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COMPARISON OF THE URBAN HEAT ISLAND SIGNATURES OF TWO TEXAS CITIES: DALLAS AND HOUSTON

Lisa S. Darby
National Oceanic and Atmospheric Administration/Earth System Research Laboratory, Boulder, CO

Christoph J. Senff
Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO and
National Oceanic and Atmospheric Administration/Earth System Research Laboratory, Boulder, CO

1. INTRODUCTION

The cities of Houston and Dallas, Texas have comprehensive networks of surface meteorology and chemistry sensors that are operated and maintained by the same agencies. The similarities of the networks and lack of significant terrain features in Dallas and Houston allow for the comparison of their urban heat islands (UHI). Since Dallas is an inland city, the Dallas UHI is unperturbed by thermal flows driven by the land/sea temperature difference. Houston, on the other hand, regularly has sea-breeze flows that cross through the metropolitan region. Analyzing the summertime UHIs from both cities allows us to isolate the effects of the sea breeze on Houston's UHI. As part of the ongoing studies of Texas air quality at the National Oceanic and Atmospheric Administration's Earth System Research Laboratory (NOAA/ESRL), we have analyzed seven summers of temperature data from both Dallas and Houston, and aerosol mixing layer heights derived from airborne DIfferential Absorption Lidar (DIAL) backscatter measurements from flights over Houston during the summer of 2006.

2. HOUSTON AND DALLAS URBAN HEAT ISLANDS

Temperature data for the seven-summer (2000-2006) temperature analysis came from the stations shown on the maps in Fig. 1. Data from these stations were downloaded from (http://www.tceq.state.tx.us/compliance/monitoring/air/monops/historical_data.html). In this study, summer is defined as all days between 1 June and 30 September. For Dallas, most stations that were operational in summer 2000 through summer 2006 were used for the analysis. Only one urban station existed for all of these summers, Dallas Hinton (C401, Fig. 1a), thus making this station the choice for the Dallas urban station. Based on land use, several stations were possible candidates for the Dallas rural station. The Cleburne station (C77) was chosen as the rural station for its consistency in being the coolest station during the early morning hours.

For Houston, a subset of available stations was used to characterize the temperature field in and around Houston. The selection of the urban station was not as clear-cut as for Dallas, and is not finalized at this time. There are several candidate stations, but it is difficult to choose because there is no "downtown station" as in Dallas and a few of the stations close to downtown are in irrigated parks. In the final analysis, a few stations may be averaged together to represent the urban conditions. For the results presented here, we have used Houston Regional Office (C81) as the urban station (Fig. 1b). Conroe, north of downtown Houston, was chosen as the Houston rural station (C65/78, Fig. 1b). (This station was relocated from one side of the Lone Star Executive Airport in Conroe to the other side in 2001, thus the station identifier change.) This station was chosen mainly for its land use, but also for its distance from the shore, and thus its immunity from sea-breeze effects.

Figure 2a shows the hourly-averaged temperatures from the Dallas stations for the seven summers. The urban station, C401, is denoted by red triangles and the rural station, C77, is denoted by blue triangles. Overall, the urban and suburban stations are warmer than the rural stations (see Table 1 for station classifications). Note that all stations have similar timing in the temperature

Corresponding author address: Lisa S. Darby, NOAA/ESRL, CSD 3, 325 Broadway, Boulder, CO, 80305; email: lisa.darby@noaa.gov

