Urban–rural contrasts in mixing height and cloudiness over Nashville in 1999
Wayne M. Angevine,1,2 Allen B. White,1,3 Christoph J. Senff,1,3 Michael Trainer,2 Robert M. Banta,3 and Mohammed A. Ayoub4

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[1] Strong contrasts in daytime mixing height (boundary layer [BL] height or \( z_i \)) between urban and rural areas were observed during the 1999 Nashville Summer Intensive field campaign of the Southern Oxidants Study. On occasion, the urban mixing height was as much as 45% (700 m) higher than that over the rural areas. The difference was quite persistent, showing strongly in statistical comparisons, with a mean difference over all hours available for comparison of 160 m. Clouds had higher bases and were more common over the urban area as well. In this paper, measurements from wind profiling radars, lidars, and aircraft are used to characterize mixing height and clouds. The urban–rural contrasts have important implications for regional air quality. The mixing height is a first-order control on pollutant concentrations. The urban–rural contrast also results in the venting of urban pollutants, affecting the local concentrations and the regional background. Clouds affect air quality by changing the radiative input for photochemistry and through changes in mixing and venting.

INDEX TERMS: 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3379 Meteorology and Atmospheric Dynamics: Turbulence; KEYWORDS: urban heat island, Southern Oxidant Study, radar wind profiler, lidar, air quality, mixing depth, boundary layer


1. Introduction

[2] A dramatic example of the effects of land-use differences, as well as modification by human activity, on local (10s of km scale) meteorology and climatology is the urban heat island. As a result of differences in surface properties—man-made buildings, roads, parking lots, etc.—as opposed to the vegetated surfaces of the rural landscape, urban areas produce less evapotranspiration during the daytime than the adjacent rural areas. The urban surface also remains warmer at night. These effects mean that the heat flux from the Earth’s surface to the atmosphere is larger over an urban area than over rural terrain.

[3] The warmer surface over cities is expected to produce a warm column of atmosphere over the urban area and several consequent effects in the atmospheric boundary layer (ABL) there. These include low-level convergence near the surface, a higher incidence of convective cloudiness over the city, and deeper mixing (the “urban dome”). The magnitude and timing of these differences is, however, not thoroughly and quantitatively documented.

[4] There is an extensive literature on urban heat island effects. Because the problem is complex, no one study has been able to completely describe all aspects of the phenomenon. One major project was the Metropolitan Meteorological Experiment (METROMEX) in St. Louis [Chagnon, 1981]. Seaman et al. [1989] report a very comprehensive model study of one day of the METROMEX data. Their model qualitatively reproduced all the observed features of the urban heat island, and provided important spatial and temporal detail. Several important findings emerged. Reduced evaporation was found to be the most important factor in producing the heat island effect. There was also a significant effect of the underlying terrain in reinforcing the urban response [Hjelmfelt, 1982]. The effects of increased roughness and increased urban size were ambiguous in the model.

[5] The precise determination of heat flux is one of the most difficult aspects of the urban heat island problem [Oke, 1987]. Airborne flux measurements are complicated by the requirements for sufficiently long flight legs over uniform conditions, although urban–rural flux and variance differences have been observed [Hildebrand and Ackerman, 1984; Ching, 1985]. In situ measurements of surface fluxes are relatively easily made, but scaling them up to the entire urban area is very challenging. An approach to such scaling based on geometric analyses of building types and Geo-
graphic Information Systems (GIS) data has been developed by Grimmond and Oke [1995, 1999a, 1999b]. Thermal infrared remote sensing from aircraft has been used to map the urban heat anomalies [Lo et al., 1997]. This is a promising technique if the expense of capturing multiple days of varying conditions can be overcome.

[6] Spangler and Dirks [1974] report measurements of mixing depth variations from several days of METROMEX, and cite a few other such measurements. Hildebrand and Ackerman [1984] also found small (100–200 m) differences. Ching [1985], however, found no such variations. Trainer et al. [1995] observed an increase of 400 m in mixing depth as air parcels passed over Birmingham, Alabama on one day. They also observed an elevated urban plume of ozone showing that the incremental mixing depth was connected with differential advection of urban pollutants.

