Observed effects of horizontal radiative surface temperature variations on the atmosphere over a midwest watershed during CASES 97

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[1] The association between ∼10-km scale horizontal variation of radiometric surface temperature ($T_s$) and aircraft-derived fluxes of sensible heat ($H$) and moisture ($LE$) is the focus of this work. We use aircraft, surface, and satellite data from a Cooperative Atmospheric-Surface Exchange Studies (CASES) field program, which took place in the southern part of the 60 × 100 km Walnut River (Kansas) watershed from 22 April to 22 May 1997, when winter wheat matured and prairie grass greened up. Aircraft $T_s$ observed along repeated flight tracks above the surface layer showed a persistent pattern: maxima over ridges characterized by shallow soil and rocky outcroppings and minima over riparian zones. $H$ and $T_s$ reached maxima in the same longitude zone on two flight tracks 40 km apart. Satellite $T_s$ data from March to June reveal similar persistent patterns with minima more persistent than maxima. Two mechanisms are suggested to explain the association of $H$ and $T_s$ maxima: (1) for winds between 6 and 8 ms$^{-1}$, modulation of the surface energy budget by vegetation effects; or (2) for winds equal to or below 4 ms$^{-1}$, a thermally driven circulation centered on $T_s$ maxima. Both mechanisms were possibly enhanced by increased static instability over the $T_s$ maxima. Owing to the small sample available, these results are suggestive rather than conclusive. Effects of rainfall and vegetation on watershed-scale $T_s$ gradients are also explored.


1. Introduction

[2] Using aircraft, satellite, and surface data from the 1997 Cooperative Atmospheric and Surface Exchange Study (CASES-97) field program, this paper focuses on the horizontal variation of near-surface fluxes of sensible heat ($H$) and latent heat ($LE$) on scales of the order of 10 km over complex terrain and its relationship to the radiometric surface temperature ($T_s$). We will show that some patterns, particularly in $T_s$, are remarkably persistent, probably because of their association with terrain features. We will suggest that $T_s$ is related to $H$ and $LE$ not only through the surface energy budget (SEB), but it also modulates $H$ and $LE$ through variations in static stability ($T_s - T(z)$), where $z$ is height within the mixed layer, and through driving mesoscale circulations. Importantly and in contrast to similar measurements over calm to moderate seas, $T_s$ represents a measurement from an indeterminate altitude above the soil-atmosphere interface as determined by the canopy above the soil. This paper emphasizes $T_s$ differences between mixed grass prairie (low canopy) and nearby riparian zones containing trees (high canopy).

[3] The association of horizontal variability in boundary layer circulations and clouds with surface characteristics is nothing new. In early micrometeorology texts [Geiger, 1966; Sutton, 1953], observations of soaring birds and reports from glider pilots were used to associate persistent updraft areas with surface “hot spots”; more recent evidence from glider pilots can be found on the Web (e.g., http://www.klima-luft.de/stein/fern/term.htm; http://www.fva.rwth-aachen.de/segelflug/thermik.html). Rabin et al. [1990] used satellite imagery to show that, during light wind conditions, mesoscale ($O: 6000$ km$^2$) areas with relatively high $H$ (and thus $T_s$) and low $LE$ (i.e., wheat
stubble) can spawn shallow cloud fields. The key, in their opinion, was the low LE as areas of high LE (active vegetation) were associated with little to no cloud formation. Shaw and Doran [2001] used Oklahoma Mesonet data to show that persistent surface convergence and divergence patterns are associated with topographical features more than surface air temperature, consistent with the modeling studies of Walko et al. [1992]. However, Shaw and Doran did not investigate Ts, which, we will show, has more variation across the landscape than air temperature.

Second, the horizontal distribution of H and LE could be modulated by larger-scale circulations. Thermally induced circulations could result if the T_s field created horizontal potential temperature (θ) gradients on the right scale and the winds were sufficiently light [Wang et al., 2000]. The resulting surface convergence would concentrate flux-transporting eddies and then loft them upward in the resulting updraft, creating maxima in turbulence intensity, H, and LE (Figure 2) as well as redistributing surface moisture through the boundary layer [Baidya Roy and Avissar, 2002]. In this model, the T_s maximum also induces a local stability minimum, which would tend to enhance the fluxes as in the SEB model described above. Except for H, which is complicated by its horizontal average becoming negative in the upper mixed layer, the maxima should persist through the mixed layer. In such cases, H and LE are positively correlated through much of the mixed layer, unless the effects of such circulations are averaged out [LeMone et al., 2003a]. It is clear that such circulations could mask horizontal variations in H and LE related to soil and vegetation characteristics. In fact, there are examples for which H and LE estimated from low-level aircraft show positive correlation spatially, even after smoothing and averaging (LeMone et al. [2003a] and data from Desjardins et al. [1992, Figures 6–11]).

With this background, we propose two conceptual models to explain the response of the horizontal distribution of H and LE at aircraft flight level to T_s patterns. First, T_s reflects processes described by the SEB, which in turn interacts with soil conditions, terrain, and vegetation to produce horizontal T_s variations such as a maximum (Figure 1). For cloudless skies, the processes at the land-surface interface produce a negative correlation between H and LE, as discussed by Priestley [1955] and LeMone et al. [2003a]. The air temperature T would be enhanced in areas with larger T_s, but, as we will show, the static stability (\(\partial T / \partial z\) – \(\Gamma\), where \(\Gamma\) is the dry adiabatic lapse rate) reaches a local minimum where T_s reaches a local maximum. The enhanced lapse rate could increase vertical exchange, and hence fluxes, locally. In this case, a perfect land-surface model and a perfect representation of the footprint function that includes static stability could predict the fluxes along a flight track at a given height.

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Observations of such mesoscale circulations are rare. Smith et al. [1994] document a coherent diurnally varying flow over the 15 × 15 km FIFE site that persisted through the 21-day July–August 1989 field season, with corresponding maxima in $T_s$, convergence, and $H$ in the afternoon, and a second convergence maximum before dawn. Since there was little horizontal variability in the net radiation, Smith et al. concluded that the feature was related to the horizontal variation of soil moisture and vegetation. Observations of an “extreme” example, forcing by a lake-terrain couplet, is discussed by Sun et al. [1998]. LeMone et al. [2002] document a watershed-scale (~50-km) circulation during CASES-97 on 10 May, with upwelling over the eastern side and downwelling over the river basin. In this case, higher-elevation areas (partially dormant grass) were warmer and probably had larger $H$ than low-lying areas (growing winter wheat), which were relatively cooler. This watershed-scale air temperature gradient, supported by a similar $T_s$ gradient could have created the circulation. This will be discussed further in section 4.

