3.2 MESOSCALE VARIABILITY IN BOUNDARY LAYER DEVELOPMENT OVER THE SOUTHERN GREAT PLAINS

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1. INTRODUCTION

The land surface is highly heterogeneous. Atmospheric mixing, however, rapidly blends small-scale variations in surface forcing. A quantitative understanding of the influence of micro- and mesoscale surface forcing on the overlying atmosphere remains elusive. Model studies suggest that landscape heterogeneity can lead to significant mesoscale flows and mesoscale variability in the atmospheric boundary layer (ABL). Observations of lake breezes and surface layer flows at scales of a few to a few tens of kilometers support these model results. Heterogeneity in surface layer turbulent fields within the atmospheric boundary layer, however, is much more pronounced than heterogeneity in the mean properties of the ABL (e.g. depth, water vapor content). Heterogeneity in mean ABL properties is arguably more relevant for processes such as convective initiation. Observational evidence of landscape-driven heterogeneity in the mean properties of the ABL at scales of ten to hundreds of kilometers is rare.

We present a case study of an attempt to find a link between the land surface and atmospheric heterogeneity. Surface flux observations, combined with remote sensing of the land surface, provide estimates of the spatial pattern of surface sensible and latent heat fluxes. Airborne water vapor lidar observations provide observations of boundary layer depth along the flight track. Rawinsondes provide thermodynamic initial conditions. Observations were collected over the 50km x 250km domain of the 1997 Southern Great Plains Experiment. Two days of data show that surface fluxes are well correlated with soil moisture shortly after rainfall, and that surface fluxes are very heterogeneous at a wide variety of spatial scales. Correlation between surface fluxes and soil moisture appears to degrade with time past rainfall, suggesting the surface vegetation and root-zone moisture becomes more important.

The potential for heterogeneous ABL forcing is found to be large. Airborne boundary layer soundings show moderate heterogeneity in boundary-layer growth at two sites 30 km to 50 km apart that are consistent with airborne surface flux measurements in these regions. Airborne lidar observations show significant heterogeneity in mean ABL properties at scales of about 100km, suggesting that smaller-scale surface features were homogenized in the atmosphere by horizontal advection and mixing. These observational results are presented along with MM5 simulations of surface fluxes and boundary-layer development to help resolve the role of surface heterogeneity on days of the case study.

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2. EXPERIMENT DESCRIPTION

The Southern Great Plains (SGP-97) field experiment occurred during late spring and summer of 1997 over northern Oklahoma and southern Kansas. The area can be characterized as sub-humid grasslands with flat to moderately rolling terrain and a maximum relief of less than 200m. Rangeland and pasture are the dominant land use types. One of the primary goals of SGP-97 was validation of the soil moisture retrieval algorithms of ESTAR (Jackson et al., 1999), an airborne passive microwave radiometer. An additional objective was to examine the effect of soil moisture on the evolution of the atmospheric boundary layer and clouds over the Southern Great Plains. To that end, the Laser Atmospheric Sounding Experiment (LASE, Browell et al., 1997), a water vapor differential absorption lidar (DIAL) was flown on a NASA P-3 aircraft alongside ESTAR. The P-3 flight track covered a 50km x 250 km SSW to NNE region roughly centered on the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) Central Facility (CF) (http://hydrolab.arsusda.gov/sgp97/explan/figure1.gif)

We analyze two days, 12 and 13 July, 1997, characterized by weak high-pressure, and generally clear skies. Data from ESTAR, LASE, AVHRR, several eddy covariance flux towers, ARM-CART rawinsondes, and in situ flux aircraft were all available on those days. A rainstorm late on 10 July provided moist but drying soils.