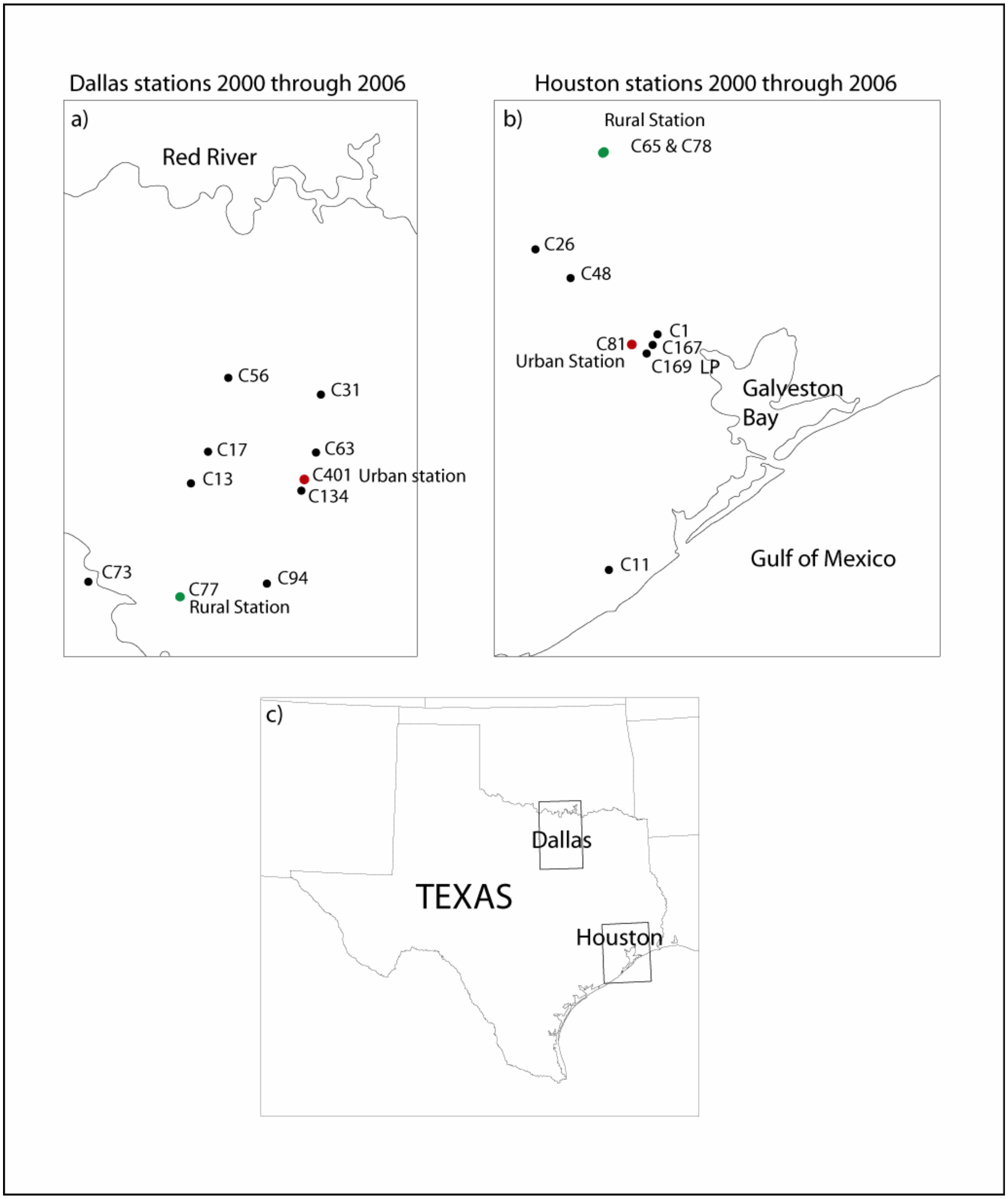

Fig. 1 Map showing meteorological stations used in the seven-summer temperature analysis. The urban stations are marked with a red dot. The rural stations are marked with a green dot. a) Dallas and surrounding region. b) Houston and surrounding region. The approximate location of the LaPorte radar wind profiler is indicated by "LP." c) Texas map showing location of the Dallas and Houston boxes.

maxima and minima. Figure 2b shows the average difference between the urban and rural station by hour of day, for each summer of the study, plus the average hourly difference over all the summers. This analysis includes all days between 1 June and 30 September, indicating that even when including all weather conditions, Dallas has an easily detectable UHI. Consistent with the literature (e.g., Fast et al. 2005; Gedzelman et al. 2003), the UHI was strongest

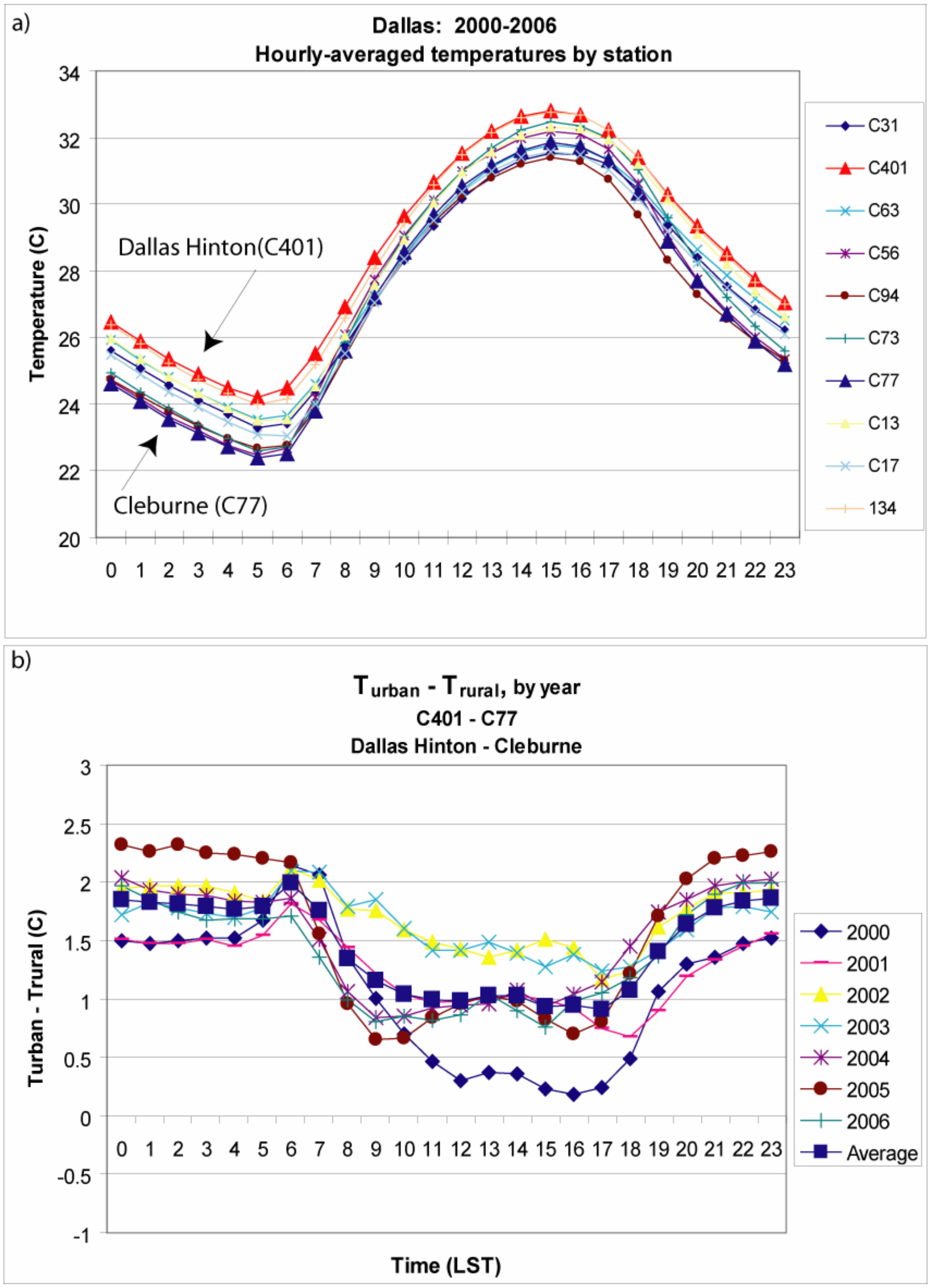

Fig. 2 a) Hourly-averaged temperatures over the course of seven summers (2000-2006) for meteorological stations in the Dallas area. b) The hourly–averaged differences in temperature between the urban station and the rural station for each summer, and the average hourly urban-rural temperature differences over all the summers.

at night, with average temperature differences between 1.5 and 2.5º C. During the day, the UHI was weaker, and there was more variability among the years, with 2002 and 2003 having stronger daytime UHIs on average, and 2000 having a much weaker daytime UHI than average. On average, the Dallas UHI was maintained during the day.

