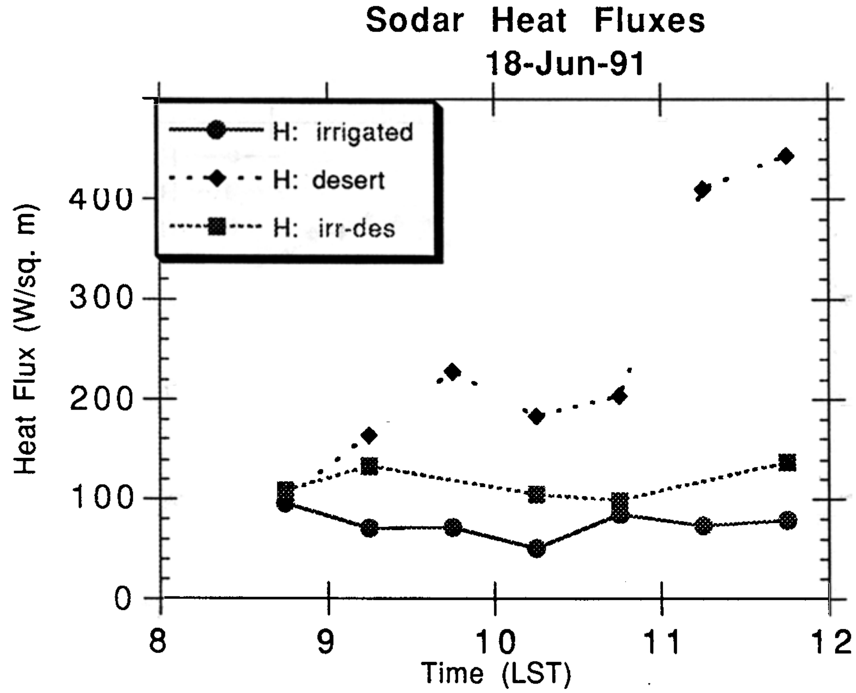

Figure 4. Sodar-derived heat fluxes from near-surface profiles above desert and potatoes. Middle profile (denoted as irr-des) is derived from "potato" profile above 80 m and has effects from irrigated and desert land.

this case, the line averages of C_T^2 at a single height are directly related to the heat fluxes from surfaces beneath them and immediately upwind. During the experiment, the potato field was irrigated more regularly than the corn field, and the effective leaf area index of the potatoes was much greater. In addition, cool weather slowed the growth rate of the corn. One would thus anticipate that latent heat flux would be relatively more important (or sensible heat flux would be relatively less important) for the potato field than for the corn field. Indeed, the C_N^2 values from the laser anemometer path in the potatoes were regularly less than from the path in the corn. The path across both crops usually indicated an intermediate value of C_N^2, but analysis and understanding are complicated because the path included a dry, bare segment (the 10-m boundary road) between the fields.

Calculated values of heat flux for 10 June 1991 from the laser anemometer data are illustrated in Figure 5. Although these absolute values cannot be assumed to be final, the relative values are presumed to be reliable.

Note the decrease after 1015 of the heat flux above both the potato field and the combined path. This is most likely due to the sprinkler system that was operating within the potato field at this time. The laser anemometer systems were, in fact, turned off at 1300 as the sprinkler passed over the potato and corn/potato paths. Evaporation of standing water on the plants and ground upwind of the path decreased the sensible heat flux even before the sprinkler passed directly over the laser path. These measurements are much more easily related to a true "average" value above the two different types of surface than those of the sodar since the signals can be much more easily related to the surface type. Even though part of the combined path was above bare soil (the road between plots), the "average" value is somewhat less than a straight mathematical average of the values over crops on either side. This may be related to the wind direction relative to the laser anemometer path which may favor the potato field.

The work described in this paper must be regarded as work in progress. A great deal more data need to be evaluated,

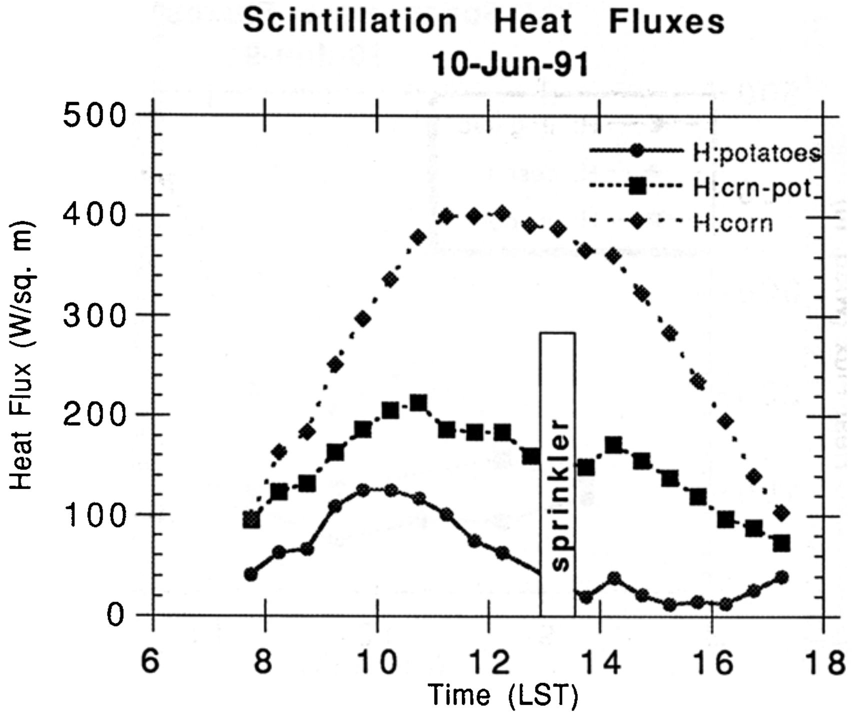

Figure 5. Heat fluxes above potatoes, corn (sparse), and combined potatoes and corn. Note period of sprinkler operation.

including C_T^2 profiles to larger heights, mixing heights and capping inversion depth from the low frequency sodar, multiple level point estimates of surface heat flux, and "surface" infrared temperatures. Measurements made from other laboratories at this site will also be invaluable in making more definitive, accurate calculations. In spite of unexpected weather conditions, the data are useful for the determination of new methods for extending local measurements of surface heat flux to larger areal averages.

Acknowledgments

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References

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