3.2 Vertical profiles of mean flow and turbulence characteristics in a downtown street canyon measured during Joint Urban 2003

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1. INTRODUCTION:

During July 2003, an extensive field campaign, JOINT Urban 2003 (JU2003), took place in Oklahoma City, USA. The main objectives of this field campaign were obtaining a better understanding of the complex flow and dispersion processes in urban areas, and the generation of reliable datasets for evaluation of numerical models capable of simulating urban scales. Such models are needed as fast response tools in the case of releases of chemical or biological agents in an urban environment. An overview of the performed measurements is presented in Allwine et al. (2004). While a large number of meteorological measurements were continuously taken all July, tracer gas samplers and additional meteorological sensors were operated during ten intensive observation periods (IOPs). During each IOP, typically three half-hour tracer gas releases as well as four puff releases took place.

As part of JU2003, a street - canyon sub-experiment was performed in a relatively narrow street in downtown Oklahoma City (Park Avenue). Previous studies have shown that street canyons are often poorly ventilated and that complex vortex flow patterns develop. More details on street canyon flow and turbulence phenomena can e.g. be found in the two recent review papers by Vardoulakis et al. (2003) and Kastner-Klein et al. (2004). However, these studies were mostly performed in wind or water tunnels, and there are only a few quality data sets from field measurements available. While laboratory experiments provide extremely useful information and have resulted in a significant advancement of the knowledge about urban flow and dispersion, there are some concerns that not all important forcings are fully replicated in wind or water tunnels. It is e.g. still an open question to what extent thermal effects influence street-canyon ventilation. Also, the majority of laboratory experiments were done with idealized building configurations where the street canyons were often simulated by long, rectangular bars with no or little variation of roof shape and height. It is questionable if a typical street-canyon vortex will develop under realistic conditions with buildings that vary strongly in shape and height. To answer such questions was the motivation for the JU2003 street-canyon study in Park Avenue for which in a multi-group effort more than 40 3D-sonics were continuously operated on towers inside the street canyon, on roof tops and at street lights. More details on the experimental set-up can be found in Brown et al. (2004).

In the present paper first results are shown from sonic measurements at two towers operated by the University of Oklahoma (OU) and located in the central part of Park Avenue. The experimental set-up of these tower measurements will be shortly described in the next section. In section 3.1, typical flow patterns in Park Avenue are illustrated by means of results for 4 exemplarily chosen days. The variation of mean flow and turbulence characteristics with upwind wind direction will then be further discussed in section 3.2, before conclusions and an outlook on future data analysis are presented in section 4.

2. EXPERIMENTAL SETUP AND DATA ANALYSIS:

The measurements were performed on two 50-ft towers that were installed in the central part of Park Avenue. Each of the two towers was equipped with 5 RM Young sonic anemometers and a Campbell Scientific CR5000 datalogger. A map with the tower locations and photos of the towers in Park Avenue are shown in Figs. 1 and 2. The height of the 5 measurement levels on each tower and the distance of the towers to the buildings along the northern side (tower 1) and southern side (tower 2) of Park Avenue are given in Table 1. The western edge of the buildings at the crossing of Park Avenue and Robinson Street was used as reference point for the lateral position of the towers (distances are also given in Tab. 1).

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Table 1: Coordinates of the sonic measurements on the two 50-ft towers operated by OU during JU2003.

	Distance from Robinson Avenue in m	Distance from building wall in m	Height of levels in m				
			h1	h2	h3	h4	h5
Tower 1	66.73	8.28	1.50	2.96	5.97	9.91	15.08
Tower 2	71.50	8.29	1.50	3.00	5.46	9.86	15.65

For additional information on the tower positions in reference to other equipment deployed in Park Avenue see Brown et al. (2004).

10 Hz timeseries of the sonic temperature and all three components of the wind vector were continuously recorded. The velocity components were defined according to the meteorological convention with positive *u*-components corresponding to winds from the west, positive *v*-components corresponding to winds from the south, and positive *w*-components corresponding to rising motions. Since Park Avenue has an East-West orientation, *u* describes also the along-canyon component, and *v* the across canyon component of the in-canyon wind vectors.