In this paper, we will show persistent features in the horizontal variation of $H$, show that they are related to the $T_s$ distribution, provide a plausible example of flux concentration by a thermal circulation for a low wind speed day, and finally document the persistent association of $T_s$ minima with riparian zones and maxima with ridges, as illustrated in Figure 3. CASES-97 data analysis procedures are described in section 2. In section 3, we show an example of flux concentration by a 10-km scale, thermally induced mesoscale circulation and an example of the SEB model with $H$ enhanced by a minimum in static stability. We also extend the aircraft-track analysis of $T_s$ to other days and to the CASES-97 domain using AVHRR data and examine the

Figure 3. (a) Wyoming King Air $T_s$ versus along-track longitude for low-level (30–40 m) legs on 10 May 97 along-track 1 (SE portion of watershed). Vertical arrows indicate persistent areas of minimum $T_s$ throughout the morning that are associated with ravines. Maxima are associated with ridges, in particular a large ridge along the track called the Big Flat Area (BFA). (b) similar to Figure 3a but for track 3 (central east portion of watershed). Dashed line box is an area of small streams and vegetation, a relatively broad riparian zone.
relationship of $T_s$ with elevation and vegetation. The discussion and conclusions appear in section 4.

2. Observations and Analysis Methods

2.1. Theory: Thermally Induced Mesoscale Circulations

As suggested by modeling studies such as McCumber and Pielke [1981], Anthes [1984], Segal et al. [1988], and Segal and Arritt [1992, and references within], on low wind days $T_s$ gradients across the landscape can produce an atmospheric response that is likely due to enhanced circulation [Segal et al., 1988]. Considering only two dimensions, $\partial U_s/\partial t = 0$, and neglecting friction, the circulation theorem, as derived by Holton [1992], can be written

$$\frac{dU_s}{dt} \approx U_s \frac{\partial U_s}{\partial s} \approx R \ln \left( \frac{p_0}{p_1} \right) \frac{\partial \theta}{\partial s},$$

where $U_s$ is the total wind along the direction, $s$, of the potential temperature ($\theta$) gradient $(\partial \theta/\partial s)$, $t$ is time, $R$ is the gas constant, and $p_0/p_1$ is the ratio of the pressures

Figure 4. CASES 97 instrument and flight track layout. Tracks 1 (green) and 3 (brown) are overlaid on maps of topography (USGS DEM) and land use (University of Kansas). Heavy black contours are the 390 and 430 m elevations outlining the track 1 and 3 BFAs on the eastern side of the watershed. Brown contour is boundary of Walnut River watershed. Streams are dark blue lines; Walnut River runs north-south. The Arkansas River is just to the west of the watershed. Triangles: ABLE wind profiler-NCAR radiosonde locations at Beaumont (BEA), Oxford (OXF), and Whitewater (WHI). Squares: NCAR eddy correlation surface flux stations. Adapted from LeMone et al. [2000].
describing the lower \( p_0 \) and upper \( p_1 \) limits of the circulation. Since we are interested in the convergence forced by the circulation, rearranging (1) gives

\[
\frac{\partial U_s}{\partial s} = \frac{1}{U_s} R \ln \frac{p_0}{p_1} \frac{\partial R}{\partial s}.
\]

Equation (2) indicates that as \( U_s \) increases, the effect of the temperature gradient decreases so we would expect to see circulations only on calm or relatively low wind days for typical horizontal \( \theta \) gradients (namely, Vidale et al. [1997]). With (2) in mind we will look at three days during CASES 97 of which only one may have met the low-wind criterion. At the heart of this approach is the assumption that, especially on low wind speed days, the \( T_s \) gradients force \( \theta \) gradients that, in turn, force the circulation.

### 2.2. Observational Data

Figure 4 shows land use, streams and lakes, ridges, and the location of flight tracks, radiosonde/windprofiler sites and surface flux station locations for CASES-97, which occurred between 21 April and 21 May [LeMone et al., 2000] over the 60 × 90 km Walnut River watershed approximately 50 km east of Wichita, Kansas. Grasses
dominate on the eastern side of the Walnut River, where areas of shallow soil are interspersed with large areas of limestone and chert outcrops. Seasonal springs emerge on the eastern boundary ridge of the watershed. West of the river, crops (primarily winter wheat) are grown in the deeper soil in rural areas, with the fraction of residential area increasing westward toward Wichita. There was no irrigation during CASES-97. During the experiment, winter wheat began to mature and approach senescence, while grasses greened up. The associated increase in NDVI to wheat began to mature and approach senescence, while grasses greened up. The associated increase in NDVI to "greener" values (Figure 5) between 29 April and 20 May was greater for the grasses than for the winter wheat.

We used data from the University of Wyoming King Air (WKA), polar orbiting satellites, and eight NCAR surface flux stations (Table 1). Our analysis focused on the CASES-97 intensive observing periods (IOPs), which were characterized by essentially cloudless skies and steady winds. AVHRR data were used to obtain Ts fields across the watershed, putting the aircraft observations into a landscape context.

During IOPs, WKA data were collected both in the morning (0900–1300 CST) and during the afternoon (1430–1830 CST), but we consider only the morning data, when T_s > θ and the boundary layer was strongly coupled to the surface. During each mission, the WKA flew 3–4 "stacks", successive 30–60 km long straight-and-level flight legs spaced through the mixed layer from ~100–200 m below the top of the mixed layer to 30–40 m above the ground, in order to observe flux profiles. The WKA used track 1 (Figure 4) for IOPs on 29 April and 10 May and used track 3 for the IOP on 20 May. Each stack, which included flight legs at four heights and a sounding, took roughly an hour. The repetition of flights along these tracks, which extended over mostly grassland east of the Walnut River, allows us to examine the persistence of T_s, H, LE and U_s patterns within an IOP and from IOP to IOP.

H and LE were estimated from WKA data using the same method employed by LeMone et al. [2003a]. Using vertical wind, θ, and mixing-ratio departures from the linear trend over the entire track, the instantaneous sensible and latent heat fluxes were calculated. These fluxes were block averaged over ~1-km lengths and then subjected to a 4-point running average for further smoothing. The same procedure was also applied to solar and infrared (IR) global radiation, and T_s, and to θ and U_s, where the prime indicates deviation from a linear trend.

