2.2 **The Urban Heat Island and Temperature Inversions Measured by a Temperature Datalogger Network in Phoenix during June and July 2001**

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1. Introduction

Surface-based temperature measurements are a basic component of routine meteorological monitoring and special field campaign programs. A new generation of temperature dataloggers have been developed that are small, inexpensive, and accurate over a large temperature range (Whiteman et al. 2000). Because they are relatively inexpensive, a large number of them can be deployed for micro- and mesoscale meteorological studies over long periods of time.

One application of temperature dataloggers is to obtain "pseudo-vertical temperature soundings" by deploying a network of sensors along terrain slopes. Whiteman et al. (2004) deployed lines of temperature dataloggers on the sidewalls of a small basin and found that the pseudo-vertical temperature soundings at night approximated free air temperature soundings over the basin center, with a mean bias and standard deviation less than 0.5^{o} C when compared with tethered balloon soundings. Pseudo-vertical temperature profiles were also obtained from Rattlesnake Mountain, Washington, a ridge that rises ~900 m above the surrounding terrain, to determine the strength and persistence of wintertime nocturnal inversions in the Columbia Basin (Whiteman et al. 2000, 2001). Many large cities in the mountainous regions of the western U.S., such as Phoenix, do not have routine measurements of temperature profiles and pseudo-vertical temperature soundings may be a practical way to obtain continuous information on the local boundary layer structure over a long period of time.

Another application of temperature data loggers is to determine the characteristics of the urban heat island (UHI) effect by deploying a network of sensors across a city. Previous observations in Phoenix, as with many large cities, have indicated the presence of an UHI (e.g. Brazel et al. 2000; Hawkins et al. 2004). However, these studies have relied on measurements from a limited number of sites that may not adequately represent the UHI effect. Measurements of surface temperature distributions across metropolitan areas are also needed to evaluate urban canopy parameterizations that are being implemented in mesoscale models (e.g. Brown and Williams 1998; Martilli; 2002). For Phoenix, Zehnder (2002) attributed the cold bias in a 2-km mesoscale simulation to the lack of a sophisticated urban parameterization in the model.

In this study, measurements are presented from a network of temperature dataloggers deployed over the Phoenix metropolitan area for a 61-day period during the summer of 2001 that encompassed a meteorological and air quality field campaign. Continuous pseudo-vertical temperature profiles obtained from one part of the network are evaluated using measurements from other field campaign instrumentation. The pseudo-vertical temperature profiles are used to determine how often nocturnal inversions occurred in Phoenix. Data from another part of the network are used to quantify the magnitude, diurnal variation, and spatial variation of the UHI and the influence of wind speed and cloud cover on the UHI magnitude.

2. 2001 Phoenix Sunrise Experiment

As part of the U.S. Department of Energy's Atmospheric Chemistry Program, a field campaign was conducted in the Phoenix area between 16 and 30 June 2001 to determine the nocturnal accumulation of ozone precursors, the interaction of ozone precursors during the break up of the nocturnal boundary layer, and the effect of vertical mixing on boundary layer chemistry during the early morning hours (Doran et al. 2003). Air chemistry measurements were obtained continuously at two levels of a tall building in downtown Phoenix and from a research aircraft that flew over central Phoenix on 12 days during the morning transition period.

The locations of meteorological instrumentation deployed to characterize the evolution of the boundary layer properties in Phoenix are depicted in Fig. 1. Radar wind profilers obtained continuous velocity profiles at the Arizona Department of Environmental Quality's (ADEQ) Vehicle Emissions Laboratory (VEL) 7 km east of downtown and at Estrella Mountain Regional Park 36 km west-southwest of downtown. The radar wind profilers included a radio acoustic sounding system (RASS) for measuring virtual temperatures. At the VEL site and at the Waddell site 35 km northwest of downtown, radiosondes obtained profiles of pressure, temperature, and humidity nine times a day on aircraft flight days and less frequently on non-flight days.