Houston temperature and UHI data are shown in Figure 3. The urban station, C81, is represented by the red triangles and the rural station, C65/78, is represented by the blue

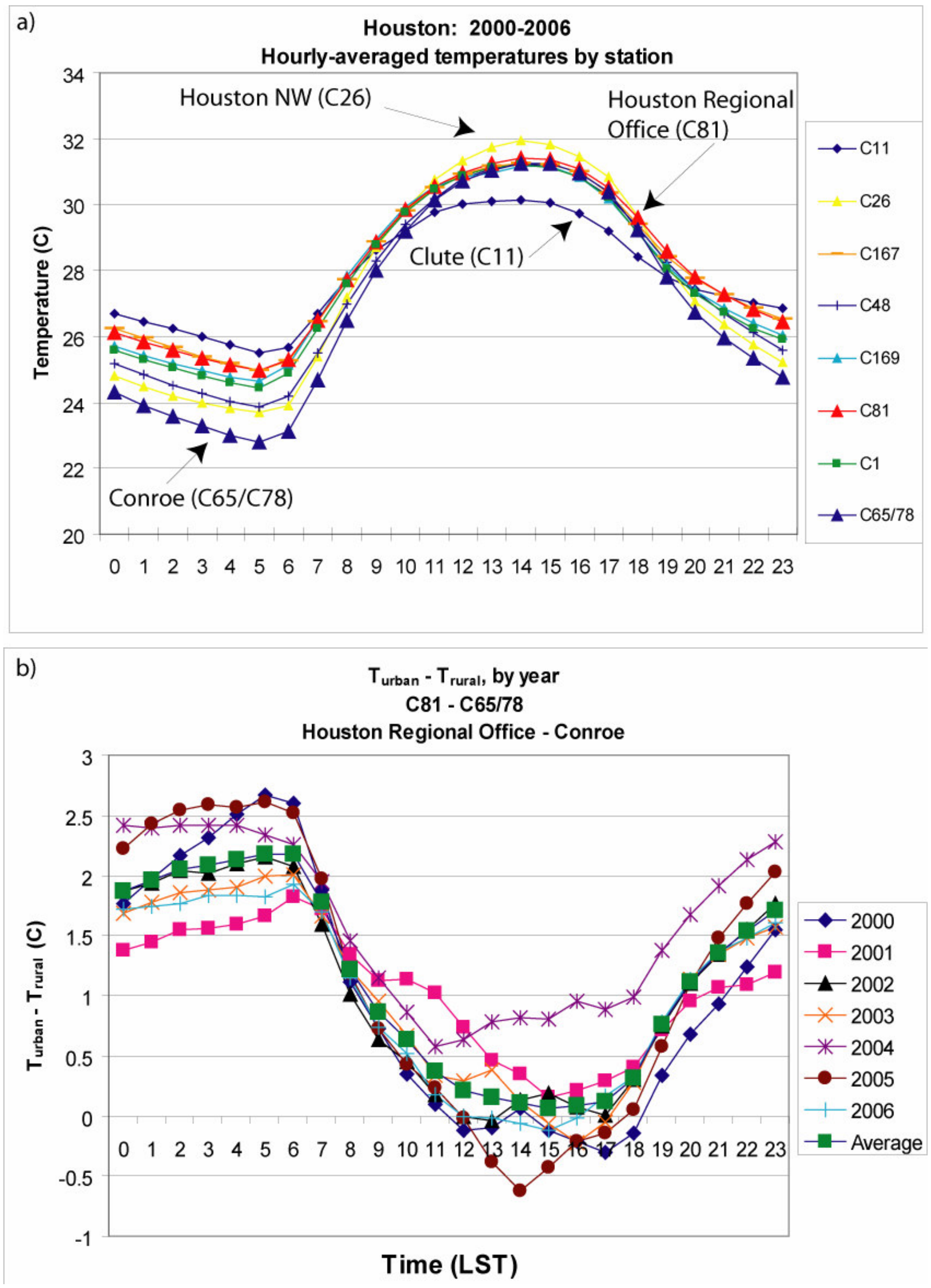

Fig. 3 Same as Fig. 2, but for the Houston area.

triangles. A significant difference was seen between these two stations during the night, but during the day, they were very similar, on average. The Houston temperature trends show the effects of the stations' distance from the coast, for instance, Clute (C11) is close to the Gulf Coast (Fig. 1b) so has a smaller diurnal range in temperature and reaches its maximum temperature earlier than the inland stations.

Figure 3b shows the Houston hourly urban-rural temperature differences for each summer in the study. Houston on average had a stronger UHI at night compared to Dallas. During the day, however, the urban-rural temperature differences indicated that the urban station was sometimes cooler than the rural station (the time series crosses below the zero-line on the plot). On average over the seven summers, the urban-rural temperature differences were close to zero in the middle of the day, between 1400 and 1600 LST. Some years were more likely to have an absence of the UHI during the afternoon than others. The intrusion of the cooler marine air behind the sea breeze front most likely accounts for this “reversal” of the urban-rural temperature differences in the afternoon.

Between the summers of 2000 and 2006, the number of Houston meteorological stations was increased. An analysis of a single summer with more stations, e.g., 2006, revealed that the newer stations to the west of downtown tended to be warmer in the daytime than the urban stations (not shown). It is suspected that the sea breeze is responsible for this surface temperature pattern.

The frequency of Gulf-breeze flows for each summer was assessed through cluster analysis. An example of the results is shown in Fig. 4 (see Darby, 2005 for more detail on the cluster analysis procedure). Because the years 2000 and 2006 were major experiment years, these are the years shown. Fig. 4a shows the Gulf breeze wind pattern. The frequency of occurrence of this cluster, by hour, for the summers of 2000 and 2006 are shown in Figs. 4b and 4c, respectively. Based on this one representative cluster (there are others that also indicate onshore flow), the summer of 2000 clearly had more instances of onshore flow in the afternoon (81 hours classified as Gulf-breeze flow between 1100 and 1800 LST) than the summer of 2006 (46 hours between 1100 and 1800 LST), consistent with the urban-rural temperature differences for these two years (Fig. 3b).

An overview of the differences between the seven-summer average of Dallas and Houston urban-rural temperature differences, by hour, is shown in Figure 5. Houston had greater urban-rural temperature differences between midnight and 0500 LST. Both cities had a similar peak in the urban-rural temperature differences at 0600 LST, and showed a quick reduction in urban-rural temperature differences after sunrise. Likewise, the increases in urban-rural temperature differences after sunset were apparent in both cities.

