# 3.20 BOUNDARY-LAYER STRUCTURE UPWIND AND DOWNWIND OF OKLAHOMA CITY DURING THE JOINT URBAN 2003 FIELD STUDY

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## 1. INTRODUCTION

The Joint Urban 2003 field study in Oklahoma City in June and July 2003 provided a comprehensive data set that included measurements from sites upwind and downwind of the downtown core of Oklahoma City where sodars, radar wind profilers/RASS (Radio Acoustic Sounding System), and radiosondes were deployed. In this paper, we first describe boundary layer structure at the upwind location during the Intensive Observational Periods (IOPs). Then, we compare boundary-layer wind and temperature structure at both sites to determine the effect of the downtown core of Oklahoma City on mean boundary-layer structure.

## 2. EXPERIMENTAL

The Joint Urban 2003 field study was conducted in Oklahoma City from June 28 to July 31, 2003 (Allwine et al., 2004). Ten IOPs were completed during the 34-day study period in which detailed meteorological, turbulence and tracer measurements were made. Conditions favorable for an IOP included boundary layer winds that were from the southwest to the southeast, and no precipitation. IOP 1, which took place on June 29, 2003, was terminated after several hours due to unfavorable weather conditions. In this contribution we will focus on IOP 2 through IOP 10, which all took place in July. Dates and time of the IOPs are listed in Table 1. Except for IOP 3 and IOP 5 on which partly cloudy conditions were encountered, there was minimal cloud cover. Sunrise in Oklahoma City in July is around 0530 CST, sunset around 1945 CST.

**Table 1**: Dates and time of IOP 1 through IOP 10

| IOP | Date | Day of year | Time of IOP (CST =UTC-6) |
|---|---|---|---|
| 1 | 6/29 | 180 | 0700-1200 |
| 2 | 7/02 | 183 | 0700-1600 |
| 3 | 7/07 | 188 | 0700-1600 |
| 4 | 7/09 | 190 | 0700-1600 |
| 5 | 7/13 | 194 | 0700-1600 |
| 6 | 7/16 | 197 | 0700-1600 |
| 7 | 7/18-19 | 199-200 | 2100-0600 |
| 8 | 7/24-25 | 205-206 | 2100-0600 |
| 9 | 7/26-27 | 207-208 | 2100-0600 |
| 10 | 7/28-29 | 209-210 | 2000-0300 |

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Two sites north and south of Oklahoma City were chosen to provide boundary conditions for modeling studies related to the dispersion study in the downtown core area. A map with the location of the two sites is shown in Fig. 1. The northern site will be referred to as the ANL (Argonne National Laboratory) location (35.51°N, 97.52°W, 354 m), the southern site as the PNNL (Pacific Northwest National Laboratory) location (35.45°N, 97.53°W, 361 m). The PNNL and ANL sites were located approximately 2 km south and 5 km north of downtown Oklahoma City, respectively. In Figure 1, the white area represents downtown Oklahoma City (also referred to as the business district area or downtown core area), and the larger urban build-up around it represents industrial, commercial, and residential areas. Both the PNNL and ANL site were located in this suburban area.

Burian et al. (2003) analyzed high resolution land use data around Oklahoma City and found that the downtown core area has 39 buildings with heights greater than 25 m and contains a fairly equal mixture of shorter and taller buildings. Average height of the buildings in the downtown area is 19.4 m, compared to 17.2 m for Phoenix, 23.6 m for Salt Lake City, and 45 m for Los Angeles (Burian et al., 2003). Morphological parameters such as the frontal area index (a measure of the frontal area per unit horizontal area), the complete aspect ratio (summed surface area of roughness elements and exposed ground divided by the total plan area), and the height-to-width ratio (the ratio of the height of the buildings to the horizontal distance, or street width, between the buildings) are relatively small compared to those in other major cities. Displacement