To find persistent patterns in horizontal variation, we organized the IOP-averaged, or composite flight legs for three height intervals into panel plots (i.e., Figures 6 and 7) of H, LE, T_s, U_s, and θ. This is because the altitude of flight legs flown above 30 m, depended upon a rapidly rising (and difficult to determine) mixed layer. Following LeMone et al. [2002], we composite the individual flight legs, normalized by the average mixed layer height (h), into ascending height intervals of z/h; where z (agl) is the aircraft altitude. The lowest layer (labeled "low") includes all the 30–40 m flight legs. However, the remaining 3, 100–200 m thick intervals, which we have called "middle 1," "middle 2," and "high," are different. Middle-1 overlapped middle-2, which extended higher. In the overlap zone legs were assigned to middle 1 or 2 to provide similar sample sizes. The high interval included legs within 100–200 m of the top of the mixed layer. Table 2 summarizes the samples in each layer. LeMone et al. [2003a] discuss the accuracy of compositing the C97 flux data [LeMone et al., 2003a, Figures 11 and 12]. In this case errors arise from time changes since we are interested in preserving horizontal variability. To reduce this error we removed a linear time trend in the data when necessary. We emphasize the small sample available to us so increasing sample size to reduce the errors was not possible.

The WKA videos were examined carefully to identify the different types of land cover and the locations of riparian zones. The riparian zones in Figure 3 were identified on the basis of more extensive groups of trees, trees extending farther than an ordinary windbreak, and by association with streams on USGS 1:25,000 maps. The
Figure 6. Composite H, low-level $T_s$, low-level $\theta$, and LE, from the Wyoming King Air versus along-track longitude for (a–c) 29 April, (d–f) 10 May, and (g–i) 20 May. For H and LE the colors indicate the level or level interval used for the composite (see legend and text). Mean $\theta$ is removed from the $\theta$ trace (magenta) to show horizontal variability. Linear regression slopes for $T_s$ and $\theta$ are also shown.

Figure 7. Composite plots of $\theta'$, low-level $T_s$, low-level $\theta$, and $U'_s$, from the Wyoming King Air versus along-track longitude for (a–c) 29 April, (d–f) 10 May, and (g–i) 20 May. For $\theta'$ and $U'_s$ the colors indicate the level or level interval used for the composite (see legend and text). Mean $\theta$ is removed from the $\theta$ trace (magenta) to show horizontal variability. Linear regression slopes for $T_s$ and $\theta$ are also shown.
identified riparian zones along track 1 were associated with low areas 5 km across or greater. The minor dip in $T_s$ at $-96.79^\circ$ (in the text and figures “-96” and “96 W” longitude are equivalent) along track 1 in Figure 3a is associated with intermittent streams feeding into Timber Creek, which comes closest to the track at this point. A similar $T_s$ minimum occurs in the western riparian zone along track 3, which corresponds to the confluence of the two creeks in Figure 4 and a dip in elevation of similar scale. Another $T_s$ minimum is associated with the eastern riparian zone; an area of intermittent streams feeding into Hickory Creek, which also comes closest to track 3 at this point.

The AVHRR 1-km resolution $T_s$ data are used to extend the analysis along the flight tracks, to put the aircraft track observations into a landscape context and to investigate seasonal persistence of the observed patterns. Using temperature and moisture profiles, atmosphere-corrected $T_s$ maps were generated from AVHRR data at Argonne National Laboratory as described by Song et al. [2000]. Data for four of the IOPs, when the skies were sufficiently cloudless for evaluation of $T_s$ over the entire Walnut River watershed, are summarized in Table 3; the satellite overpass for the fifth IOP occurred too early in the morning for our use. Using Geographic Information System (GIS) tools, the images were registered to within 1 km referencing lakes, streams, and the Walnut River. To show $T_s$ gradients and their persistence, the image average was subtracted from each pixel producing a “deviation” map, and the deviation maps were averaged to form a CASES-97 composite. The standard deviation at each pixel indicates variability; this variability can be compared to the mean as a measure of persistence. To further investigate persistence we also looked at monthly $T_s$ composites along the flight tracks for March-June. Each monthly composite is based on 3 to 5 clear-sky AVHRR images that were not registered as closely as the IOP images; and the split-window technique was used for the atmospheric correction instead of thermodynamic profiles.

GIS was used to associate $H$, $LE$, and $T_s$ from the WKA to 1-km resolution NOAA/AVHRR estimates of $T_s$, land use, terrain elevation based on Digital Elevation Model (DEM) data, lakes and streams, the watershed boundary, and accumulated rainfall. Before plotting, $H$, $LE$ and $T_s$ values from the 3 to 4 WKA legs on a given day were normalized by their leg averages, and then averaged at each of the ~40 points plotted along the tracks in Figures 8–10. Thus values of “1” on the maps correspond to the composite leg average. Four of the ten classes of land use data from the University of Kansas database were used to represent land use in the vicinity of the flight tracks: grassland, cropland, water, and trees. Grassland and cropland are the most common land use classes in the watershed. Trees occupy a small percentage of the landscape, but those along riparian zones may have a large influence on $T_s$ gradients. The location of these types of land cover was verified from the WKA forward looking videos. The accumulated rainfall was based on high-resolution raingage-calibrated data from NCAR’s S-band Polarized radar (SPOL; Brandes et al. [1999]; Yates et al. [2001]) which was colocated with the Wichita NOAA/NWS WSR-88 Doppler storm radar, ~50 km to the west of the center of the watershed.

### Table 2. Samples in Each Layer for Height-Dependent Composites (Figures 6 and 7)

<table>
<thead>
<tr>
<th>Layer</th>
<th>$z/h$</th>
<th>29 April</th>
<th>10 May</th>
<th>20 May</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>≥0.7</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Middle 1</td>
<td>0.2−0.4</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Middle 2</td>
<td>0.1−0.2</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Low</td>
<td>≤0.06</td>
<td>4</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

### Table 3. NOAA 14 Satellite Overpass Information for CASES 97

<table>
<thead>
<tr>
<th>Date</th>
<th>Time, CST/GMT</th>
<th>Satellite View Angle, deg</th>
<th>Solar Zenith Angle, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>29 Apr.</td>
<td>1507/2007</td>
<td>4</td>
<td>32.75</td>
</tr>
<tr>
<td>10 May</td>
<td>1447/1947</td>
<td>34</td>
<td>27.25</td>
</tr>
<tr>
<td>16 May</td>
<td>1522/2022</td>
<td>18</td>
<td>32.25</td>
</tr>
<tr>
<td>20 May</td>
<td>1438/1938</td>
<td>44.5</td>
<td>24.25</td>
</tr>
</tbody>
</table>
change little with altitude. Recall that the features represented in the figures represent averages of four hours, suggesting persistence in time as well as space.

[22] By 10 May (Figures 6 and 7d–7f) the prairie grass along track 1 had begun to green up while winter wheat was approaching maturity. The average wind was 188°/4.1 ms⁻¹ from the south; the lowest of the three IOPs analyzed. As a result of convective rainfall three days prior, the soil moisture was higher and more variable spatially than on 29 April. The track-scale Tₛ and θ patterns look similar (increasing to the east) but at a lower rate than 29 April. There are two collocated local maxima, one within the BFA and one just to the east (Figure 7e).