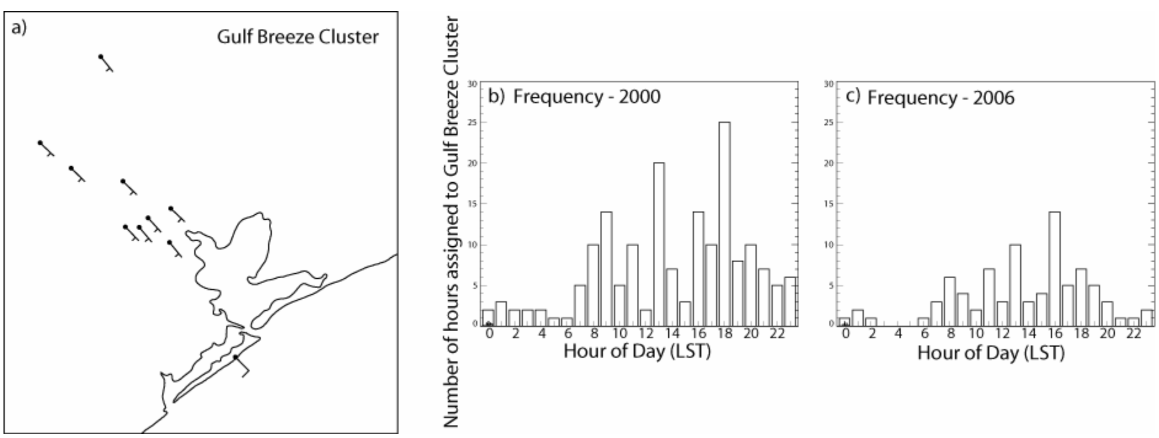

Fig. 4 a) Wind barbs representing gulf breeze flow, as determined through cluster analysis of 10 Houston stations over the summers of 2000-2006. A ½ barb represents 5 m s^{-1} winds and a full barb represents 10 m s^{-1} winds. Barbs point into the wind. b) Frequency of occurrence versus hour of day (LST) for the gulf breeze cluster in summer 2000. c) Same as in b), but for summer 2006.

3. AEROSOL MIXING LAYER HEIGHTS

During the Texas Air Quality Study II (TexAQS II) field program in the summer of 2006, NOAA/ESRL deployed a DIAL system on a NOAA Twin Otter aircraft. The TOPAZ (Tunable Optical Profiler for Aerosol and oZone) DIAL system measured profiles of ozone and aerosol backscatter along the flight track between approx. 3000 m ASL and the surface at a horizontal resolution of about 600 m and a vertical resolution of 90 m (ozone) and 6 m (aerosol backscatter). From the aerosol backscatter profiles, mixed layer heights were calculated using a Haar wavelet transform method that generally followed the approach of Davis et al. The Haar wavelet method is employed to detect the steepest gradient in

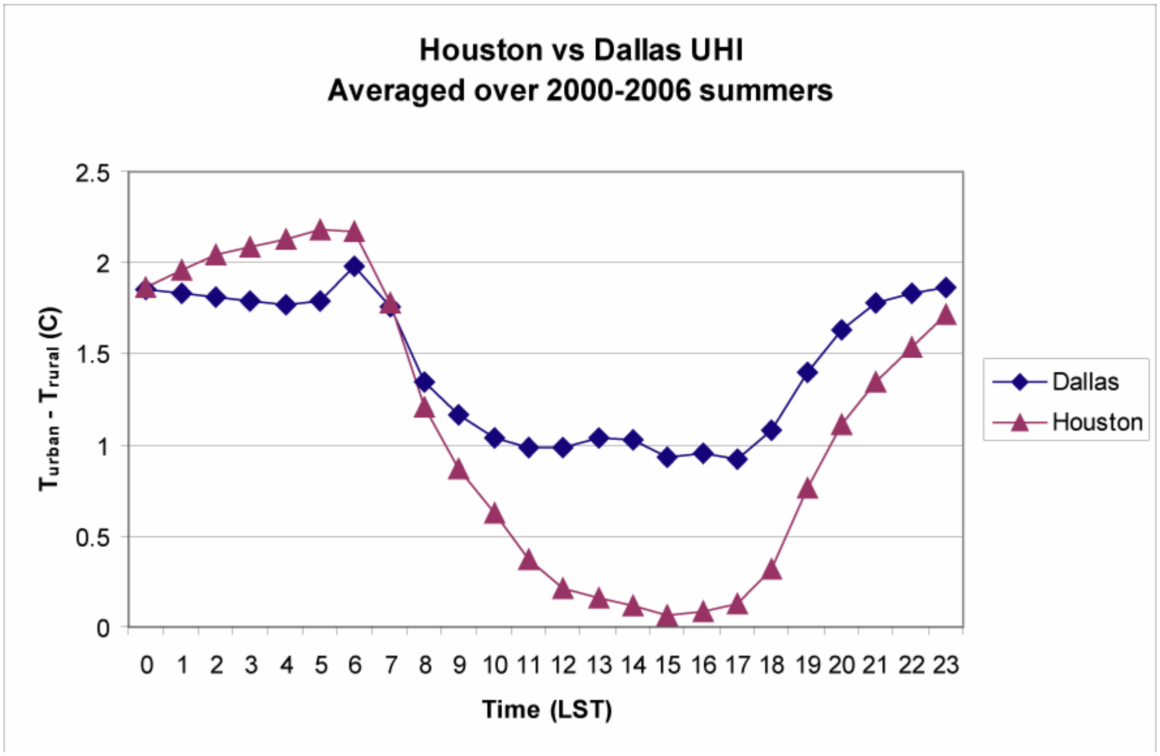

Fig. 5 Comparison of seven-summer hourly averages of the urban-rural temperature differences between Dallas and Houston.

aerosol backscatter between the boundary layer and the free troposphere. The altitude (above ground level) of the sharpest aerosol gradient is taken as the local mixed layer height and is here referred to as the aerosol mixed layer height (AMLH). Limitations of this method included conditions with minimal contrast in aerosol loading between the boundary layer and the free troposphere, multiple aerosol layers, or the presence of clouds. Under these conditions, results of the AMLH retrieval have to be further screened and interpreted carefully.

Our analysis of the aerosol mixed layer height (AMLH) involved breaking down the Houston region into geographic “bins” by broad land use characteristics and surface temperature behavior learned from the UHI portion of the study. Figure 6 shows the bins used for the analysis. Data from all Houston flights with usable AMLH values were binned into the geographic sections and plotted versus latitude, longitude and time, color-coded by bin. For brevity, we show AMLHs versus longitude only. Unfortunately, no flight data are available over Dallas to make a comparison of AMLH behavior between the two cities.