Quality assurance (QA) checks were performed on all records. Data outside a window of the 5-minute mean ± 4 times the standard deviation were flagged as outliers. On two channels at tower 2, drift errors occurred and data for periods with drift errors were removed. Half-hour mean values and first order statistics were then processed for all QA checked records, and using these data the horizontal wind speed and direction as well as turbulence kinetic energy were computed. Furthermore, the data were normalized using the 250-m measurements of wind speed and direction at the PNNL sodar (Allwine at al., 2004) as reference data. These data were chosen since they should provide information about the undisturbed (non-urban) flow conditions. Even for northerly wind directions, for which the sodar is located downwind of the downtown core, the urban influence on the measurements at 250-m height can be assumed to be small.

3. RESULTS

3.1. Typical flow patterns

During July, southerly wind directions are dominant in Oklahoma City and in the planning phase of JU2003 the positions of the source and tracer gas samplers were selected to optimally fit winds from the south. Accordingly, the upwind wind direction became a very important criterion for the decision to run an IOP. Based on a 24h forecast, an IOP took place the following day if the predicted winds were dominantly from the south for the whole duration of the tracer gas releases. For most of the IOPs, the observed conditions met the predictions and the wind directions were mainly within the sector south-east to south-west

To illustrate typical flow patterns in Park Avenue during IOP days, the diurnal variation of wind direction, horizontal wind speed and the vertical velocity component are plotted in Figs. 3 and 4 for 07/09/2003 (IOP 4) and 07/25/2003 (IOP 8). The upwind reference wind direction and wind speed measured at the 250 m level of the PNNL sodar are also shown (black symbols). During both days, the reference wind speed is roughly 12-15 m/s during the night, and around 10 m/s in the afternoon.

During IOP 4 southerly to south-westerly wind directions occurred, while during IOP 8 the winds were mainly from the south-south-east. By comparing Figs. 3 and 4, it becomes obvious this variation in upwind wind direction has a strong influence on the flow pattern inside Park Avenue. During IOP 4, with a westerly component in the upwind flow, the results from both towers and all five levels are very similar. The wind directions are all from the west which indicates strong channeling inside Park Avenue, the horizontal wind speeds are nearly constant within the canyon, and the vertical velocity components, while small in magnitude are mostly positive.

During IOP 8 however, with an easterly component in the upwind flow, pronounced directional shear was observed at both towers. For the biggest part of the day, easterly wind directions were observed at the two upper sonics (h5 and h4) while westerly wind directions were measured at the lower levels (h1-h3). Additionally, much stronger vertical gradients of the horizontal wind velocity, were found than during IOP 4: At the upper sensors the horizontal wind speed is close to zero, while at the lowest sonics velocities up to

2.5 m/s were recorded. Differences can also be noted for the vertical velocity components: While at tower 2 the values are still mostly positive and fairly small, at tower 1 stronger upward motions occur near the ground and downward motions are observed at the upper levels. All theses features indicate some type of wake recirculation developing inside Park Avenue. It is possible that for south easterly wind directions the Bank One tower, a 150-m tall building just east of Park Avenue (see Fig. 1), strongly influences the in-canyon flow.

As discussed above and particularly seen in Fig. 4, small variations in upwind wind direction are crucial for the type of flow pattern observed in Park Avenue. This becomes even more obvious from the results plotted in Figs. 5 and 6 which correspond to the two days following IOP 4 and 8 respectively. During 07/10/2003 (Fig. 5) the upwind wind direction changes from south westerly flow in the early morning to north easterly directions in the afternoon. Inside Park Avenue, westerly winds are observed as long as the upwind flow has a westerly component, and shifts to easterly in-canyon flow as soon as the upwind flow has an easterly component. This documents again the strong channeling inside the street canyon. For the north-easterly wind directions pronounced downward motions are observed; on tower 1 on the upper levels and on tower 2 on all levels.