[23] Similar to 29 April, the 10 May θ distribution shows a maximum over the BFA at all altitudes. The low-level maxima in θ, H and Tₛ all center at around the same place (−96.78° to −96.80°) in the BFA, but the eastern maxima in the three variables (around −96.66° to −96.68°) are slightly offset (Figures 6d and 6e). As for 29 April, LE minima tend to correspond to Tₛ maxima, and vice versa, as would be expected from the SEB; but the relationship is not as strong. The LE maxima within the BFA at middle 1 and high levels overlie the low-level H maximum at −96.78° to −96.80°, consistent with concentration by a large eddy. However, the low-level LE minimum at −96.82° corresponds to LE minima between −96.82° and −96.94° at the high and middle 1 levels, respectively (Figure 6f).

[24] By 20 May (Figures 6 and 7g–7i), the prairie grass had greened up, while winter wheat was mature, so there was little difference in color and water demand between the two grasses. A strong convective storm had passed over the area the night before, leaving the ground saturated with widespread standing water. Wind was 80°/6.1 ms⁻¹ with the largest along-track component (5.5 ms⁻¹) of the three days.

[25] Consistent with the widespread precipitation and trajectories from similar source regions, this day had the least Tₛ and θ variation along the track, with a nearly flat track-scale variation in Tₛ. However, a track-scale gradient in θ (Figure 7h) was evident indicating forcing was not local. A broad but shallow Tₛ maximum occurs in the BFA. Remarkably, the θ pattern (Figure 7g) showed little vertical coherence. We attribute this to the small horizontal variability in surface characteristics and, possibly, the effect on the boundary layer of flow over an upstream “escarpment” (see contours in Figure 4). The H distance series is dominated by a low-level H maximum at the western edge of the BFA (Figure 6g). This H maximum is due in part to one high flux event sampled during one of the three legs flown. However, the H maxima from the other two legs also occurred over the western BFA. H and LE (Figures 6g and 6i) show little coherence with height, and the relationship between Tₛ and LE is the weakest for the three days. This is not surprising, given the low horizontal variability in vegetation and soil moisture, flow conditions, and the relatively poor sampling (three stacks versus four on the other IOPs).

### 3.2. Aircraft θ' and Uₛ Observations: Looking for Evidence of Circulation

[26] If the concentration of H and LE over the BFA that we observe is related to a mesoscale circulation as described in section 2, then we should be able to observe it by comparing the observed horizontal variations of θ' and Uₛ. According to (2), divergence occurs for air traveling from low to high θ, and convergence would occur for air traveling from high to low θ. We can see if along-track variations in temperature contribute to the circulation by rearranging (2) to obtain the ratio, C, expressed in finite difference form

$$C \approx \frac{R}{Uₛ} \ln \left[ \frac{pₘ}{pₛ} \frac{\Deltaθ}{\Delta H} \right].$$

In Table 4 we compare ∂Uₛ/∂s from (1) multiplied by Δs, to along-track θ' gradient, which is compared to ∂Uₛ/∂s multiplied by Δs along the same longitude interval, and their ratio C from (3). The pressure ratio is here taken to correspond to 800 m, the typical depth of the mixed layer around noon during CASES-97. A value of C > 1 indicates that a circulation was possible with C = 1 being a perfect association between forcing (numerator) and response (denominator). In the table, only 10 May comes close to matching the C ~ 1 criterion for a thermally forced mesoscale circulation. This is not surprising: both the total wind and the along-track wind were the weakest of the three days, and LeMone et al. [2002] document a watershed scale-circulation on this day. We do not expect exact correspondence between the calculations and observations because of the implicit assumption of two-dimensionality, the use of data from the low-level flight legs only, and the fact that the vertical extent of the circulation is unknown. Not surprisingly, 29 April and 20 May do not appear to have thermally forced circulations. On 29 April, the wind was probably too strong; thermal circulations could have formed only if the θ gradient along the track had extended well upstream. On 20 May, the θ gradients were the smallest of the three days, and 5.5 ms⁻¹ airflow normal to the gradients allowed little time for the flow to respond.

[27] If the circulation is confined to the mixed layer, one would expect upper-mixed layer convergence over low-level divergence, and vice versa. In Figure 7f, accelerating Uₛ at low levels corresponding to the in-
crease in $\theta$ between $-96.82^\circ$ and $-96.90^\circ$ longitude lies beneath a zone of convergence in the upper mixed layer. Similarly, a zone of divergence surmounts the zone of convergence corresponding to the decrease in $\theta$ between $-96.71^\circ$ and $-97.77^\circ$ longitude.

### 3.3. Satellite AVHRR Versus $T_s$, $H$, and LE: Relating the Tracks to the Landscape

[28] We have seen a tendency for a relationship between $T_s$, $\theta$, and low-level $H$ along tracks 1 and 3, especially for 29 April and 10 May where it is present above the lowest flight level. Previous CASES 97 work [Chen et al., 2003; Yates et al., 2003] showed that soil moisture and vegetation influenced the fluxes of CASES-97, as we would expect. We have suggested that terrain influences such relationships as well, through its control of vegetation type and soil moisture. Proposed mechanisms were the horizontal variability in the SEB and static stability, and concentration of fluxes by standing eddies forced by a combination of thermal forcing as in (2) or terrain as discussed, e.g., in the work of Walko et al. [1992]. Therefore we turn to satellite imagery to see whether: (1) the distribution of $T_s$ around the flight tracks is consistent with the patterns observed along the flight tracks, and (2) the patterns persist in time, an indication of the importance of the terrain and its effect on soil moisture since the effects of the vegetation changed radically during CASES-97.

[29] The mean values of $T_s$ from the AVHRR and WKA (Table 5) show broadly similar trends for CASES-97 and both show a decrease for the IOP sequence 29 April, 10 May, and 20 May, despite the seasonal increase in insolation. The trend is broken by the mean AVHRR $T_s$ for 16 May, which is comparable to that for 29 April. The AVHRR image used to compute $T_s$ statistics was a rectangle just large enough to contain the entire Walnut River watershed so some pixels lay outside the watershed boundary. Table 6 shows the $H$, LE, and albedo values associated with the WKA $T_s$ decrease during CASES 97. The $T_s$ decrease results from a combination of increasing LE and increasing albedo (less absorbed insolation) due to prairie grass green up and maturing winter wheat. From consideration of the SEB, this would result in a decrease of $H$ as observed. The monthly $T_s$ averages increase with insolation as expected. The differences in the AVHRR and WKA $T_s$ mean values for each IOP reflect the fact that the data are collected over different domains.