3.1 *30 August 2006*

The binned AMLH heights for the 30 August flight, plotted against longitude, are shown in Fig. 7. The flight path and AMLH field for the flight are shown in Fig. 8. The winds were northerly all day until a late sea breeze formed, after the flight was completed. The flight on 30 August 2006 was designed to capture ozone and aerosol measurements downwind of Houston. Figure 7 shows that there was not a large variation in AMLHs with longitude on this day, with heights falling between 900 and 1700 m above ground level (AGL). The bins to the south of the urban area tended to have slightly higher AMLHs than the urban bin. For instance, the south suburban bin had an average AMLH of 1472 m AGL and the southeast suburban bin had an average AMHL of 1458 m AGL versus an average AMHL of 1354 m AGL in the urban bin. The lowest AMLHs tended to be in the areas labeled Transition 1, at the north end of Galveston Bay, and Northeast Rural, with an average AMLH of ~1000 m AGL. Of course, changes in AMLHs with time were also occurring during the flight, but it is beyond the scope of this paper to incorporate these in detail.

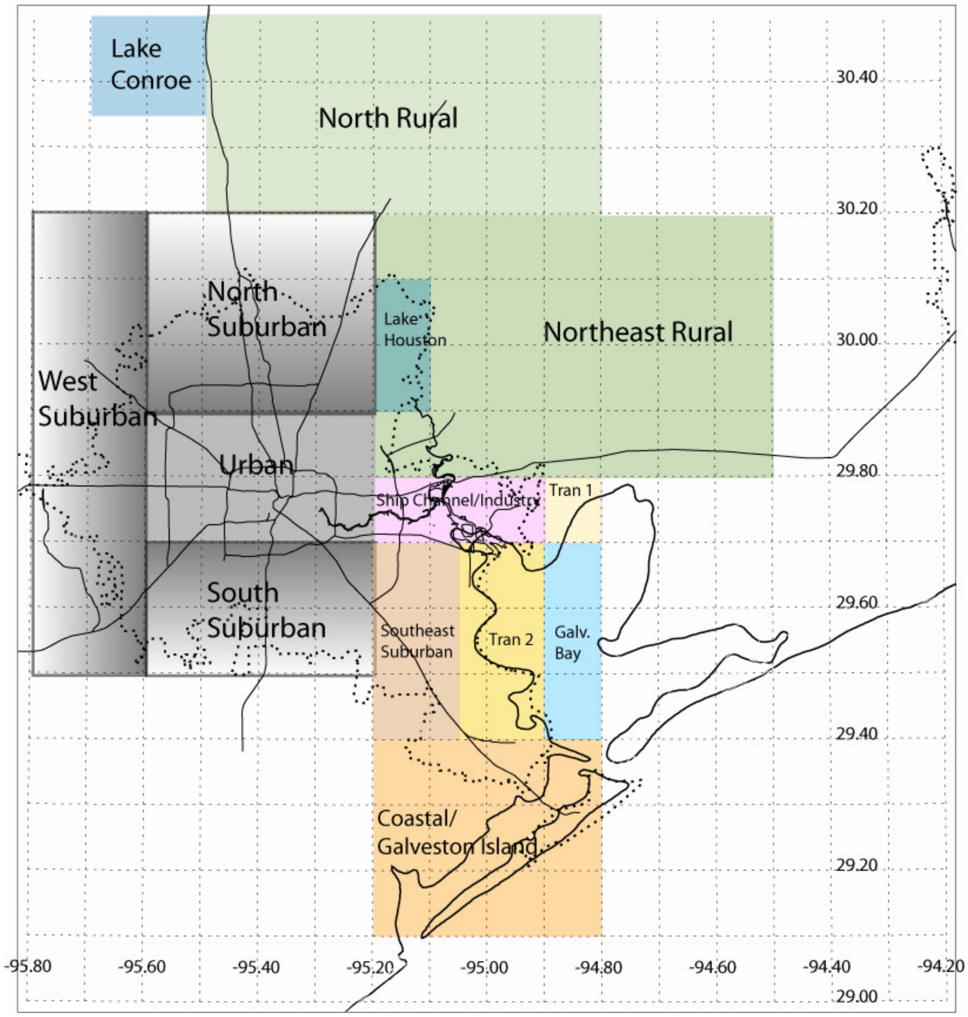

Fig. 6 Map of Houston area with labeled geographic bins used for the aerosol mixed layer heights analysis.

However, as an example, the lower AMLHs seen in the urban bin were measured in the earlier portion of the flight.

Hourly averages of surface temperature and surface winds are shown in Fig. 9 for 30 August 2006 from 1400 to 1700 LST, during the Twin Otter flight. Northerly winds are seen here, along with warmer surface temperatures in the downtown area, and west and north of downtown, consistent with the analysis of hourly averages of summer 2006 temperatures (not shown). The stations closer to Galveston Bay and the Gulf of Mexico were cooler.

The southerly displacement of the highest AMLHs in the airborne data (Fig. 8) indicates the advection of the higher AMLHs from the urban area to the south and southeast. The LaPorte radar wind profiler data for this day (not shown) indicate northerly or northwesterly flow between 900 and 1700 m AGL during the flight, supporting the advection scenario.

3.2 *16 August 2006*

The AMLHs for the 16 August flight, plotted against longitude, are shown in Fig. 10. This day started out with westerly flow and then a transition to onshore sea-breeze flow, thus the flight track (Fig. 11) was designed to capture pollution transport from Galveston Bay to the northwest of the city. AMLHs during this flight ranged from 500 m to 2000 m AGL, with higher heights to the northwest and the lowest heights over the Gulf coast and northeast rural region. The urban bin had an average AMLH of 1626 m AGL. Only Lake Conroe was slightly higher at