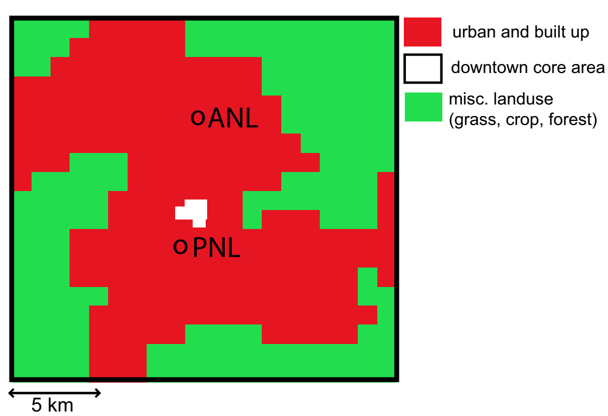


**Fig. 1**: Land use in a 25x25 km$^2$ area around Oklahoma City. The ANL and PNNL sites are depicted by the open circles. (source: USGS 30 arcsec. data and Burian et al., 2003).

height and roughness length for Oklahoma City estimated using various methods (e.g., Grimmond and Oke, 1999) are around 13 m and 2.5 m for the downtown core area and an order of magnitude smaller for the surrounding suburban areas (Burian et al., 2003).

Radiosonde profiles were measured during 6 daytime IOPs typically beginning at 0700 CST and ending at 1600 CST (launches at 07, 08, 09, 10, 12, 14, 15, 16 CST), and during 4 nighttime IOPs beginning at typically 2100 CST and ending at 0600 CST (launches at 21, 22, 23, 00, 02, 04, 05, and 06 CST). The radiosondes that were used were of type Vaisala RS-90. A few of the sondes, mainly at the ANL site, were equipped with GPS to measure wind speed and direction. Typical ascent rates of the balloons were on the order of 4 m $s^{-1}$.

Sodars and radar wind profilers operated almost continuously during the entire month of July. The radar wind profiler collected data with a vertical resolution of 55 m (from 82 m to about 2700 m) and a consensus interval of 25 minutes. For 5 minutes each half-hour, the wind profiler system measured virtual temperature using its Radio Acoustic Sounding System (RASS) mode. The wind profiling radar data at both the ANL and PNNL sites were processed using the NCAR Improved Moment Algorithm (NIMA; Cornman et al., 1998; Morse et al., 2002). Sodar data were obtained with a vertical resolution of 5 m at the ANL site (from 15 m to 200 m) and 10 m (from 30 m to 500 m) at the PNNL site. The temporal resolution was 15 minutes for both sodars. A comparison of the sodar and radar data with wind measurements at a nearby tower and radiosonde wind profiles revealed that radar data at the PNNL site are not reliable below the range gate height of 357 m.

## 3. RESULTS

### *3.1. Boundary-layer wind and temperature structure at the PNNL site*

The wind structure during the IOPs for the PNNL site is shown in Figure 2. Only the hourly values at selected height levels are shown. The data at the lowest two levels are from the sodar, the other levels are from the radar wind profiler. Winds during the IOPs were predominantly from the south so that the PNNL location was located on the upwind site (this was also the case for most of the time outside the IOP periods). During the nighttime IOPs, winds at the start of the IOP frequently came from southeasterly directions but veered towards southwesterly directions in the course of the night. An increasing wind speed with height with a wind speed maximum larger than 15 m $s^{-1}$ at heights of 300-500 m is a recurring feature on almost every night. The presence of such a nocturnal jet is a well-known characteristic of the stable boundary layer over the Great Plains (e.g., Bonner, 1968). Most of the daytime IOPs started with southwesterly flows and flows stayed southerly during the day. Typical wind speeds in the daytime boundary layer ranged from 3 to 10 m $s^{-1}$ with relatively large wind speeds on IOPs 3 and 4.