[30] Although the sampling of different domains lead to different magnitudes, $\sigma_{T_s}$ from both aircraft and satellite decrease with time for the 3-IOP sequence represented by the aircraft data, suggesting weaker gradients with time. We suggest that the trend relates to greenup and timing of rainfall relative to IOPs. The monthly average $T_s$ and $\sigma_{T_s}$ show an opposite trend, increasing along with insolation through the growing season. However, the seasonal increase in $\sigma_{T_s}$ is interrupted by a slight decrease from April to May, the time of CASES-97.

[31] Direct comparison of aircraft $T_s$ with satellite-derived $T_s$ in Figures 8–10 provides a test for consistency and extends our analysis beyond the track line. This is an important step, which enables us to look for associations between fluxes and $T_s$ patterns upstream of the flight track [Song and Wesely, 2003]. The $T_s$ sampling is different for the two data sets, with aircraft $T_s$ obtained from a narrow-beam instrument averaged over about 4 hours and subject to a low-pass ($\approx 4$ km) spatial filter, while the satellite $T_s$ sampled the area only once during the IOP and at 1-km resolution. Figure 3 shows that the spatial patterns in $T_s$ are preserved even though the absolute temperature is increasing with time so the difference in time-of-day between the AVHRR image and aircraft trace should not affect our appreciation of the spatial distribution of $T_s$. We will focus on patterns of the order of 10 km across, well resolved by the 1-km AVHRR pixels and the filtered aircraft data.

[32] The WKA $T_s$ variations along track 1 on 29 April (Figures 8 and 6) show a good comparison to the AVHRR $T_s$ and land surface features. Higher WKA $T_s$ values (Figure 8a, red dots) are generally associated with relative maxima on the AVHRR image (lighter pixels), ridges, and grass, while the WKA and AVHRR $T_s$ minima are collocated and associated with riparian zones and associated vegetation. The western $T_s$ minimum is associated with winter wheat and creeks feeding the Timber Creek Lake to the north, and a minimum associated with Grouse Creek to the east; Grouse Creek is not in the Walnut River watershed. The riparian zone associated with the center minimum is not seen in Figure 8 but is visible on the aircraft videos. Similarly, higher values of AVHRR $T_s$ are associated with grasses and ridges, while lower values are associated with cropped areas and riparian zones. $H$ (Figure 8b) tends to be higher over and north of areas with warmer $T_s$, and lower over and north of areas with cooler $T_s$. The BFA (between $-96.7^\circ$ and $-96.85^\circ$) is evident in relative maxima of $T_s$ and $H$. The cool, cropped areas to the south of Timber Creek Lake could account for the high values of LE in Figure 8c.

[33] On 10 May (Figures 9 and 6) the association between aircraft and AVHRR $T_s$, $H$, and LE along track 1 is robust, especially over the BFA where all three reach a maximum. The three $T_s$ minima occur at the same locations as on 29 April. Also consistent with 29 April, LE maxima

### Table 5. $T_s$ (°K) Statistics Based on Satellite and Aircraft Data

<table>
<thead>
<tr>
<th>Date</th>
<th>Lower Watershed (AVHRR)</th>
<th>WKA Dataa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median Mean $\sigma_{T_s}$</td>
<td>Median Mean $\sigma_{T_s}$</td>
</tr>
<tr>
<td>29 Apr.</td>
<td>308.1 307.7 3.1</td>
<td>308 4.9</td>
</tr>
<tr>
<td>10 May</td>
<td>302.7 302.9 2.0</td>
<td>306 4.6</td>
</tr>
<tr>
<td>16 May</td>
<td>307.8 307.8 1.4</td>
<td>305 2.6</td>
</tr>
<tr>
<td>20 May</td>
<td>296.5 296.3 1.9</td>
<td>302 2.7</td>
</tr>
<tr>
<td>4 IOP average</td>
<td>303.6 303.7 1.5</td>
<td>304 2.5</td>
</tr>
<tr>
<td>March average</td>
<td>293.2 293.1 1.0</td>
<td>302 2.7</td>
</tr>
<tr>
<td>April average</td>
<td>304.5 304.4 1.4</td>
<td>305 2.7</td>
</tr>
<tr>
<td>May average</td>
<td>308.9 308.9 1.3</td>
<td>302 2.7</td>
</tr>
<tr>
<td>June average</td>
<td>313.4 313.5 1.8</td>
<td>303 2.7</td>
</tr>
<tr>
<td>March–June average</td>
<td>305.0 305.0 1.0</td>
<td>302 2.7</td>
</tr>
</tbody>
</table>

aFor track 1, 29 April and 10 May; for track 3, 20 May. Data from LeMone et al. [2002].

### Table 6. CASES 97 IOP Grand Average WKA Flux and Albedo

<table>
<thead>
<tr>
<th>Date</th>
<th>$T_s$, °C</th>
<th>$H$, W m$^{-2}$</th>
<th>LE, W m$^{-2}$</th>
<th>Albedo</th>
<th>LE Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>29 Apr. 1997</td>
<td>308 (4.9)</td>
<td>127</td>
<td>161</td>
<td>0.15</td>
<td>0.55</td>
</tr>
<tr>
<td>10 May 1997</td>
<td>306 (4.6)</td>
<td>120</td>
<td>253</td>
<td>0.17</td>
<td>0.68</td>
</tr>
<tr>
<td>20 May 1997</td>
<td>302 (2.7)</td>
<td>100</td>
<td>261</td>
<td>0.18</td>
<td>0.73</td>
</tr>
</tbody>
</table>

aValues of $T_s$ in parentheses are the standard deviation across each track.
Figure 8. WKA $T_s$, $H$, and LE along track 1 plotted on the 29 April AVHRR image. University of Kansas land use for the area is also plotted. Darker shades are cooler. Wind is from south. (a) $T_s$. (b) $H$. (c) LE. $T_s$ is normalized by the leg average before compositing. Red dots, above average; blue dots, below average. Magnitude of the departure from the mean is given in standard deviation. Timber Creek flows into Timber Creek Lake (north of track) and confluences with Dutch Creek to the west. Grouse Creek is the watercourse shown at the eastern end of the track; it is not within the Walnut River watershed.
Figure 9. Same as Figure 8 but for 10 May (track 1). Wind is from south.
Figure 10. Same as Figure 8 but for 20 May (track 3). Hickory Creek is to the south of the track, and Little Walnut Creek is to the north of the track. Wind is from northeast.
(Figure 9c) tend to be over or just downstream of cropped areas and riparian zones, and maxima over or downstream from grassy areas or ridges; however, the magnitudes of the variations are larger on 10 May.