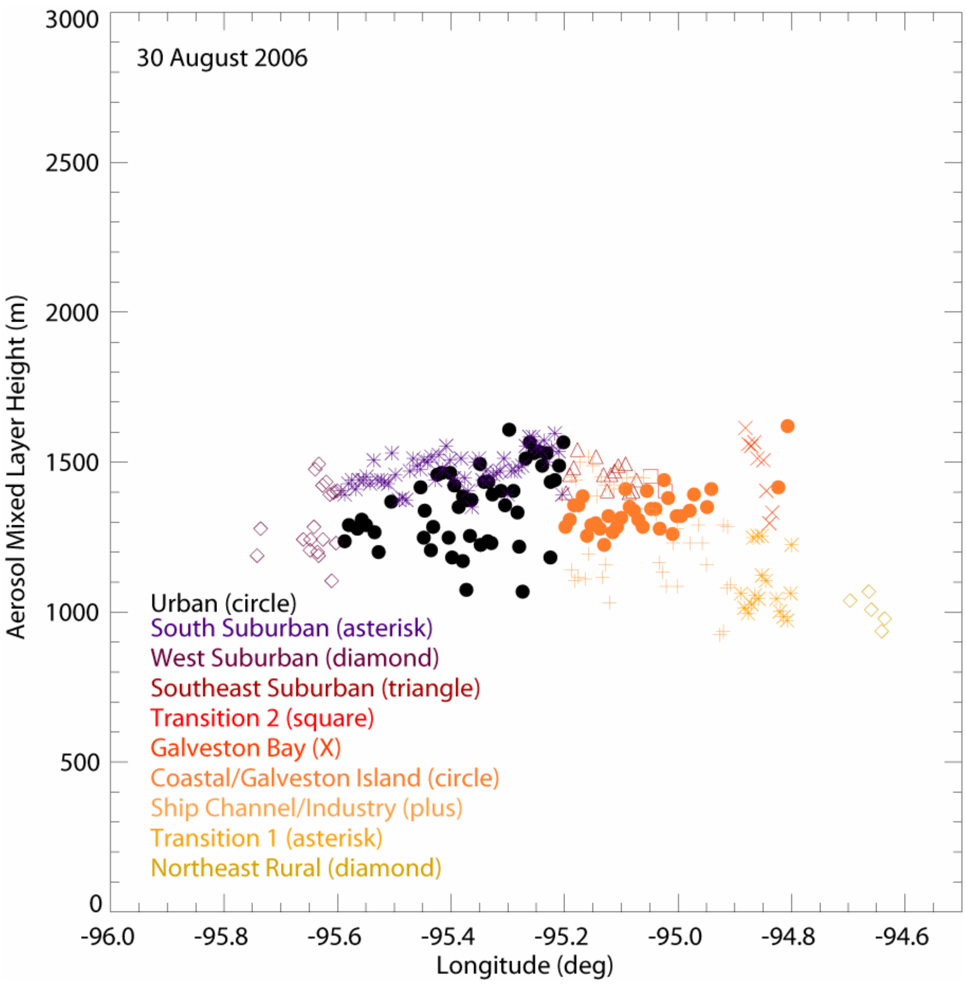

Fig. 7 Aerosol mixed layer heights versus longitude for the 30 August 2006 NOAA/ESRL Twin Otter flight. Symbols and colors represent geographic bins, as noted on the legend.

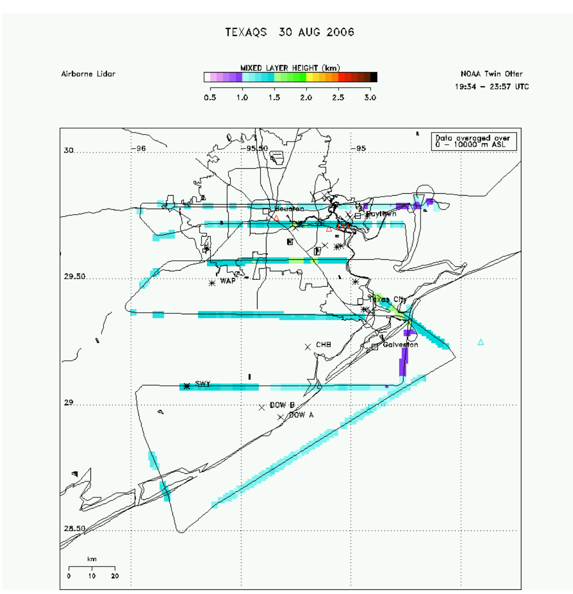

Fig. 8 Flight track and aerosol mixed layer heights for the 30 August 2006 NOAA/ESRL Twin Otter flight. Color bar refers to the aerosol mixed layer heights, in km.

1687 m AGL. This indicates the northward advection of the higher heights associated with the UHI, since under quiescent conditions the average AMLH over Lake Conroe would probably be lower, since it is a large body of water.

Figure 12 shows the hourly-averaged surface winds and temperatures for the flight times on 16 August. Overall, this day was warmer than 30 August, with warm temperatures occurring downtown and to the west and north of downtown. Coastal stations were cooler. The southeast to northwest surface temperature gradient supports the slope in AMLHs with longitude, and the warmer surface temperatures