[7] METROMEX was largely motivated by the observation of enhanced precipitation downwind of St. Louis. Bornstein and Lin [1999] found a correlation between thunderstorm activity and convergence caused by the urban heat island of Atlanta. Orville et al. [2001] reported an increase in lightning over Houston possibly attributable to the urban heat island effect.

[8] In the Southern Oxidants Study 1995 Summer Field Intensive a difference in mixing depth was noted between two major land-use types in the vicinity of Nashville [Banta et al., 1998] using instrumented aircraft and 915 MHz radar wind profilers located in contrasting rural or suburban environments. Airborne lidar cross-sections clearly showed the urban mixed-layer dome over the city on a day with light boundary layer winds.

[9] To summarize the present state of knowledge: Urban areas have warmer surfaces than rural areas, both in daytime as well as at night. The warmer urban surface temperature and lower evaporation due to reduced vegetation result in greater sensible heat flux and less latent heat flux over the urban area. As a consequence, under sufficiently light wind conditions, the mixing depth will be larger over and downwind of the urban area. Low-level convergence is also likely, and may contribute to the formation or at least influence the location of cloud and thunderstorm formation. There is a possibility that topography may interact with urban effects. Most published studies have been of at most a few days. The amount of increase of mixing depth is not well characterized. The effects of the urban heat island on pollutant transport are only suggested by the existing literature.

[10] In this paper, we use data from Nashville to provide examples of mixing depth increases and the spatial structure of the urban dome, and to show that the dome is persistent and robust. During the Southern Oxidants Study 1999 Nashville Summer Intensive, a profiler was located near the Nashville urban center at the Cornelia Fort Airport (CFA), with another profiler sited at one of the same rural profiler locations (Dickson) used in SOS-95. This placement allowed us to investigate the effects of the urban heat island on differences in mixing depth between the urban area and a rural site. Three other profilers were also located outside the urban area. In addition to the profilers, measurements from ceilometers, airborne lidar and in situ sampling aircraft are assembled here to characterize the contrasts between urban and rural areas in and around Nashville. We find systematic differences in mixing depth and cloud fraction between the urban and rural areas. This study concentrates on daytime contrasts. Daytime boundary layer heights measured by the profilers were consistently higher in the city than outside, and on one day (4 July) the difference at midday was 700 m.

[11] Urban–rural contrasts in physical quantities are interesting from a physical point of view, but they also have important implications for atmospheric chemistry and air quality. The mixing depth is a first-order control on pollutant concentrations [e.g., Alapaty et al., 1995]. Horizontal inhomogeneity of mixing depth leads to removal of pollutants from the local area (venting) and to longer-range transport.

2. Experiment Description

[12] An intensive field campaign was conducted in and around Nashville, Tennessee by the Southern Oxidants Study in June and July 1999. A map of the study area is shown as Figure 1. In addition to the measurements described below, numerous surface and airborne chemical measurements were taken.

2.1. Site Locations and Conditions

[13] The ground-based observation network was centered on the Cornelia Fort Air Park (36.19°N, 86.70°W, 126 m MSL), which is located in the Cumberland River valley 8–9 km northeast of downtown Nashville. Cornelia Fort is frequently strongly influenced by the surrounding city and suburbs. Instruments at Cornelia Fort directly relevant to this study include a 915-MHz wind profiler and laser ceilometer.
In contrast, the Dickson site (36.25°N, 87.37°W, 225 m MSL) was located in an area of mixed deciduous forest and pastureland approximately 53 km west-northwest of the center of Nashville. This site has primarily rural characteristics. A 915-MHz wind profiler and laser ceilometer were also operated at Dickson. In addition, surface fluxes were measured at two sites in the vicinity.