[34] 20 May (Figures 10 and 6) shows a broad area of elevated $T_s$ (Figure 10a) along track 3 associated with a ridge between two riparian zones within the BFA along the western half of the track. The $T_s$ minima are again associated with riparian zones: the minimum to the west overlies the confluence of the Little Walnut Creek (north) and Hickory Creek (south), while the minimum to the east is associated with streams feeding Hickory Creek, observed on the aircraft videos and USGS topographic map, that were below the 90 m horizontal resolution of the DEM (Figure 3). $H$ (Figure 10b) and $LE$ (Figure 10c) show high correspondence only within a portion of the zone of elevated $T_s$. As noted previously, confidence is low due to a smaller sample than for the other days and the low amplitude of the variations. This, plus the relatively uniform surface conditions implies that the positive correlation between $H$ and $LE$ is probably spurious \[\text{[LeMone et al., 2003a]}.\]

3.4. Persistence of $T_s$ Patterns During CASES 97

[35] To assess the persistence of $T_s$ patterns during CASES-97, we averaged the $T_s$ fields for the 4 IOPs (Table 3). The $T_s$ values along track 1 (Figure 11) reveal that the general $T_s$ pattern for 29 April and 10 May continues to exist on 16 May, and, to a lesser degree on 20 May, in spite of shifts in the mean value, the track-scale trend, and the changes in vegetation during the period. The minimum at the west end of the track was associated with the riparian zones along streams, below the 90 m horizontal resolution of the DEM, feeding Timber Creek Lake (Figure 4), and is identifiable on all four days. On both tracks 1 and 3 the warmer areas were associated with rocky outcroppings and shallow soil depths.

[36] The 4-IOP AVHRR mean $T_s$ field over the Walnut River watershed in Figure 12a shows a broad southwest-northeast gradient, with cooler values to the southwest. Associated with sufficiently light winds, this gradient might be expected to produce a mesoscale circulation similar to that discussed by LeMone et al. [2002], but with the upwelling air to the northeast and the downwelling air to the southwest. The general patterns in the flight tracks (dots) are consistent with the surrounding pixels. Most importantly, the western (red pixels) zone on the flight tracks we used to identify the BFA corresponds to a zone of relatively warm $T_s$ (white pixels to the south, red pixels around track 3) that extends from south of track 1 to north of track 3. Note there are several such areas, on the order of 10–15 km across, that are candidates not only for persistent $H$ maxima, but also for creating $\theta$ gradients capable of forcing mesoscale thermal circulations.

[37] If we define pixel $T_s$ persistence by how much its absolute value exceeds the pixel standard deviation, the large-scale gradient is clearly persistent as evidenced by the blue pixels in NE and SW part of Figure 12b. For track 1, the warmer area we associated with the BFA, is marginally persistent (mean comparable to standard deviation) with a less variability (standard deviation much larger than absolute value of the mean) but the cooler
areas bracketing it have more persistence, consistent with Figure 11. This indicates that while the area of maximum Tₛ may “move around” within the BFA, the associated gradients associated with it are more persistent probably due to the anchoring effect of the smaller riparian zones. For track 3, the BFA is marginally persistent with a small persistent area, with a cooler “variable” area at the eastern end. The zone of Tₛ minimum associated with the “below-DEM-resolution” streams near the east end of the track lie in a zone that is marginally persistent to persistent.

3.5. Emergence of the Riparian Zones in Tₛ Patterns

[38] The relationship between warm/cool spots and ridges/riparian zones was much stronger on 20 May than on 29 April (Figure 13). There is little correspondence between Tₛ and riparian zones for 29 April (Figure 13a); rather the strong differences between winter wheat and dormant grasses seem to dominate the Tₛ pattern (compare Figures 8 and 13a) after over a week of drydown. The wet soil from recent rainfall and more uniform vegetation on 20 May led to cooler Tₛ in the riparian zones and higher Tₛ on ridges (Figure 13b). This is especially apparent in the northern part of the image. We suspect that the IOP differences also reflect a broader trend since vegetation greenness became more uniform and the soil moisture, though interrupted by drydowns, increased between 21 April and 20 May [see LeMone et al., 2000].

3.6. Seasonal Persistence of BFA Tₛ Maximum

[39] Having determined that the warm zone associated with the BFA persisted over the monthlong CASES 97 period, we now examine its persistence over the Spring growing season (Figure 14). Examination of the Tₛ extrema shows that, in varying degrees, the warm zone was present within the BFA in March, April, to a lesser degree in May, but not in June, when it shifted to the west, probably due to the changes in albedo, evapotranspiration, and roughness associated with the winter wheat harvest in mid-June. However, the persistent minimum associated with a riparian zone to the east of the BFA (at \( \frac{C_24}{C_26} \)) that we noted in Figure 11 remained through the March-June period. In general, the riparian zones remained cool during the day more continuously than the ridges remained warm. The track-scale Tₛ gradient shows cooler values to the east during March, May, and June, but shows warmer values to the east during April.

3.7. Variation of Tₛ With Elevation: The Role of Land Use and Rainfall

[40] To further explore the tendency for Tₛ to increase with elevation, we use GIS to examine the relationship between AVHRR Tₛ and DEM elevation for each IOP, for the entire watershed, and for each of three land use types: grassland, cropland, and woodland (mainly riparian zones) in Figure 15. From the figure, the relationship of Tₛ to elevation is strongest on 29 April (Figure 15a), and weakest.
on 10 May (Figure 15b). This is at least partially due to the relationship of the most recent rainfall with elevation: the last rainfall, which was 10 days before 29 April, was concentrated primarily at low elevations, while the rain 3 days prior to 10 May fell mostly at higher elevations. Scatterplots relating rainfall to elevation are not shown due to space considerations. The rain-induced cooling at lower elevations reinforced the tendency of $T_s$ to increase with elevation on 29 April, while the rain-induced cooling at higher elevations reduced it on 10 May. The intermediate

Figure 13. (a) AVHRR-derived surface temperature, $T_s$ ($\degree$K) overlaid with streams and Walnut watershed boundary for 29 April 1997. (b) Same as Figure 13a for 20 May 1997.
slope for 20 May (Figure 15c) is consistent with the more evenly distributed rainfall. The contrast between Figures 13 and 15 illustrate the difference between simple elevation dependence and riparian zones vs. ridges: the riparian zones show up better on 20 May, but the stronger elevation dependence is on 29 April because the southern part of the watershed, where it had rained, is cooler. Thus while the increase in AVHRR $T_s$ with elevation in Figure 15 is consistent with the airborne observations (Figures 6 and 7), the trend suggests a vegetative effect. Grasses tended to be warmer than winter wheat and, along with shallow soil depths, were predominant at higher altitudes; especially in the eastern part of the watershed.