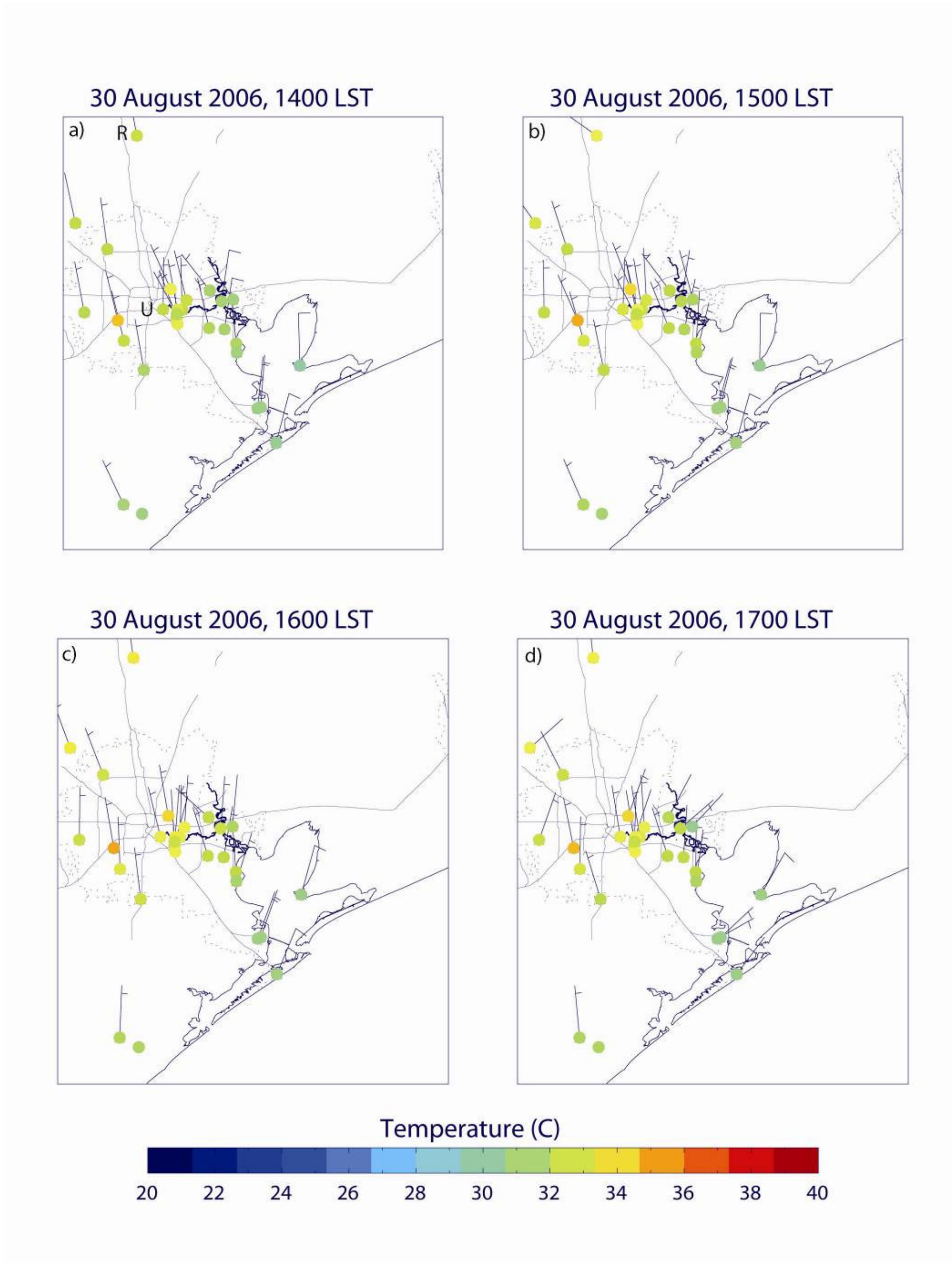

Fig. 9 Hourly-averaged surface temperatures (ºC) and surface winds for 30 August 2006, covering the times of the Twin Otter flight. A ½ barb represents 5 m s^{-1} winds and a full barb represents 10 m s^{-1} winds. Barbs point into the wind. Station circle shows the surface temperature, as indicated by the color bar. Winds and temperatures were averaged over the hour preceding the label on each plot. In panel a) *the urban station has a "U" placed to its left and the rural station has an "R" placed to its left.*

support the higher heights. Southerly component winds between 500 and 2000 m AGL, as seen in the LaPorte profiler measurements (not shown), also aided in the advection of AMLHs northward.

4. SUMMARY AND FUTURE WORK

The Houston UHI was more complex than the Dallas UHI, with the sea breeze leading to the displacement of the UHI at the surface and aloft. In addition to the analysis of the urban-rural temperature differences and the sea-breeze effects, in the continuation of this study other

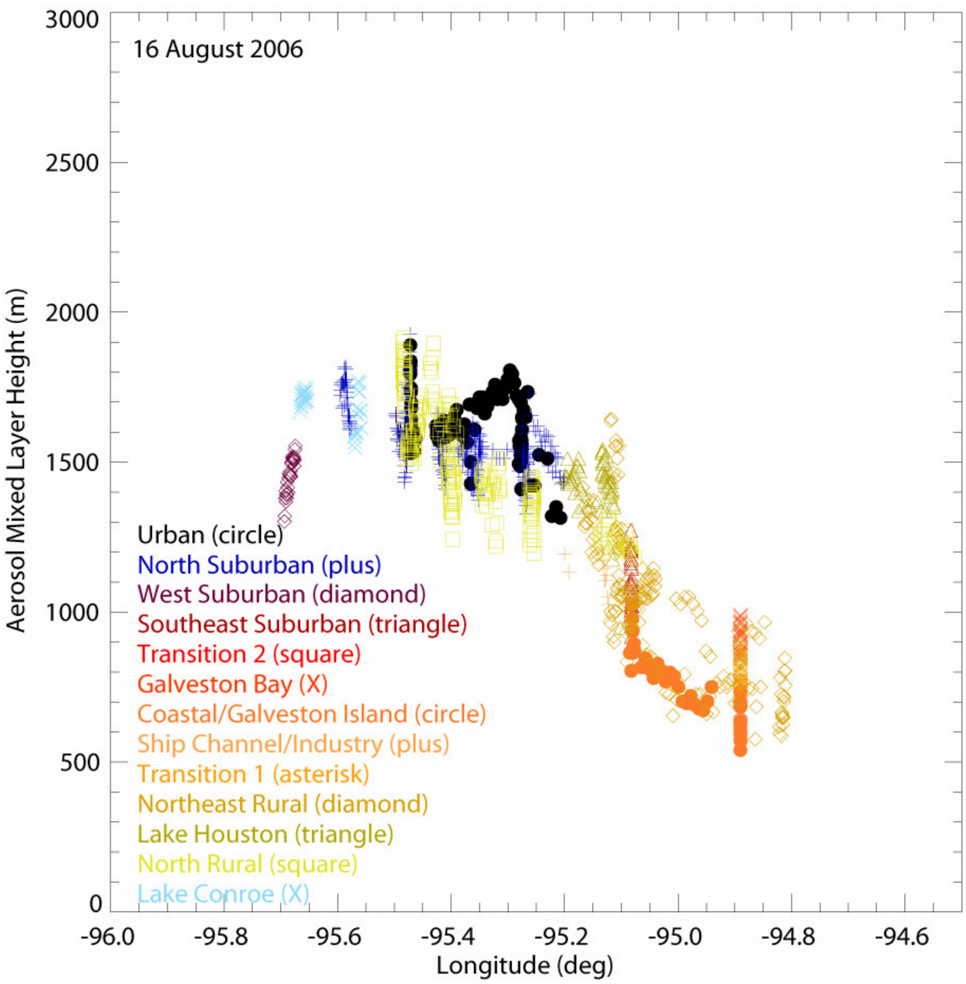

Fig. 10 As in Fig. 7, but for 16 August 2006.