Three other rural sites, Gallatin (northeast of Nashville), Cumberland (northwest), and Eagleville (south), also had profilers (see Figure 1). Ozonesondes were launched from the National Weather Service site at Old Hickory (36.25°N, 86.57°W, 181 m MSL) at 1200 h CST daily.

### 2.2. Instruments

Boundary layer wind profilers [Carter et al., 1995] have become critical components of air quality and small-to-meso-scale meteorological field experiments. Usually operating at 915 MHz, they provide measurements of winds and boundary layer height (BL height, mixing depth, or \( z_i \)) at half-hourly or hourly intervals with vertical resolution of 60 m. The measurements have been extensively validated by comparison with other platforms [Angevine and MacPherson, 1995; Angevine et al., 1998]. The mixing depth measurement in particular [Angevine et al., 1994; Grimsdell and Angevine, 1998; Cohn and Angevine, 2000] has been extensively used in air quality studies. Mixing depth is found by a (usually manual) examination of the radar reflectivity, in which the BL top appears as an enhancement. In general confidence in the measurement is good when the convective boundary layer is well defined. Under conditions where the scientific definition of the convective BL is unclear, the measurement is also indeterminate. Such conditions include precipitation, low pressure systems, and complete overcast.

Laser ceilometers are relatively simple operational instruments which provide an estimate of the height of clouds. It is important to note that individual samples from the ceilometer do not necessarily indicate cloud bases, since in cumulus cloud fields the narrow laser beam often hits the sides of clouds. This effect and ways to counter it are discussed by Grimsdell and Angevine [1998]. The rapid sampling rate of the ceilometer allows for an estimate of cloud fraction, although caution should be used. Cloud fraction will be underestimated compared to standard (human observer) definitions at low cloud fractions due to purely geometrical considerations.

The NOAA/Environmental Technology Laboratory (ETL) airborne UV-lidar system was flown on a DeHavilland Caribou aircraft to profile ozone and aerosol from the

![Figure 2](image2.png)

**Figure 2.** Mixing depths from wind profiler measurements at five sites for 30 June and 4 July 1999. Solid line with dots is Cornelia Fort, dashed line is Dickson, dash–dot line is Gallatin, dotted line is Eagleville, and plain solid line is Cumberland.

![Figure 3](image3.png)

**Figure 3.** Potential temperature and relative humidity profiles at 1200 CST on 30 June and 4 July taken from ozonesondes launched at Old Hickory.
Figure 4. Winds measured by the wind profilers at Cornelia Fort (a) and Dickson (b) on 4 July 1999. The dot in circle symbols show the mixing depth.
surface to about 2500 m above ground level in the Nashville area. A description of the lidar system is given by Alvarez et al. [1998]. Aerosol backscatter and extinction profiles were deduced from the lidar data following the approach of Fernald [1984], and the methodology of retrieving range resolved ozone concentration with a UV-DIAL system is described by Browell et al. [1985]. To reduce noise the lidar data were averaged in range and time prior to the aerosol and ozone retrieval. The resulting time resolution for ozone and aerosol is 10 s or about 600 m horizontal and the vertical resolution is 90 m and 15 m for ozone and aerosol, respectively. In addition to the lidar, a downward-looking infrared radiometer was flown onboard the Caribou aircraft to measure surface skin temperature. Details about this instrument, its calibration, and the skin temperature retrieval method are given by Shaw and Fedor [1993]. To determine boundary layer (BL) height from the lidar data we applied a Haar wavelet algorithm to the aerosol backscatter profiles following the approach described by Davis et al. [2000]. The Haar wavelet transformation provides an objective way to determine the altitude of the steepest gradient in aerosol backscatter in the transition zone between the mixed layer and the free troposphere, which we take as a measure for BL height. We chose a width or dilation of the Haar wavelet of 300 m. The results are not sensitive to the exact dilation value within a broad range.

The NOAA P3 aircraft, primarily used for chemical sampling during the field campaign, also carried a downward-looking radiometer identical to the one on the Caribou. Measurements of surface temperature from the radiometer are used to reinforce the results below.