Both the daytime and nighttime evolution of the thermal structure showed a large variability from IOP to IOP (Fig. 3). During the daytime IOPs, typical maximum boundary layer heights were on the order of 1500 m. Lower boundary layer heights were present on IOP 5 (Fig. 3d), a day with significant (~50%) cloud cover (and thus smaller sensible heat flux). On IOP 2, the boundary layer grew up to relatively large heights of around 2000 m, caused by weak upper air stability. This day was also the warmest of the IOPs with mean potential temperatures reaching 310 K in the boundary layer. During the nighttime IOPs, the strength and depth of the nocturnal boundary layer varied significantly. On IOP 8 and to a lesser degree on IOP 9, gusty winds established a deep nocturnal boundary layer with the potential temperature profiles on IOP 8 appearing mechanically mixed in the lowest few hundred meters.

### *3.2. Differences between upwind and downwind location*

A comparison was made of the wind and temperatures structure between the ANL (downwind) and PNNL (upwind) sites. For the comparison of the temperature, radiosonde data were used. The data were interpolated to 10 m intervals, the temperatures at the PNNL site were subtracted from temperature at the ANL site, and the differences were grouped into 50 m height bins. Results of the analysis are shown in the box-and-whisker plot in Fig. 4. The box-and-whisker plot shows the minimum and maximum value, the median, and the lower and upper quartile (or 25th percentile) of the data. The average value of the data in each 50 m height bin is also shown with the blue square. Data higher than 1200 m are not shown because it is likely that the PNNL temperatures there are measured directly above the downtown core area assuming a typical ascent rate of 4 m $s^{-1}$ and a horizontal wind speed of 5 m $s^{-1}$. Temperatures measured above about 1200 m are therefore not representative anymore for atmospheric conditions upwind of the downtown core area. Both the day- and nighttime comparison show a tendency towards higher temperatures at the ANL site, especially in the lower 150 m. Differences are on the order of 0.3 K during the day and 0.5 K at night, a small but significant difference given that an intercomparison between twin radiosonde launches results in a maximum average difference of 0.13 K (Antikainen et al., 2002). Differences at heights above 150 m become negligible during the day, but stay positive during the night. A similar analysis was performed from RASS data and a similar tendency towards larger temperatures at the ANL site than the PNNL site during the night at the lowest range gates was found. Unfortunately, the analysis was not feasible at the higher range gates and during daytime because there was poor agreement with radiosonde data in those occasions. Daytime boundary layer heights obtained from potential temperature profiles were compared between the ANL and PNNL site but no consistent differences were found.

For the comparison of the winds between the ANL and PNNL site, sodar data were used up to a height of 100 m and radar data from 357 m to 2500 m.