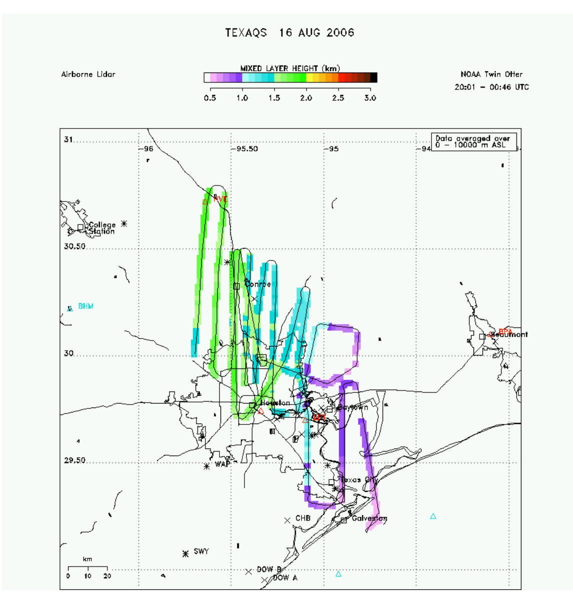

Fig. 11 As in Fig. 8, but for 16 August 2006.

factors to consider include the effects of the distance from the coast for the individual stations.

In both cases presented here, the horizontal distribution of the AMLHs relative to the urban bin was consistent with the boundary-layer winds, i.e., winds above the surface but below the maximum AMLH. On the northerly wind day, the higher AMLHs were slightly south and southeast of the urban bin, consistent with the upper-level winds. On 16 August, the sea breeze day, the low heights to the southeast and higher heights to the northwest, were consistent with both the upper-level winds and the horizontal surface temperature gradient.

Additional future work includes testing a more rigorous refinement of the bin boundaries using land use data, statistical analysis of the binned AMLHs, analyzing UHI patterns after grouping days by surface wind patterns (e.g., offshore flow days versus Gulf breeze days for Houston)

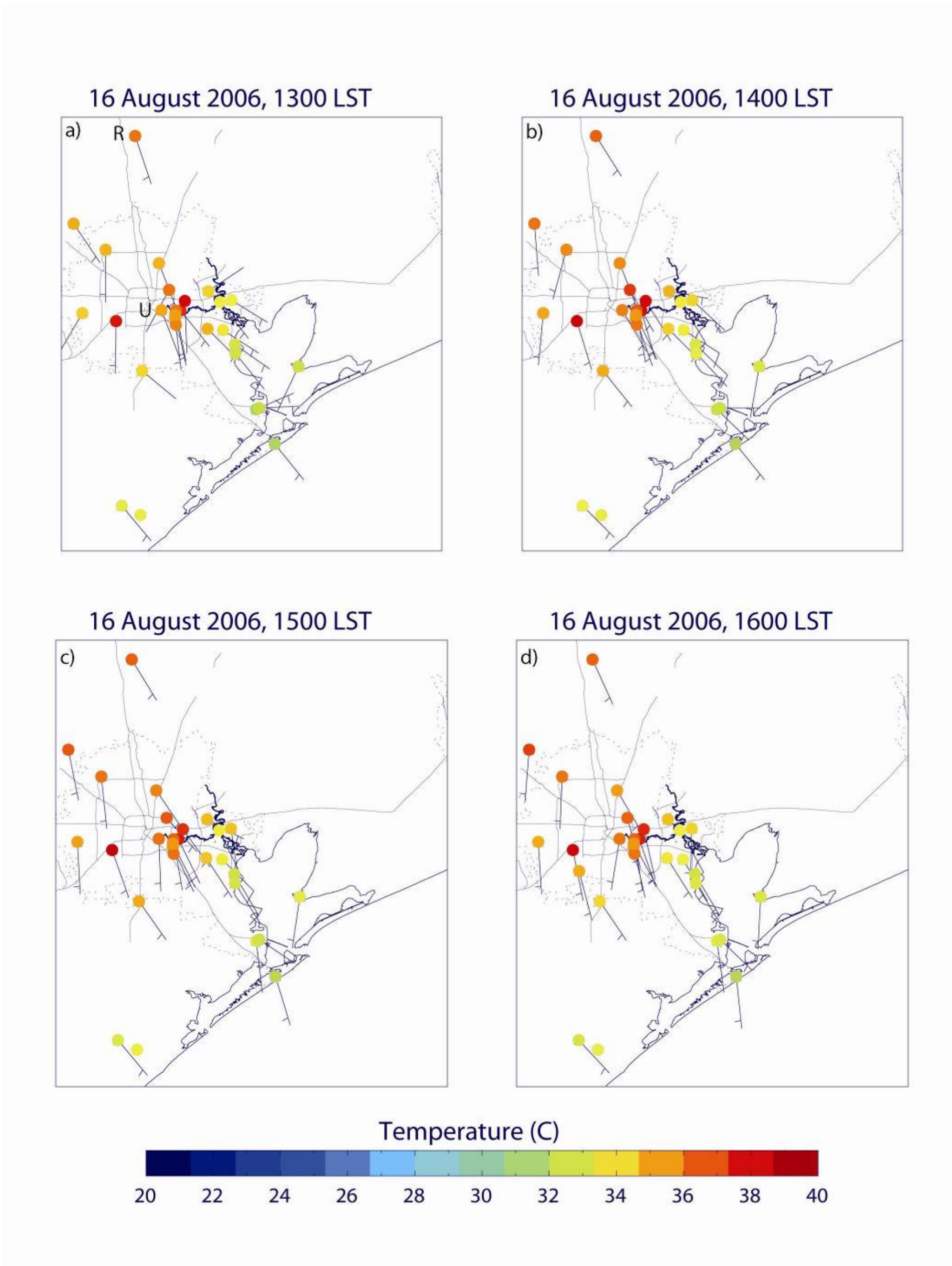

Fig. 12 As in Fig. 9, but for 16 August 2006.

and relating the UHI characteristics to air quality in Houston and Dallas. An analysis of the AMLH measurements versus time and latitude will also be included in future work.

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Table 1

Dallas Site	Classification	Houston Site	Classification
Dallas Hinton C401	Urban	Houston Regional Office C81	Urban
Boys' Club C134	Urban	Galena Park C167	Urban
Frisco C31	Suburban	Milby Park C169	Urban
Dallas North C63	Suburban	Houston East C1	Urban
Denton Airport South C56	Suburban	Houston Wharton C48	Suburban
Fort Worth Airport C13	Suburban	Conroe C65/78	Rural
Keller C17	Suburban	Houston NW C26	Rural
Cleburne C77	Rural	Clute C11	Gulf Coast
Midlothian Tower C94	Rural		
Granbury C73	Rural		

Table 1 Stations used in the seven-summer UHI temperature analysis and their general land use classifications.