3. Results

3.1. Sample Cases

In this section we describe two sample days from the experiment, 30 June and 4 July. On both days the winds were from the south so that Cornelia Fort and Old Hickory were downwind of downtown Nashville. Figure 2 shows the mixing depths (convective boundary layer height or $z_i$) on 30 June and 4 July measured by five wind profilers using the techniques described by Grimsdell and Angevine [1998] and Angevine et al. [1994]. Four of the five measured quite similar heights; all four of these were located outside of the urban area. The fifth profiler, located at the Cornelia Fort Airpark just northeast of downtown Nashville, measured a
Figure 3 shows radiosonde profiles of potential temperature and relative humidity taken at 1200 h CST on 30 June and 4 July. Both days have relatively weak inversions at the CBL top. For a particular value of temperature contrast between urban and rural areas, a weaker inversion allows for a larger difference in mixing depth. These profiles were measured by ozonesondes launched from the National Weather Service site at Old Hickory, northeast of the urban area.

The effect of a surface temperature or flux contrast will also depend on wind speed (R. M. Banta and A. B. White, Delta z\textsubscript{i} between land use types: Dependence on wind speed, submitted to *Journal of Geophysical Research*, 2002, hereinafter referred to as Banta and White, submitted manuscript, 2002). Stronger winds dilute the effect of the greater urban heat flux. Boundary layer winds during the day were quite weak on many days of the study. For example, Figure 4 shows the winds on 4 July at Cornelia Fort and Dickson. A shift in wind direction in the middle of the boundary layer, discernable despite the very low wind speeds, explains the sudden decrease in mixing height at Cornelia Fort after 1830 h UT. The shift to westerly winds simply results in the urban dome being advected away from rather than toward Cornelia Fort. In Figure 4 we can also see that the urban dome was not perfectly coupled to the lower BL, as shown by the difference in wind speed and direction between 1500 and 2000 m at 1730 and 1830 h UT.

The "urban dome" shown here affected the transport and fate of pollutants emitted in the city. On 4 July, the urban plume emitted into the dome layer was found by the airborne lidar several hours later downwind above the rural boundary layer.

The basic premise of an urban heat island or dome is that the heat flux from the urban surface is substantially larger than from the rural surface. Figure 5 shows patterns of radiative temperature from the downward-looking radiometer on the NOAA WP3 on 30 June. Although these are raw measurements, not corrected for possible emissivity differences, they clearly show large contrasts in surface temperature between urban and rural areas. Even relatively small features such as the Cumberland River are visible on the plot.

The airborne lidar and radiometer provide a unique spatial perspective on mixing depth and surface temperature. Figure 6 shows mixing depth, radiometric skin temperature, and ozone for two flight patterns on 6 July 1999. This day had 20–25% cloud cover in midday. The clouds were fairly spatially uniform, but with a discernable maximum in cloud fraction to the southeast (where the urban plume was found) and a minimum northeast of the city. The enhancement of mixing depth due to the urban area is clearly visible in both patterns, and especially strongly in the later (1200–1340 h CST) pattern. The largest enhancement was southeast of Nashville, downwind as might be expected. The boundary layer averaged ozone shows the drift of the urban plume in that direction, and reinforces the idea that the mixing depth enhancement was due to the urban area. Overplotted on the ozone plots are back trajectories starting near the center of the enhanced-ozone area that was found southeast of Nashville. The back trajectories (shown as a sequence of arrows) were calculated from the wind profiler network data averaged in altitude between 200 and 1000 m AGL. Each arrow corresponds to the path traveled by an air parcel in 1 hour. The back trajectories clearly confirm that the area of enhanced ozone and increased mixing depth to the southeast of Nashville was part of the urban plume, which has been advected to this location by the large-scale northwesterly flow. The patterns of skin temperature measured by the radiometer on the lidar aircraft are quite consistent with those shown in Figure 8 for 30 June, although the magnitude of the urban–rural contrast was even stronger on 6 July. The Cornelia Fort profiler site was on the edge of the urban dome on this day due to the northwesterly wind direction. The lidar shows that the urban dome on 6 July was of similar magnitude (~700 m) to that seen by the profilers on 4 July (Figure 2). The mixing depths measured by the airborne lidar are consistent with those measured by the profilers (not shown). Good agreement was also seen in 1995 [White et al., 1999]. It is clear that some of the variation in the difference between Cornelia Fort and Dickson mixing depths.
Figure 7. Mixing depth measured hourly by the wind profilers at Cornelia Fort and Dickson on 17 June–14 July.
was due to the wind direction, that is, whether Cornelia Fort was directly under the advected urban dome or not.