3. SURFACE FLUXES

Surface energy fluxes are highly variable across the domain, as shown by aircraft fluxes and flux towers. The variability is due in part to highly heterogeneous

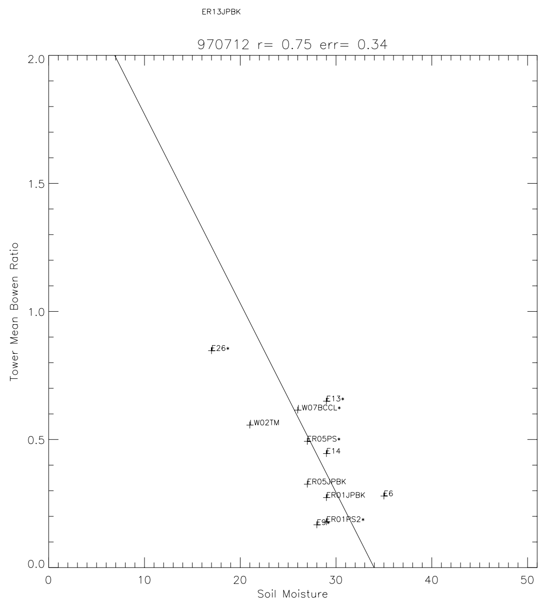

Figure 1: Relationship between ESTAR derived soil moisture and tower-derived mid-day Bowen ratio on July 12, 1997.

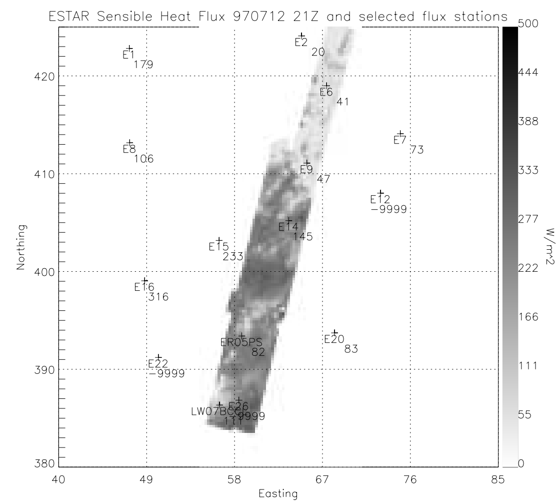

Figure 2: ESTAR soil moisture – Bowen ratio model applied to the whole ESTAR area for July 12. Maps shows estimated sensible heat flux.

land-use, as well as precipitation patterns. The density of direct flux measurements is not at all sufficient for directly mapping surface fluxes across the domain of the lidar ABL depth and water vapor measurements (50km x 250km). In order to map surface fluxes across the domain with sufficient resolution to explain heterogeneous ABL development, we compare directly observed fluxes to remotely sensed surface characteristics that do span the domain. Our goal is not a robust method of computing fluxes from remotely sensed data, but a simple approach for extrapolating observed energy fluxes across this specific domain for these two days.

Tower-based sensible and latent heat fluxes were compared to AVHRR vegetation indices and airplane-mounted passive microwave soil moisture measurements across the Southern Great Plains Experiment area (SGP-97) for July 12 and 13. Both vegetation and soil moisture should influence the surface energy balance, as roots can draw out deep soil moisture for transpiration and surface wetness will contribute to evaporation. Results showed weak correlation between Bowen ratio and NDVI. The correlation between remotely sensed soil moisture and Bowen ratio was much higher, suggesting that evaporation was the main control on surface fluxes during this relatively wet period. A linear relationship (see Figure 1) between soil moisture and Bowen ratio was used to produce estimates of surface energy flux over the SGP-97 region. Linear fits were produced for all daylight hours

The resulting fits were then used to create surface energy flux maps over the 50km x 250km region covered by ESTAR. An area average value for ground heat flux and net radiation derived from the surface flux towers was used in combination with the ESTAR-derived Bowen Ratio to compute sensible and latent heat fluxes for the entire region. Clear sky conditions and tower data indicated that assuming net radiation and ground heat flux to be constant in space was, to first order, reasonable. A resulting sensible heat flux map for 12 July is shown in Figure 2. High sensible heat fluxes in the south result from relatively low soil moisture. Rain in the north on the 10th caused relatively high soil moisture values and our estimates of relatively small sensible heat fluxes.