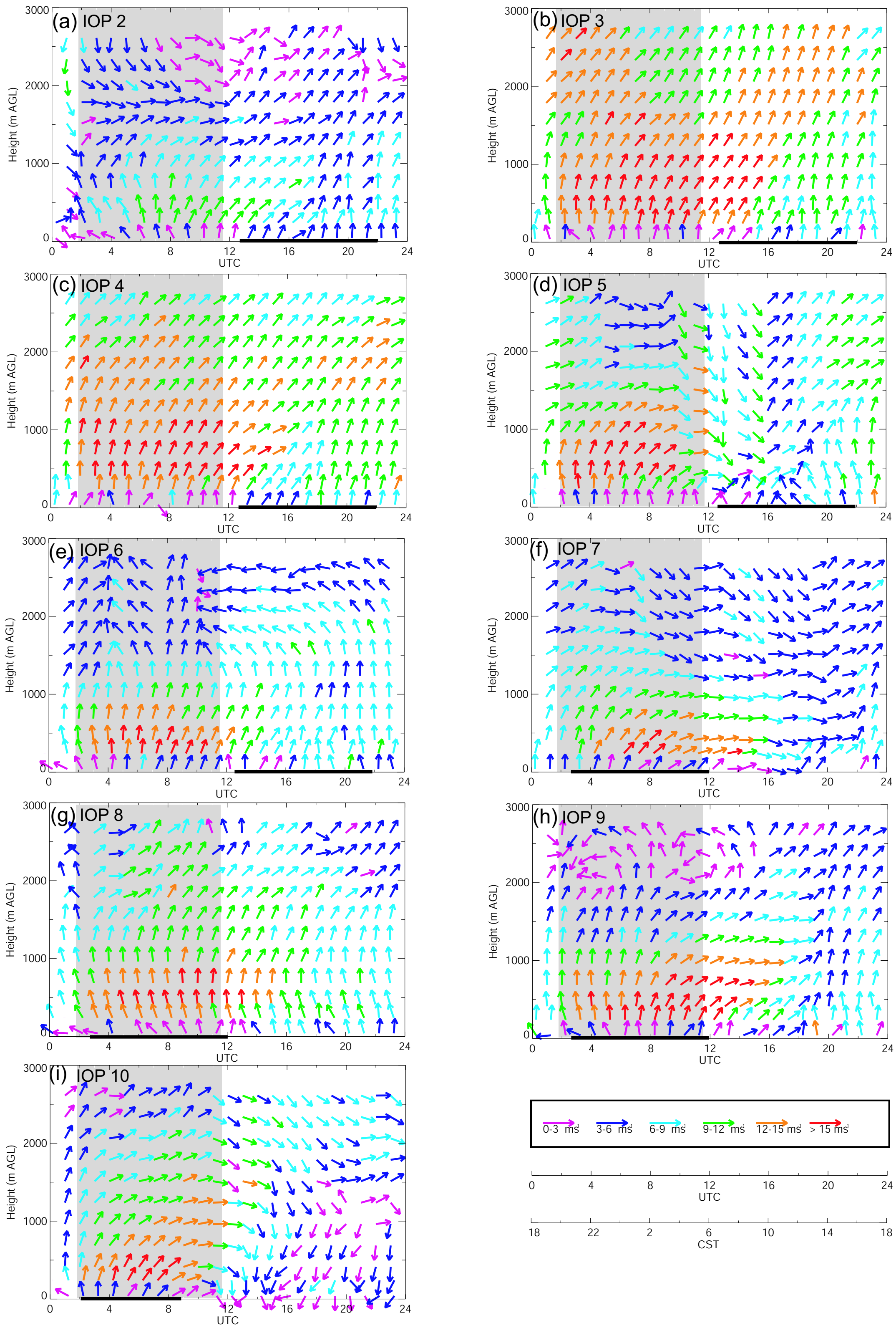


**Fig. 2**: Time-height cross sections of horizontal wind speed and direction at the PNNL site as a function of time and height during IOP2-10 (a-i). Arrow color indicates wind speed. The lowest two levels are from sodar data. The grey-shaded area depicts the night-time period. The solid bar on the time axis indicates the IOP time.