The results for 07/26/2003 (Fig. 6) are particularly interesting since they highlight the sensitivity of the in-canyon flow regime towards small variations in upwind wind direction. During this day, the reference wind direction at around 8 am changes from slightly south-easterly to slightly south westerly, and later at around 6 pm returns back to slightly south-easterly. It is clearly seen, that whenever the upwind wind direction changes from slightly south-east (<180°) to slightly south-west (>180°) the in-canyon flow changes from wake-type flows characterized by directional shear, significant vertical gradients and vertical components to fairly homogenous channeling-type flow. A variation of upwind wind direction by less than 10 degrees has thus a strong influence on the in-canyon flow. This will be further illustrated in the next session, in which the variation of mean flow and turbulence kinetic energy data with upwind wind direction is discussed.

3.2. Variation of mean flow and turbulence kinetic energy with upwind wind direction

To further analyze the influence of upwind wind direction, all available 30-min averages of horizontal wind speed, wind direction, vertical velocity components and turbulence kinetic energy are plotted against reference wind direction in Figs. 7-10. The data are normalized using the reference wind speed measured at the 250-m level of the PNNL sodar. To identify possible influences of atmospheric stability, the plots in the top row of Figs. 7-10 show all data, the middle row nighttime data (10 pm-6 am), and the bottom row afternoon data (12pm-8pm).

The lowest horizontal wind speeds (Fig. 7) are observed for south-easterly to southerly wind directions. It is also seen, that for these wind directions, lower velocity values are observed at the upper sonic levels than close to the ground. This phenomenon appears to be more pronounced during nighttime than in the afternoon. Interestingly, the highest horizontal wind speeds are not observed for wind directions parallel to the street (90° and 270°), but for oblique wind directions, whereby larger values of U_{hor}/u_{ref} are observed in the afternoon than during the night. It must be further investigated if these differences between nighttime and daytime conditions can be attributed to thermal effects. It is also necessary to verify that the 250-m level is an appropriate choice for the reference speed during daytime and nighttime conditions. Depending on the structure of the nocturnal boundary layer, the 250-m level might be above the surface layer and not a good choice as reference level.

The channeling of the flow inside the street canyon is clearly seen in Fig. 8. There are predominantly three wind direction regimes observed inside Park Avenue: Fairly uniform westerly flow occurs pretty much for all wind directions within the sector south to north (sector I). For northerly wind directions some scatter is observed, but there are only a few data sets available for such conditions. Within the sector north to south- easterly (sector II), easterly flow varying from about 60° at the top sonics to roughly 140° close to the ground can be found. The strongest directional shear and the largest scatter are observed for south-easterly to southerly wind directions (sector III). No significant differences were found between daytime and nighttime conditions.

The strongest vertical velocities are also observed for the situations with directional shear. For sector II downward motions were measured with all sonics on tower 2, while upward motions were found at the lower levels on tower 1. Taking into account the pattern of the wind directions, it can be hypothesized that some kind of vortex spiral develops inside Park Avenue for winds within sector II. We will further investigate to what extent the results for sector II are related to the building geometry on the northern side and upwind of Park Avenue. There are a few relatively low buildings and an alley way along Park Avenue to the north east of the towers which may significantly influence the in-canyon flow pattern. For sector III, relatively small but positive vertical velocities were observed at tower 2, while downward motions occurred at the upper levels of tower 1. This indicates that some type of vortex forms inside the street canyon, whereby the wind direction data allow concluding that typical 2D-street canyon vortices are less likely. In most cases, a significant along-canyon component persists.

Finally, information about the turbulence characteristics inside Park Avenue is provided in Fig. 11. Obviously, higher turbulence kinetic energy values are found for wind directions resulting in formation of vortex or wake flow types inside the street canyon. Comparing the daytime and nighttime data, large differences can be found. The afternoon values are more than a factor of 2 larger than the nighttime values. It is again necessary to further investigate if these differences can be explained by thermal effects or if the choice of the reference wind speed plays a role.