4. ABL DEPTH HETEROGENEITY

This study is motivated by DIAL observations of strong spatial heterogeneity in the depth and water vapor content of the ABL on both 12 and 13 July. Figure 3 shows a line plot of observed ABL depth on 12 July (C. Senff, personal communication) derived using an edge-detection algorithm (Davis et al., 2000). A similar pattern emerged on both days and on each of four or more passes over the same domain flown each day; a deeper and drier ABL in the southern portion of the SSW to NNE swath covered by the NASA P-3. The ABL was deeper and the S to N contrast greater on 12 July. A secondary, elevated layer containing relatively high aerosol and water vapor content existed on both days as well. Determining the source of the observed heterogeneous ABL development is the purpose of this study.

The map of sensible heat flux in Figure 2 provides thermodynamic forcing for ABL growth that is qualitatively consistent with the observations. This supports that hypothesis that large-scale heterogeneity in surface fluxes driven by recent

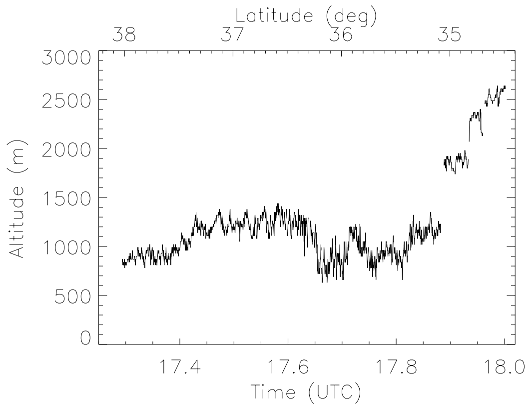

Figure 3: LASE observed ABL depth from the NNE to the SSW of the SGP97 region on 12 July, 1997. A map of the SGP97 domain is available at http://hydrolab.arsusda.gov/sgp97/explan/figure1.gif

precipitation can lead to heterogeneous ABL development. The observed ABL depth does not closely follow the smaller-scale surface flux heterogeneity shown in Figure 2. It is likely that brisk southerly mean winds have homogeneized the mean ABL structure at smaller scale despite heterogeneous surface forcing.

A more quantitative comparison between surface forcing and heterogeneous ABL development is attempted by computing the potential for heterogeneous ABL development solely from surface flux heterogeneity. The ESTAR-derived surface flux maps are used in combination with a 14 UTC ARM-CART Central Facility rawinsonde thermodynamic profile and a simple mixed layer encroachment model (e.g. Garratt, 1992) to calculate potential mid-day ABL depth variability across the experiment area. We call it potential heterogeneity because this extreme estimate assumes no mean wind and no turbulent mixing among adjacent columns of air.

Figure 4 shows the ABL heights estimated at 21 UTC using this method. The approximate magnitude of ABL depth variability and S-N spatial pattern is reasonably consistent with the observations at 18 UTC. A very notable difference is that the mixed layer model shows the boundary between deep and shallow ABLs to be farther north than do the 18 UTC observations. The modeled ABL depths prior to 18 UTC are more homogeneous than the observations. The elevated mixed layer structure causes a slowing in modeled ABL growth at about 700 m above ground at the base of this layer. Once the inversion between the layers is eroded, rapid growth up to about 1500 m ensues. Thus the thermodynamic structure of the atmosphere on that day both suppresses (15 to 18 UTC) and enhances (18-21 UTC) ABL depth heterogeneity.