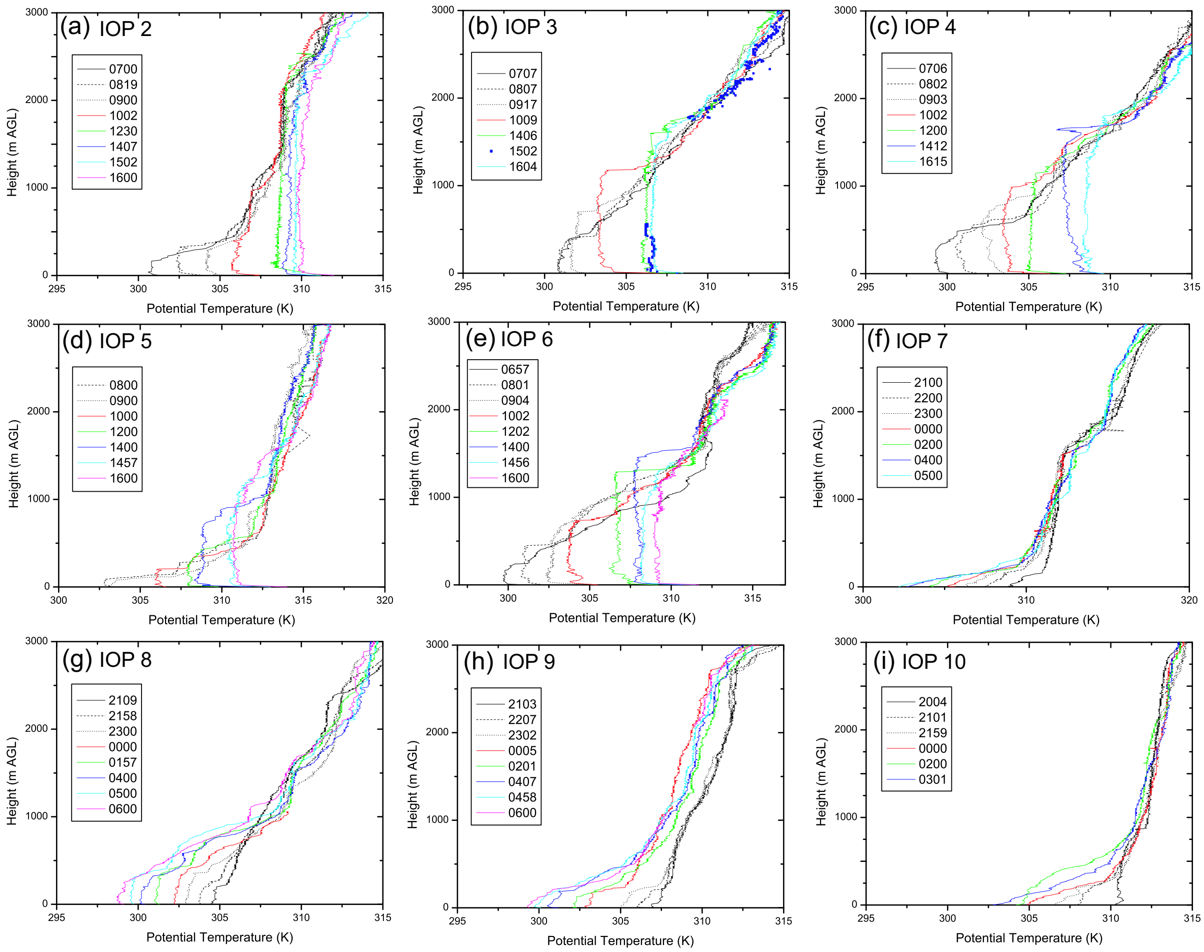


**Fig. 3**: Vertical potential temperature profiles from the radiosonde launches at the PNNL site for IOP2-10 (a-i).

Between 100 m and 357 m, data quality was not good enough to allow a thorough comparison. The analysis was done for all available data in July (about 25 days) and for wind directions from 160 to 200˚ (which were found more than 50% of the time). Results are shown in maximum difference of about 1.3 m $s^{-1}$ at 60 m while there was a veering of the wind of 5˚ at 60 m between the PNNL and ANL site. Differences in wind speed become smaller with height and become negligible at heights above 1000 m.

## 4. DISCUSSION

The response of the boundary layer to changes in surface characteristics at the city edges is well known. (e.g., Oke, 1987). Downwind from the transition from rural to suburban land use, an internal 'urban boundary layer' starts to form. In our situation, we have two locations that are located in a suburban area in which the surface characteristics are distinctively different from the downtown core area. Even though we do not have a rural-urban but rather a suburban-urban transition, it was expected that an internal boundary layer would

Fig. 5. Night-and daytime differences are comparable except for the lowest 100 m where the differences are larger at night. Wind speed at the ANL (downwind) site was larger than at the PNNL (upwind) site, reaching a

develop at the edge of the downtown core area and that urban effects would be seen at the downwind ANL site. Indeed, there is a small, but significant difference in boundary layer temperature and wind between the upwind and downwind sites visible, with both larger temperatures (~ 0.5 K) and wind speeds (~ 1 m $s^{-1}$) at the downwind site. Our preliminary analyses show that wind and temperature differences are larger and extend to larger heights (in the case of temperature) at night. It remains to be investigated whether this difference is due to the downtown core area or due to other effects.