4. CONCLUSIONS AND FUTURE WORK

The results have shown that street canyon flow patterns crucially depend on upwind wind direction. This result was generally expected, but the drastic changes observed for small variations of upwind wind direction are somewhat surprising. It is also clearly shown that strong channeling can be observed inside an urban street canyon. For wind directions perpendicular to the canyon, vortex type flows are found, but even under such conditions along-canyon components are typically significant. The results indicate that tall buildings near Park Avenue and the non-uniform building height on the northern side of Park Avenue influence in-canyon flow patterns. We will try to further investigate these effects whereby we will also make use of wind-tunnel studies that are currently performed at the University of Hamburg. These studies will allow removing or modifying certain buildings, so that the influence of individual obstacles can easily be identified.

The analysis of nighttime and daytime conditions has revealed differences in the mean flow and turbulence characteristics which need to be further investigated. For this purpose, the structure of the upwind boundary layer must be analyzed in detail. In the future, it is also planned to compute and analyze the turbulent momentum and sensible heat fluxes and to test different scaling concepts. Additionally, the results will be compared with the data measured at towers operated by other teams of the JU2003 street canyon experiment.

5. ACKNOWLEDGEMENTS

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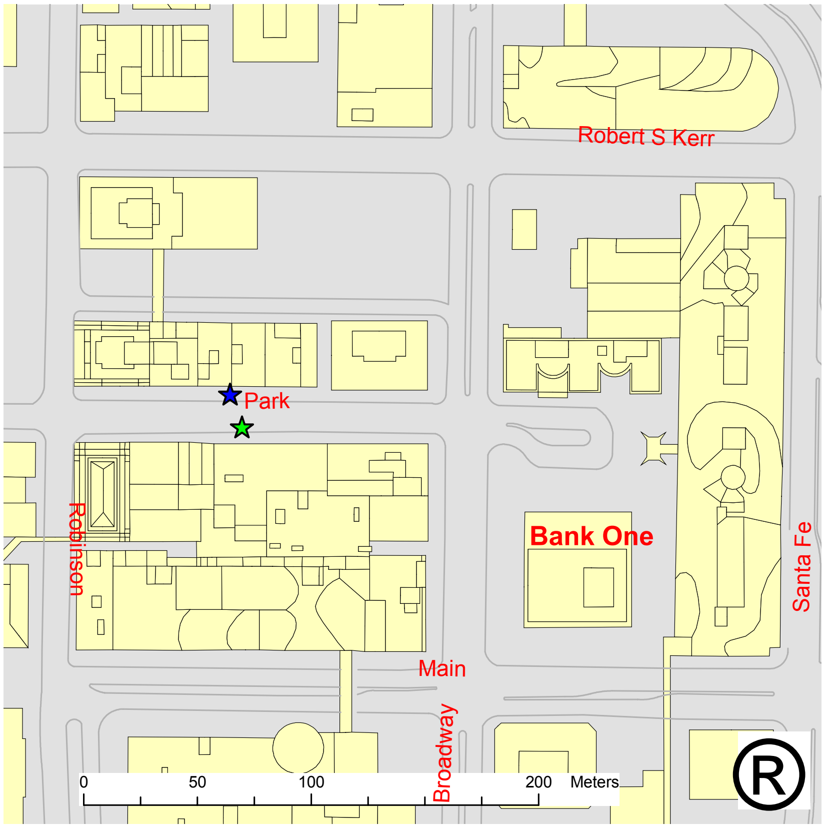

Fig. 1: Map of Park Avenue with approximate locations of tower 1 (blue star) and tower 2 (green star) (Map courtesy of May Yuan, Center for Spatial Analysis, University of Oklahoma).

Fig. 2: Photos of the two towers mounted in Park Avenue (left) and close view of the RM Young sonic anemometers installed on tower 2 (right).