3.2. General Results

Figure 7 shows the hourly mixing heights retrieved for Cornelia Fort and Dickson for a segment of the field study. No data are shown for days and hours when the mixing depth was ill-defined due to overcast or precipitation. Early in the study period the mixing heights were similar at the two sites due to relatively strong winds or unfavorable wind directions. On 3 July in the early afternoon a local thunderstorm formed over Nashville that did not affect Dickson. Figure 8 shows a scatterplot of hourly mixing heights from all daytime hours (between 0800 and 1700 h CST) for the whole study period, comparing the Cornelia Fort profiler to the Dickson profiler, located northwest of the city. The urban dome effect occurred most of the time and was quite robust statistically. Comparisons between Cornelia Fort and other rural sites are similar. Comparisons between pairs of rural sites show similar scatter but much less bias (Table 1). Note that only a subset of the hours in Figure 8 is included in Table 1 because we required all sites to have good measurements for the table, whereas only Dickson and Cornelia Fort were required to have good data for Figure 8. Mixing heights at Eagleville (southeast of Nashville) were systematically higher than the other rural sites but not as high as at Cornelia Fort. The area around Eagleville was primarily pasture and agriculture, while the other sites were in more forested areas, and this probably accounts for the difference between Eagleville and the other rural sites.

Clouds occurred preferentially over the urban area, as can be seen in Figure 9, which shows data from laser ceilometers measuring cloud heights at Cornelia Fort and Dickson. The cloud bases are consistently higher over the urban area.

Table 1. Statistics of Mixing Depth Comparisons Between All Pairs of Profiler Sites

<table>
<thead>
<tr>
<th>First Site</th>
<th>Second Site</th>
<th>Mean Difference</th>
<th>Median Difference</th>
<th>Standard Deviation of the Difference</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFA</td>
<td>DIK</td>
<td>150</td>
<td>160</td>
<td>250</td>
<td>0.86</td>
</tr>
<tr>
<td>CFA</td>
<td>CMB</td>
<td>120</td>
<td>110</td>
<td>300</td>
<td>0.79</td>
</tr>
<tr>
<td>CFA</td>
<td>GAL</td>
<td>170</td>
<td>160</td>
<td>310</td>
<td>0.83</td>
</tr>
<tr>
<td>CFA</td>
<td>EGV</td>
<td>80</td>
<td>110</td>
<td>260</td>
<td>0.88</td>
</tr>
<tr>
<td>DIK</td>
<td>CMB</td>
<td>-30</td>
<td>-50</td>
<td>310</td>
<td>0.77</td>
</tr>
<tr>
<td>DIK</td>
<td>GAL</td>
<td>20</td>
<td>10</td>
<td>280</td>
<td>0.86</td>
</tr>
<tr>
<td>DIK</td>
<td>EGV</td>
<td>-50</td>
<td>-40</td>
<td>220</td>
<td>0.92</td>
</tr>
<tr>
<td>CMB</td>
<td>GAL</td>
<td>50</td>
<td>90</td>
<td>380</td>
<td>0.74</td>
</tr>
<tr>
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<td>EGV</td>
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<td>10</td>
<td>380</td>
<td>0.73</td>
</tr>
<tr>
<td>GAL</td>
<td>EGV</td>
<td>-90</td>
<td>-50</td>
<td>260</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Sites are Cornelia Fort (CFA), Dickson (DIK), Cumberland (CMB), Gallatin (GAL), and Eagleville (EGV). Mean and median differences (first site minus second site) and standard deviation of the difference are shown along with the linear correlation coefficient. Observations from all hours with good mixing heights between 0800 and 1700 h CST are shown. For all pairs except those containing EGV, the number of hours included is 225, those containing EGV include 98 hr due to data outages at EGV.