A simple calculation (based on formulas derived form wind tunnel studies, e.g. Garratt, 1992) can be made of the height of an internal boundary layer resulting from a change in roughness. With the surface characteristics in our area of interest, this results in an internal boundary layer that can reach up to about 1000 m 5-6 km downwind of the transition. The positive

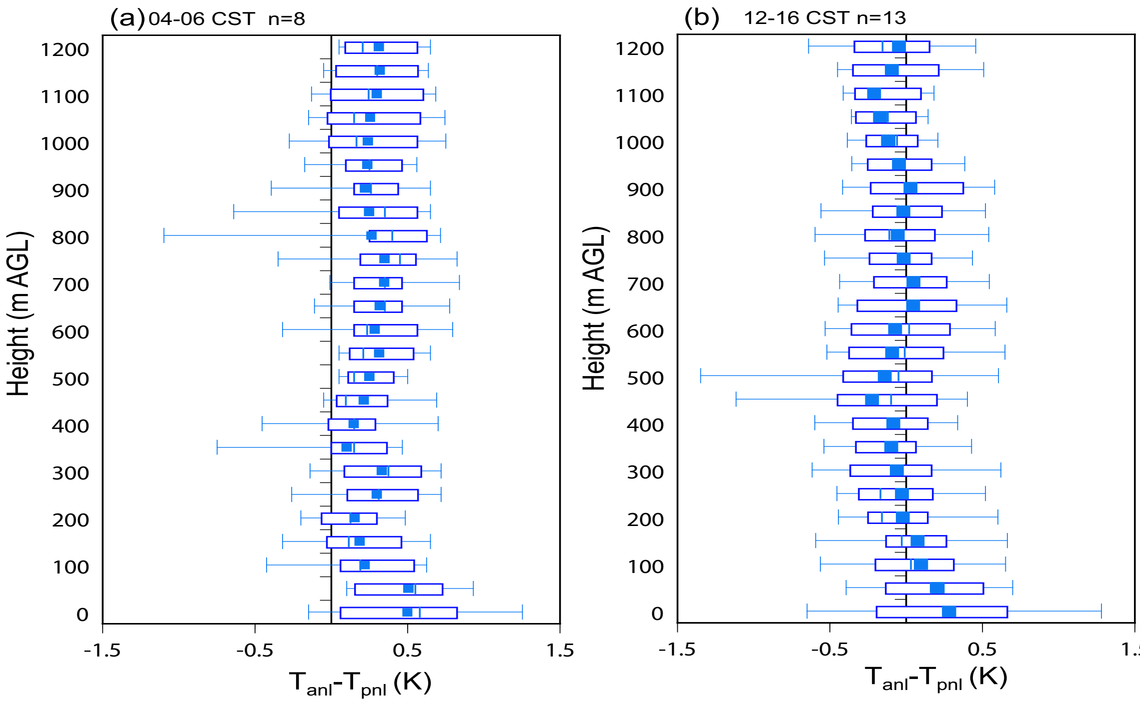


**Fig. 4**: Box and whisker plots of the temperature difference between the ANL and PNNL site for the time periods 04-06 CST (a) and 12-16 CST (b). n is the number of radiosonde pairs considered in the analysis.