In addition to the meteorological profiling instrumentation, a network of 41 HOBO™ temperature dataloggers (Whiteman et al. 2000) was deployed along two lines: the first one running north-south for a distance of about 28 km and the second one running east-west for about 72 km. The two lines intersected in downtown Phoenix where many of the air chemistry measurements were collected. The east-west line spans the metropolitan area so that the eastern and western dataloggers were located in semi-rural areas. Most of the HOBOs were mounted at 3 m AGL on utility poles adjacent to large streets in areas of open exposure. Six surface meteorological stations were also deployed: one at Estrella, one at both ends of the north-south line

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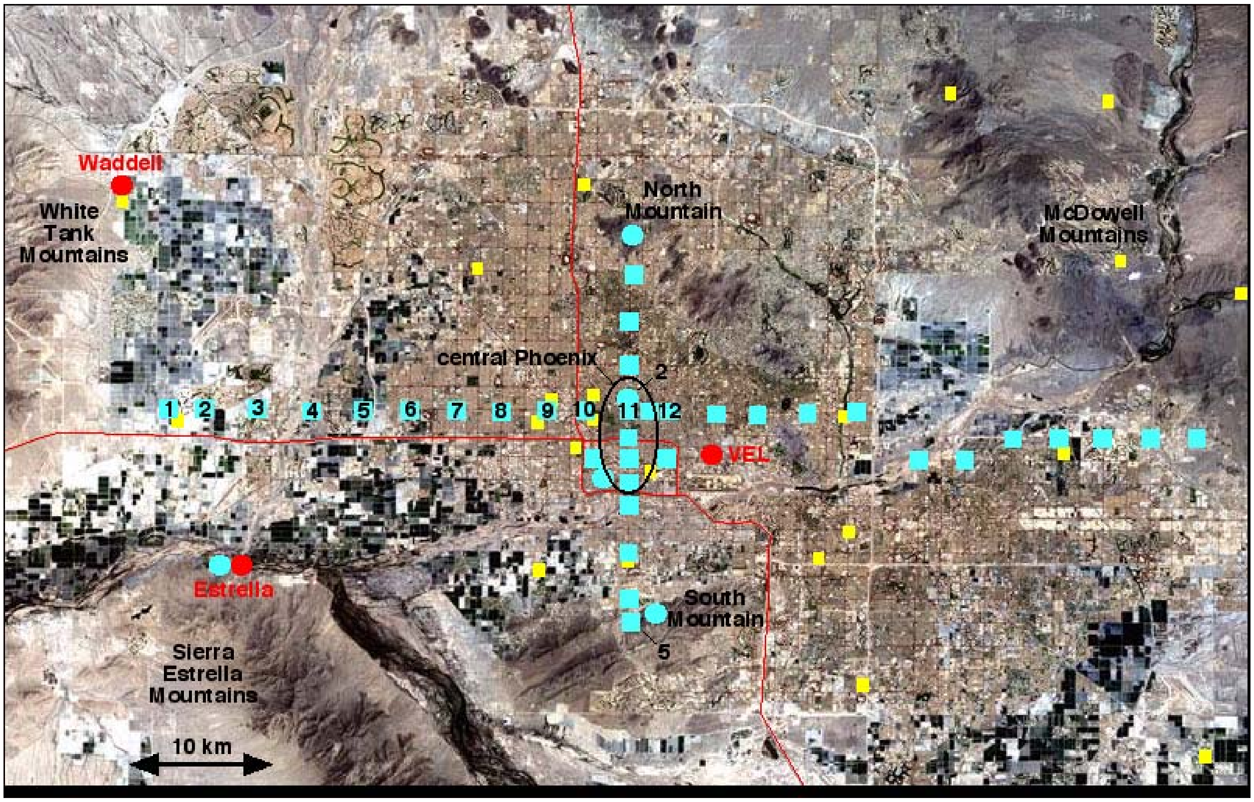

Fig. 1 Landsat image of Phoenix (courtesy of U.S. Geological Survey, http://landsat7.usgs.gov/index.php) and the location of the temperature dataloggers (blue squares), primary meteorological profiling sites during the Phoenix Sunrise Experiment (red dots), supplemental surface meteorological stations (blue dots), and operational meteorological stations (yellow squares). Interstate highways denoted by red lines.

and three on the tops of buildings (15, 40, and 110 m AGL) in central Phoenix. The HOBOs operated between 8 June and 3 August 2001, while most of the other field campaign instrumentation, including the meteorological stations, operated between 16 and 30 June. Data from the HOBOs and the meteorological stations were obtained at 5-min intervals.

The terrain along the western and middle portions of the east-west line and along the middle portion of the north-south line was relatively flat. The elevation of the dataloggers gradually increased from 305 – 315 m at the western end of the east-west line to around 340 m in central Phoenix. At the southern edge of the McDowell Mountains, the terrain slope increases significantly so that the elevation of the easternmost datalogger was at 556 m. The terrain slope also increases at the ends of the north-south line so that the meteorological stations located at the summit of North and South Mountains were 310 and 490 m above the valley floor, respectively.