4. Discussion and Conclusions

[41] This investigation was motivated by a search for atmospheric processes that would result in a persistent late morning to midday $H$ maximum over an area that supported a persistent $T_s$ maximum. Using aircraft and satellite data, we found that $T_s$ maxima (and to a lesser degree $H$ maxima) were associated with ridges, while $T_s$ minima tended to be associated with riparian zones. The $T_s$ features persisted through CASES 97, showing up not only for the IOPs, but also in the monthly averages for March through May. The minima, associated with riparian zones, were more robust than the maxima, associated with grass-covered ridges and areas of shallow soil depths.

4.1. Flux Patterns and Mechanisms for Flux Concentration

[42] Examination of the horizontal distribution of $H$ and $LE$ for the 3 IOP days (29 April, 10 May, and 20 May) revealed some common features. First, there tended to be maxima in $H$ over the Big Flat Area (BFA), an area of relatively flat terrain between $-96.7^\circ$ and $96.85^\circ$ longitude; these maxima were often collocated with $T_s$ and $q$ maxima; especially at the low-level (30–40 m) aircraft altitudes. Second, on one day (10 May), the low-level $H$ maximum was associated with an $LE$ maximum at higher altitudes, as one might expect if fluxes were concentrated by a mesoscale circulation. Third, there was a tendency for $H$ minima to correspond to riparian areas having $T_s$ minima. Fourth, the relationship between $H$ and $LE$ was mixed: some $H$ maxima correlated with $LE$ minima, as expected from the SEB; however, some others were not, possibly an effect of the small sample available to us [LeMone et al., 2003a].

[43] We propose two mechanisms to explain persistent features in the flux field: first, the effect of vegetation on the SEB (and hence capable of replication by LSMs), plus, at aircraft levels, possible enhancement by a larger static instability or, second, concentration of $H$ by a thermally induced mesoscale circulation. In the first case, spatial maxima in $H$ would correspond to minima in $LE$ at the lowest aircraft level, 30–40 m. In the second case, a circulation would be observed in association with a spatially coherent $\theta$ field, and possibly local maxima in $H$ collocated with $LE$ maxima in the upper mixed layer. Such a circula-
Figure 15
tion could also produce collocated low-level maxima in H and LE, but the sample is too small to make this diagnostic [LeMone et al., 2003a]. We found suggestive evidence of both mechanisms.

[44] To be related to the \( T_s \) distribution, both mechanisms required a relationship between \( \theta \) and \( T_s \). We found it to be strong at the aircraft level (30–40 m) for scales of the order of tens of kilometers. On this scale, \( \theta \) maxima were associated with the \( T_s \) maxima and extended through the depth of the mixed layer on the two days (29 April and 10 May) with winds from the south (parallel to the long axis of the watershed). There was no vertical coherence on 20 May, when the wind was parallel to the track and normal to a large-scale vegetation and a strong elevation gradient at the eastern watershed boundary. There was evidence of a thermal circulation only on 10 May, the day with the lowest wind speed (4.1 m s\(^{-1}\)). There was evidence of 10-km scale areas of increased superadiabatic lapse rate on all three days. The horizontal variation of \( T_s \) in all cases was much larger (1–6 K) than the corresponding \( \theta \) variation (0.1–0.2 K) leading to increased static instability over the zone with the \( T_s \) maximum which we have referred to as the BFA.

[45] Increased static instability would promote more vigorous vertical exchange, reinforcing flux concentrations related to the SEB. On light-wind days, enhanced vigorous vertical exchange of sensible heat would warm the air over unstable “hot spots” and should enhance the horizontal \( \theta \) gradient, increasing the likelihood of mesoscale thermal circulations. With slightly stronger winds, \( T_s \) maxima at 30–40 m appear to be associated with areas of increased static instability. It is highly likely that the height of the boundary layer over these areas of buoyancy flux concentration is higher than surrounding areas, but we have no means to check this. Though we had \( H \) and \( LE \) data only along two tracks on the eastern side of the watershed, we postulate that other similar or larger, more intense subwatershed-scale \( T_s \) patterns create similar patterns in \( H \).

4.2. Observed Spatial and Temporal Distribution of \( T_s \)

[46] Within a persistent, watershed-scale gradient (cooler to SW) the magnitude and distribution of subwatershed-scale gradients across the landscape changed over the monthlong period of CASES 97, with much of the apparent seasonal change actually due to timing of rainfall events relative to the IOPs. On 29 April, after over a week without rain, the horizontal gradients were mostly associated with vegetation differences or horizontal rainfall distribution. By 20 May, the \( T_s \) distribution seemed to be tied mainly to the terrain, with maxima associated with ridges and minima with valleys/riparian zones. We ascribe the low amplitude of the \( T_s \) distribution on 20 May to nearly uniform vegetation greenness and heavy convective rainfall the night before.

4.3. Seasonal and Subseasonal Changes

[47] Despite the seasonally increasing insolation and increase in monthly averaged \( T_s \) values from April to May, the IOP average \( T_s \) decreased in the sequence 29 April, 10 May, and 20 May (Table 5). We attribute the apparent \( T_s \) trend to the change in vegetation from heterogeneous to more uniformly green; the timing of rainfall events with respect to the IOPs may have also been a factor. This led to an increase in \( LE \) and decrease in \( H \) during the IOP sequence (section 3.6 and Table 6).

4.4. Synthesis and Suggestions for Future Research

[48] Observations of the horizontal variation of \( T_s \), \( H \), and \( LE \) that can be successfully associated with well-defined surface features are likely to be reproduced over similar surface features. For instance, Rabin et al. [1990] attribute cloud formation to mesoscale areas of increased \( H \) (thus \( T_s \)) compared to surroundings and Shaw and Doran [2001] have shown that topographic features appear to affect local wind patterns in a persistent and consistent way. In our case the surface features that affect \( T_s \) and low-level \( \theta \) (especially on low wind days) include: topography (including elevation and geology), vegetation, and antecedent rainfall (soil moisture). Thus the geomorphology of a landscape may be a primary consideration in understanding its land-atmosphere interaction characteristics in addition to its hydrology [Milne et al., 2002].

[49] Our analysis suggests that during calm or low to moderate wind (\(<8 \text{ m s}^{-1}\)) sensible heat “flux concentration” appears to be associated with thermal gradients “forced” by vegetation differences; the chief difference being that between mixed grass prairie (ridges) and nearby tree-covered riparian zones. Our analysis and discussion is mainly based upon the following general relationship, \( T_s = f(LE, H, R_n, G) \), where the RHS terms are related through the SEB. Using the SEB, Table 7 summarizes a heuristic analysis based upon an assumption of equal insolation and downwelling infrared radiation over both areas. It leads to an explanation of why the Big Flat Area is relatively warm. In fact, we believe it is better to pose the problem as “Why the neighboring riparian zones are cool?”