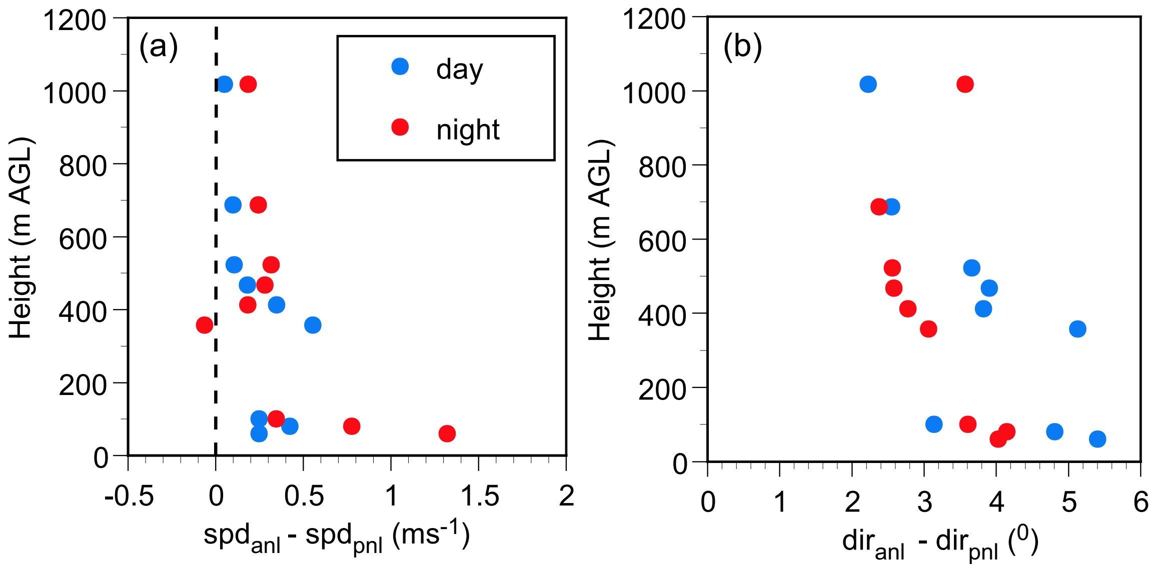


**Fig. 5**: Difference in wind speed (a) and direction (b) between the ANL and PNNL sites during day and nighttime.

temperature difference at night seen in Fig. 4a in layer of about 1000 m may be a result of the growth of such an internal boundary layer downwind from the downtown core area. During the day, the differences in temperature between the upwind and downwind site are negligible at heights above a few hundred meters, which implies that the effect of the downtown core area may not have been felt in the boundary layer 6 km downwind.

The large wind speeds observed in the boundary layer may have diminished the effect of the urban area on the downwind convective boundary layer as shown previously in observational studies (Shea and Auer, 1978) and numerical studies (Martilli, 2002). Thus, in daytime and high wind speed conditions, vigorous mechanical and convective mixing may restrict the development of an internal boundary layer to shorter distances from the downtown core area than 5-6 km.

It is questionable whether the wind- and temperature differences seen in the lowest 100 m can be explained by an urban effect. A temperature and wind difference in the surface layer could be explained by differences in surface characteristics at the sites themselves. Grimmond et al. (2004) show that there is a large spatial variability of the sensible heat flux in the suburban area of Oklahoma City with typical maximum values of 250-300 W $m^{-2}$. A simple calculation shows that the difference in boundary layer temperature between the two sites of up to 0.5 K can be explained by a difference in surface sensible heat flux of 25 W $m^{-2}$. Similarly, a difference in wind speed in the lowest few hundred meters may be explained by a difference in surface roughness.

It should be noted that Angell and Bernstein (1975) also found larger wind speeds downwind of the city center on a scale of about 10 km which they argue to be the result of the transport of faster moving air aloft to low levels from sinking motions induced by the city itself. We are not able to investigate the existence of such a mechanism with our data.

## 5. CONCLUSIONS

The Joint Urban 2003 field study in Oklahoma City in July 2003 provided a comprehensive data set that included measurements from sites upwind and downwind of the downtown core of Oklahoma City where sodars, radar wind profilers/RASS, and radiosondes were deployed. Southerly flows prevailed during the IOPs and during daytime IOPs, CBL up to about 1500 m were observed. On all nighttime IOPs, a pronounced wind speed maximum at heights around 300-500 m was observed. Boundary-layer wind and temperature structure at both sites were compared. Temperatures and wind speeds are higher downwind of the downtown core area and the differences are larger at night than during the day. We believe that a combination of vigorous convective mixing and high wind speeds during the day diminished the effect of the downtown core area on the downwind convective boundary layer.

In future work, we will examine the day-to-day variability of the differences between the downwind and upwind sites, thereby also using additional data from a radar wind profiler located in a more rural area south of Oklahoma City (near Norman). We also plan to evaluate the effect of downtown Oklahoma City on regional flows using a numerical mesoscale model and a variety of urban parameterization schemes.

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