3. Results

3.1 *Pseudo-vertical temperature profiles*

Temperatures from six dataloggers along the northern slope of South Mountain and a meteorological station at the summit were used to the compute pseudo-vertical temperature profiles. These profiles were compared with temperature profiles obtained from radiosondes and the RASS at the VEL site. Because the RASS measures virtual temperatures, the radiosonde and datalogger temperatures were converted to virtual temperatures. The radiosonde virtual temperatures were computed from the measured temperature, relative humidity, and pressure. The datalogger virtual temperatures were based on moisture measurements from the NWS station at the airport. Since the absolute humidity was usually low (~6 g kg^{-1}), the difference between temperature and virtual temperature was about 1^{o} C or less.

An example of the temperature profiles from the three instrumentation types at 05 LST on 17 June is shown in Fig. 2. Just before sunrise at 05 LST, the radiosonde profile indicated a strong inversion with temperatures at 150 m AGL 8 K warmer than at the surface. While the RASS measurements were similar to the radiosonde, the 60-m range gates that start at 105 m AGL were too coarse to resolve the strong near-surface inversion and the temperatures aloft were about 1 K warmer than those from the radiosonde.

After sunrise, surface heating eroded the inversion by 09 LST. At this time the radiosonde and RASS temperatures were nearly identical and temperatures from three of the dataloggers over South Mountain were as much as 2 K warmer than those over the valley center. By the late afternoon at 17 LST, the sounding indicated a well-mixed convective boundary layer with an adiabatic lapse rate. Not surprisingly, surface heating along the mountain slopes produced temperatures warmer than the valley center.

A comparison of the pseudo-temperature profiles with all the available radiosonde and RASS profiles indicate that the pseudo-vertical temperature profiles along South Mountain closely approximated the free atmosphere temperatures over the valley center through the night and up until a few hours after sunrise. One reason for this agreement is that South Mountain, like Rattlesnake Mountain (Whiteman et al. 2000; 2001), has few vegetation and terrain complications that can create micro-climates along the slope.

Near-surface vertical temperature differences (within 230 m of the valley floor) greater than 3^{o} C around sunrise occurred on 11 days in June and 3 days in July. The largest temperature inversions were associated with clear skies throughout the night. Periods of mid to upper level cloudiness lead to the nocturnal boundary layer being less stable in July than during June. The pseudo-vertical temperature profiles indicated that when there was a temperature inversion around sunrise during June and July, it occurred at or below 130 m above the valley floor 41% of the time and below 230 m above the valley floor, 84% of the time.

3.2 *Urban heat island effect*

An example of wind and temperature distributions in the vicinity of Phoenix at 01 LST 25 June is shown in Fig. 3. As a result of daytime heating of the mountainous terrain northeast of Phoenix, westerly up-slope flow occurred most of the previous afternoon. Just before sunset at 18 LST, westerly winds and temperatures greater than 37^{o} C were observed at most stations. At 01 LST, the UHI was clearly evident with temperatures at the western end of the east-west line 5^{o} C cooler than in central Phoenix. The UHI gradually decreased in magnitude to 3^{o} C by 06 LST. Westerly winds persisted throughout the night until just before sunrise and easterly down-slope winds did not form Phoenix until 06 LST. The easterly down-slope flow pushed through central Phoenix, but lasted for only a few hours until daytime heating eroded the near-surface inversion around 09 LST. The near-surface circulations observed during this evening were similar to those during many other nights of the field campaign, in contrast with the behavior in most other mountainous regions where down-slope flows normally form shortly after sunset.

While the overall development of the UHI during the evening of 24 - 25 June was similar to many other evenings, the magnitude, time of peak UHI, and location of peak UHI varied during the period. The UHI was quantified during the 61-day period by using the 5-min temperature data from the dataloggers along the east-west line west of downtown Phoenix. Dataloggers east of downtown Phoenix were not employed because the easternmost sites were located as much as 222 m higher than downtown Phoenix and elevation differences would contribute to the computed horizontal temperature differences, especially at night. Elevations west of Phoenix, however, differed by less than 27 m.