[50] For CASES 97 the heuristic argument leads to the conclusion that evapotranspiration (LE) is the chief reason \( T_s \) is cooler over the riparian zone. Relatively low \( T_s \) over riparian zones was also observed by Hall et al. [1995], Sun and Mahr [1995], and Ogunjemiyo et al. [1997]. There are four components of the SEB leading to cooling of the riparian zone during the day: LE, canopy storage, and canopy exposure to ambient air. Compared to the ridges LE is greater over the riparian zone for these reasons: (1) there is more vegetation per unit area; (2) there is more soil moisture via groundwater transport; and (3) the soil moisture is likely higher at deeper levels, often tapped by large trees, while grasslands tap soil moisture from a shallower root zone.

[51] Canopy depth probably contributes to the cooling of the ravines relative to the ridges. The canopy that contributes to \( T_s \) is deeper for the tree-covered riparian zone relative to the grass-covered ridge. The canopy in the

Figure 15. (a) Mean AVHRR-derived \( T_s \) versus DEM-derived elevation for the entire Walnut River watershed. \( T_s \) conditionally sampled for cropland (diamonds), grassland (squares), and woodland-riparian zones (triangles). Linear regression lines and equations are shown for each category of land use for 29 April 1997. (b) Same as Figure 15a for 10 May 1997. (c) Same as Figure 15a for 20 May 1997.
The riparian zone will not heat as fast as the grassland, because the solar heating is distributed over a deeper layer. Finally, during the daytime in clear conditions when a superadiabatic lapse rate is present, the height of the canopy in the riparian zone exposes it to cooler air temperatures than the shallower grassland canopy, further contributing to the cooler riparian T_s [Mahrt and Ek, 1993]. We have labeled this second effect “exposure to ambient air” in Table 7.

[52] Our analysis further suggests that while soil-rock storage is relatively small within a given diurnal cycle, heat retained by the shallow soils and exposed limestone outcroppings on the grassland ridges might contribute to the day-to-day and seasonal persistence of a warm BFA that we observe; in this case soil (rock) storage is important. However, riparian zones are likely to be cooler than the ridges over night under light wind conditions due to cold air drainage [LeMone et al., 2003b]. Both processes lead to the maintenance of the ridge-riparian zone gradient over long time periods.

[53] Warming components for the riparian zone are due to radiative effects. Absorbed solar radiation is greater over the riparian zone because of a lower albedo due to more complex canopy structure. The lower T_s over the riparian zone leads to lower upwelling IR, contributing to a relative warming of the riparian zone. However, cooling effects dominate.

[54] Obviously, soil moisture variations, especially those associated with recent rainfall, must also be considered as that can be an important component of soil heat capacity. However, recent rainfall is not specifically covered in this discussion. Also the BFA is not as “flat” as the 90-m resolution DEM suggests; the BFA is characterized by small rolling hills which might increase heat absorption during the day and slow cooling in the evening since only a fraction of the upwelling IR will be specular and lost to space. Lastly, our data indicate that the cooler, narrow riparian areas had less spatial variability of T_s than the broader grassland ridges indicating that the ridges were subject to more variations in vegetation and soil moisture than the riparian zones.

[55] We have given a reasonable heuristic argument for the differences in T_s between grassland ridges and riparian ravines observed in CASES 97. Further definition and quantification of these reasons must depend upon: (1) a good, economical method for measurement of moisture flux from riparian zones; (2) a well-defined field project specifically designed to explore these differences; coupled with (3) a coupled land use-hydrology-atmosphere model that takes into account the difference in vegetation and height of the two canopies.

[56] While the study focused on the persistence of T_s patterns over hours to weeks and their interplay with H and LE, more robust statistics are needed, particularly for the fluxes [e.g., LeMone et al., 2003a] in order to properly quantify the effects of those patterns. The addition of satellite data strengthened the case for persistent T_s patterns and clarified aspects of the horizontal flux distribution. Further use of aircraft flux data at more than one level and on more than one day to determine persistent spatial patterns should increase confidence. A small sample inhibited our conclusions; ideally one would want to repeat the experiment with more than 3–4 flight legs at low levels. We also found that the resolution of airborne videos is especially important in this kind of analysis and recommend the highest quality video cameras be used in land-atmosphere investigations using aircraft.

[57] Some land surface features that are below the 90-m horizontal resolution of the DEM we used and the effective 1 km resolution of the land-use data base normally available to researchers may have a measurable effect on an LSM’s ability to replicate the observed horizontal variation of T_s, H, and LE. This needs to be addressed in future observational and modeling efforts.

[58] Future work should include a similar analysis of the more statistically robust (up to 10 flight legs at 60 m) 2002 International H_2O Experiment (IHOP; http://www.joss.ucar.edu/ihop/) data set, part of which was gathered along track 1 by the WKA. The impact of the terrain and vegetation on fluxes, T_s, and mesoscale circulations should be explored through the use of mesoscale models or larger domain large eddy simulations that have been tested on data sets such as produced by CASES 97 or IHOP. Such models, coupled to observationally tested LSMs, must be able to reproduce the distribution of observed T_s in order to adequately model the atmospheric boundary layer.

[59] Our study shows that the complex interplay among geomorphology, vegetation, antecedent rainfall, and the boundary layer can be analyzed and used to improve our understanding of land-atmosphere interaction over complex terrain. The analysis of these complex data sets is well served by GIS technology. This analysis also emphasizes the fact that a monthlong investigation of land-atmosphere interaction, such as CASES 97 and the recent IHOP, is not long enough; at least a growing season (3–4 month) period of observation, similar to FIFE 87, is necessary to approach an understanding of land-atmosphere interactions.

[60] Acknowledgments. This work is dedicated to the memory of our coauthor and colleague, Marvin Wesely, who was instrumental in making the Walnut River watershed a long-term observational area for the study of hydrology and land-atmosphere interaction (ABLE and CASES projects are located there). Marv passed away during the writing of this paper. The professional work of the University of Wyoming/National Science Foundation King Air Flight Facility (Ernie Gasaway and Mark Horshor, pilots; Glenn Gordon, project manager, sometimes copilot) is much appreciated. Chuck Bardeen performed well as our GIS expert, gave helpful suggestions for presentation, and supplied many of the figures. RLG was supported by NSF grant ATM-0296159. The support of the National Center for Atmospheric Research (NCAR) for the participation of MAL and the availability of computing facilities is gratefully acknowledged. The many specialized instruments were deployed in CASES 97 were supported by the NSF Deployment Pool under the auspices of the NCAR Atmospheric Technology Division, whose dedication and hard work are also gratefully acknowledged. MLW and JS were supported by the U. S. DOE, Office of Science, Office of Biological and Environmental Research, for the “Water Cycle Observations, Analysis and Modeling Project” under contract W-31-109-Eng-38. Operation of the Atmospheric Boundary Layer Experiment facility was supported by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research under contract DE-AC02-06CH11357.
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