On a smaller scale, airborne flux measurements and vertical profiles flown over two 30km tracks on 12 July

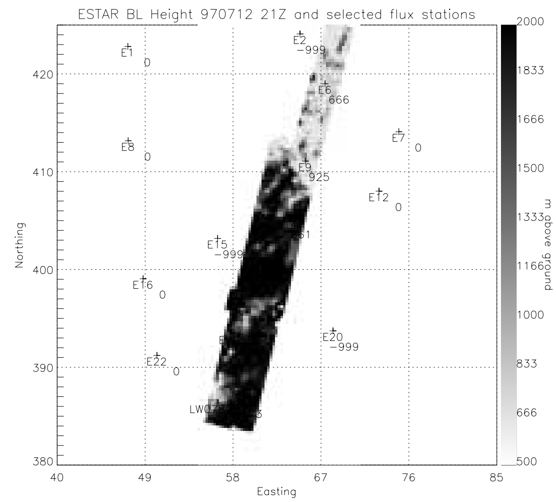

Figure 4: Mixed-layer model of potential ABL depth for 21 UTC on July 12, 1997.

are roughly consistent with ESTAR-derived fluxes. Sensible heat fluxes measured along the El-Reno track (E-W, near point ER05PS on Figure 2) were persistently lower than those observed along the Kingfisher track (N-S, crossing 400 Northing and at about 60 Easting on Figure 2). This is consistent with the ESTAR-derived flux estimates shown in Figure 2. Aircraft soundings of ABL depth at these tracks show ABL depths to be a few hundred meters deeper over the Kingfisher track, consistent with this trend in surface heating. It is not yet clear whether or not the observed small-scale variability in ABL depth found via LASE around 17:48 UTC in Figure 3 is persistent and clearly associated with these smaller-scale surface flux features.

Advection and divergence, not analyzed with this simple model, are also important in determining boundary layer depth. It is likely that divergence was important on 13 July where the soil was drier and surface heat fluxes were greater than on 12 July, but the observed ABL depths over the entire region were significantly lower than those observed on 12 July.

5. MODELED ABL DEPTH

We have run MM5 with varying land-surface flux parameterizations as a more complex and realistic test of the impact of surface flux heterogeneity on ABL development. Simulated ABL depths from various simulations are shown by Reen et al (2001). It is noteworthy that even the simplest land surface simulation where surface flux heterogeneity is driven by a land use map (CLIMO), predicts a deeper, drier ABL in the southern portion of the study domain on 12 July. This run, however, also shows drier conditions and larger sensible heat fluxes along the southern portion of the P-3 flight track. Thus these findings are consistent with our previous results. Soil moisture distributions determined by observed precipitation and a land surface model (offline PLACE) match ESTAR-observed soil moisture patterns quite well (Reen et al, 2001). When ESTAR-derived soil moisture contents are incorporated into the land surface model (PLACE+ESTAR), the more subtle variation in ABL depth in the northern portion of the domain is also simulated by the model. The modeled ABL depth is quite variable in space and these results are for one case study at one time of day, thus these results should not be over-interpreted.

6. CONCLUSIONS

This experiment showed that for the Southern Great Plains experiment, on two relatively clear, cloudless days in July shortly after a rainfall, soil moisture derived from ESTAR passive-microwave brightness temperature has a relatively good correlation to the Bowen ratio. This correlation is greater than the correlation with vegetation cover as measured with a standard spectral vegetation index, NDVI, derived from AVHRR. This suggests that surface energy flux variability in the Southern Great Plains is driven more by moisture availability than vegetation cover and type in July when soils are relatively moist.

Sensible heat fluxes mapped from the soil moisture relationship were used to drive a thermodynamic boundary layer height model. The model, while not matching boundary layer height at all points, probably due to the lack of advection and entrainment in this simple model, did reproduce the large scale height gradient in the boundary layer. The broad, though not specific, similarity between observations and mixed-layer growth model results suggests that surface flux variability did exert a strong control of ABL depths at spatial scales of order 100km. Smaller-scale heterogeneity may also be the result of spatial structure in surface buoyancy flux. Mesoscale model simulations also supported this general conclusion, and show the potential benefit of more detailed soil moisture observations in simulating mesoscale detail in ABL development.

7. ACKNOWLEDGEMENTS

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