We expect the magnitude of the urban dome or any other mesoscale contrast to decrease with increasing wind

Figure 9. Plots of ceilometer cloud heights for the entire Nashville field campaign. Top: Composite hourly average cloud height for Cornelia Fort Airpark (CFA) and Dickson (DIK). Middle: Composite hourly cloud fraction. Bottom: Frequency of occurrence of cloud heights.
speed. A similar analysis to that of Banta and White (submitted manuscript, 2002) is shown in Figure 10. We have chosen 10 days with little or no cloud and well-defined boundary layers. The plot shows the maximum difference in mixing depth between 1000 and 1400 h CST versus the average BL wind speed in the hour between 1100 and 1200 h CST. Except for two points at the lower left, there is a strong correlation. The two anomalous points are: 18 June (lowest speed, near zero difference) which despite the weak winds had a consistent wind direction from the northeast, advecting rural air over Cornelia Fort; and 28 July (most negative difference) which had rain on the previous two days. The data do not show a strong dependence on wind direction, suggesting that Cornelia Fort is under urban influence when the winds are light unless they have a very consistent unfavorable direction as on 18 June.

4. Summary

[29] In this paper we have reported observations contributing to the study of urban–rural contrasts and the urban heat island. We have presented case examples of many of the expected phenomena with the new perspective provided by radar wind profilers and the airborne ozone and aerosol lidar. We have also shown statistics made available by the continuous profiler measurements.

[30] A dome of increased mixing depth formed over Nashville. The dome was sometimes very pronounced, up to 700 m or 45% increase relative to the rural areas. Its presence was statistically robust. The dome layer was loosely coupled to the lower BL. It receives surface emissions but can be advected in a different direction and at a different rate. On days with little cloud, the depth of the dome was inversely dependent on wind speed. The area of increased mixing depth extended downwind along with the urban pollutant plume. More cloud was observed over the urban area than over the rural area.

[31] The urban dome is primarily caused by a strong contrast in daytime sensible heat flux between the urban and rural areas. However, it is also likely that the nighttime BL over the urban area is less stable than over the rural area, and this may contribute to the daytime dome effect. Unfortunately, representative flux measurements over urban areas are very difficult in daytime and may be impossible at night. Previous studies indicate that some contribution from terrain and/or contrasts among nonurban land uses cannot be ruled out [Hjelmfelt, 1982; Seaman et al., 1989; Banta et al., 1998].

[32] Urban–rural contrasts and the urban heat island have been extensively studied, but the community’s understanding remains qualitative and anecdotal. General, quantitative understanding awaits well-designed future studies. Such studies should include careful measurement of urban heat flux by aircraft and by GIS-based scaling of in situ measurements [e.g., Grimmond and Oke, 1995], airborne lidar to map the spatial distribution of mixing height and pollutants, and a comprehensive radar profiler network for continuous measurements. The physics and chemistry of fair-weather cumulus layers also deserve careful attention.

References


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W. M. Angevine and M. Trainer, NOAA Aeronomy Laboratory, 325 Broadway, Mail Stop R/E/AL3, Boulder, CO 80303, USA. (wangevine@al.noaa.gov)

M. A. Ayoub, Department of Atmospheric Science, University of Alabama in Huntsville, Huntsville, Alabama, USA.

R. M. Banta, NOAA Environmental Technology Laboratory, Boulder, Colorado, USA.