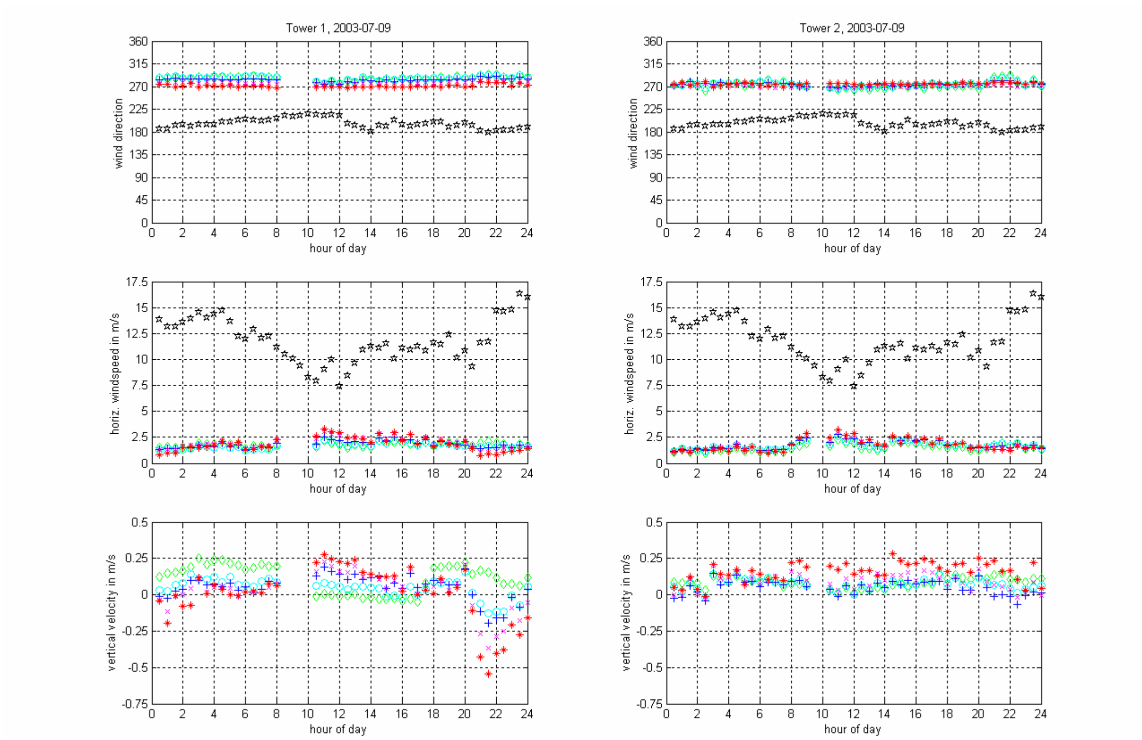

Fig. 3: Diurnal variation of wind direction (top) and mean wind speed (middle) at the 250 m-PNNL sodar reference level (black symbols), as well as wind direction (top), horizontal wind speed (middle), and vertical velocity component (bottom) measured at the five levels (red: h5, pink: h4, blue: h3, turquoise: h2, green: h1) on tower 1 (left diagrams) and 2 (right diagrams) for July 09, 2003. All data correspond to 30min averages.