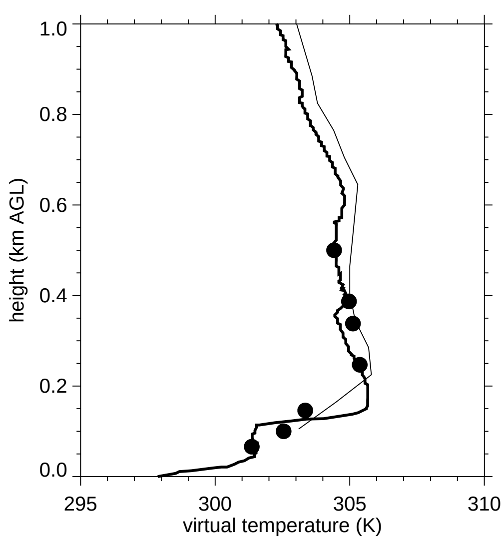

Fig. 2. Temperature profile from the radiosonde (thick line) and RASS (thin line) from the VEL site and the pseudo-vertical temperature profile (dots) derived from the instrumentation along South Mountain at 05 LST on 17 June.

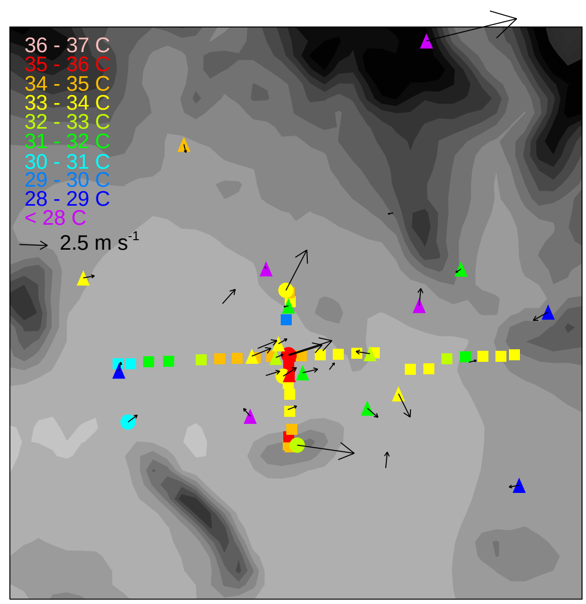

Fig. 3. Observed winds and temperature from the operational and field campaign instrumentation at 01 LST June 25. Gray shading denotes topography at 100 m intervals.

The simplest way of determining the UHI is by taking the temperature difference between dataloggers 1 and 11 (Fig. 1). This did not always produce the maximum temperature difference between the urban and rural areas because the highest temperatures often occurred just west of downtown and the lowest temperatures occasionally occurred at dataloggers 2 - 4. Therefore, the UHI for each 5-min interval was computed by first using the minimum temperature among 1 - 4 and the maximum difference between that value and the temperatures among dataloggers 6 – 12.

A summary of the UHI between 8 June and 3 August is shown in Fig. 4. During the day between 9 and 18 LST, central Phoenix was usually 1 – 2^o C warmer than the rural areas. After sunset the average UHI increased to 3 – 3.5^o C, but a wide range of values as high as 10^o C were observed. In general, the peak UHI occurred around midnight and then decreased by 0.5^o C and remained roughly constant until around sunrise. Interestingly, an UHI of 2 – 3^o C usually persisted 2 – 3 hours after sunrise. This coincided with bservations of a shallow stable layer that often persisted a few hours after sunrise (Doran et al. 2003), despite the intense heating at the surface during the summer.

The spatial characteristics of the UHI, as well at the relationship between the UHI and meteorological parameters such as wind speed and cloudiness will be presented at the conference. The behavior of the UHI in Phoenix differs in some respects from the UHI reported for other cities (e.g. Oke 1978). Additional details of the temperature datalogger measurements in Phoenix during the summer of 2001 are described in Fast et al. (2004).

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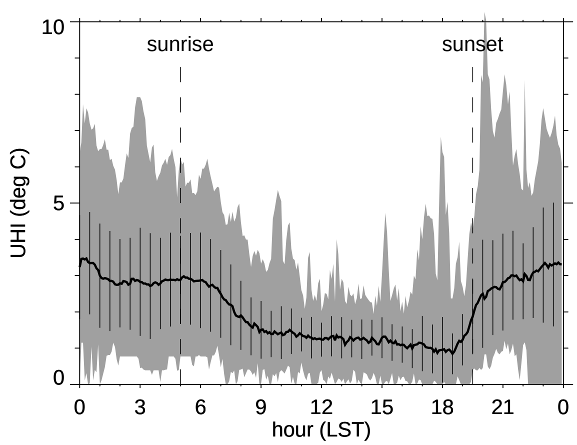

Fig. 4. Average UHI as a function of time of day between 8 June and 3 August (black line). Gray shading and vertical lines denote the range and standard deviation of the UHI, respectively.

4. Refereneces

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