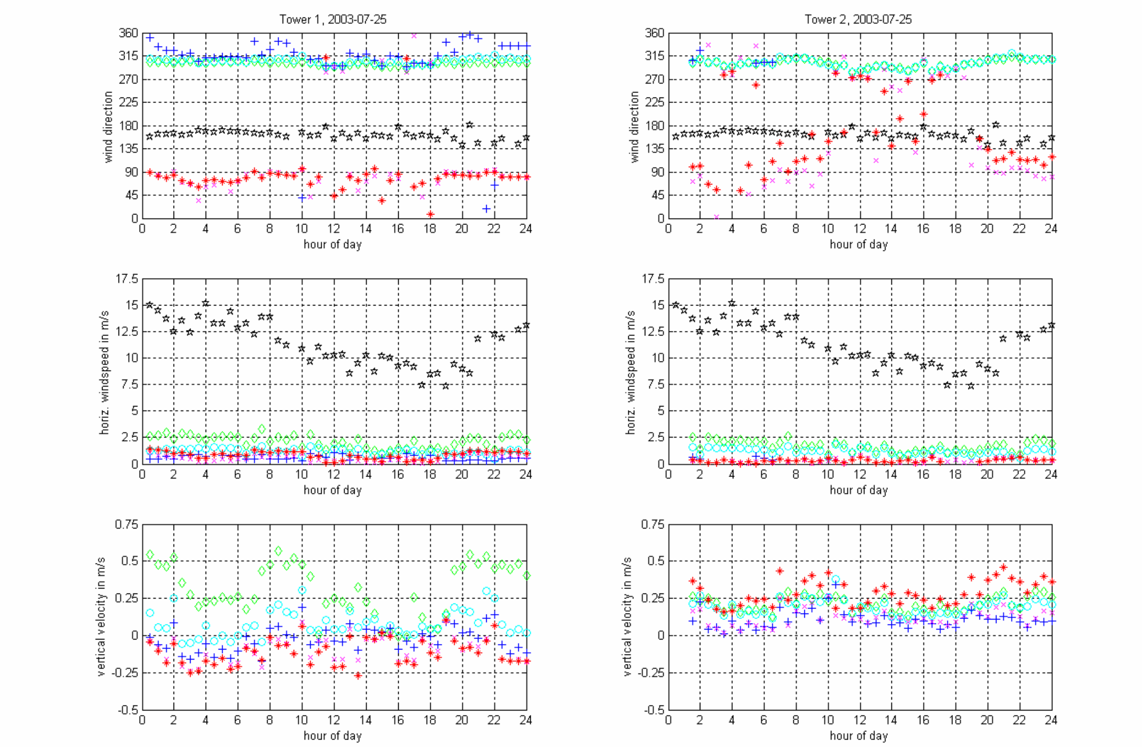

Fig. 4: Same as Fig 3, but for July 25, 2003.

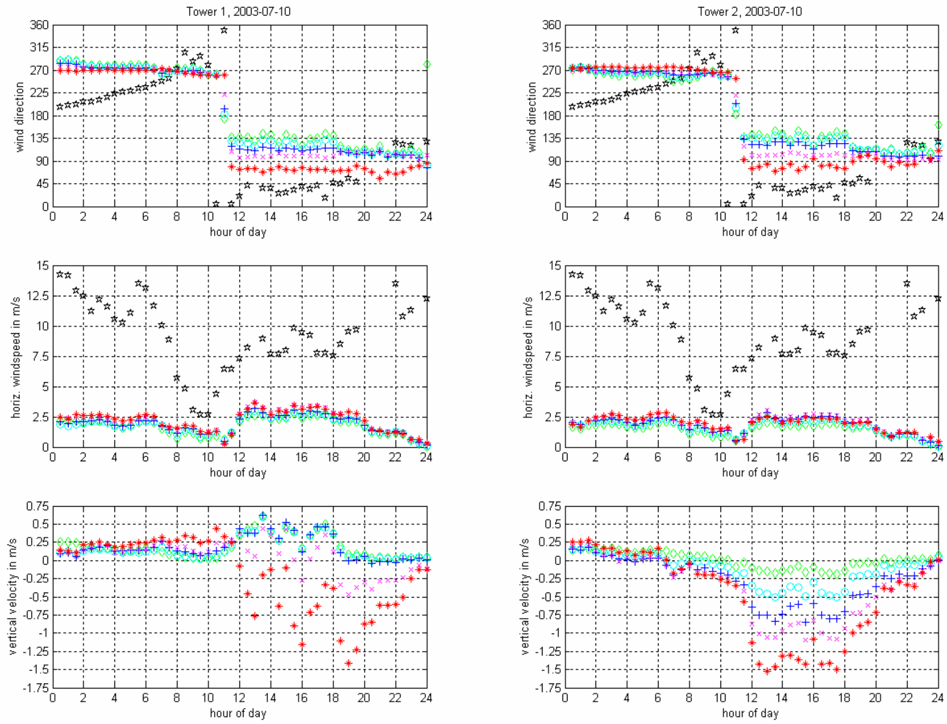

Fig. 5: Same as Fig 3, but for July 10, 2003.

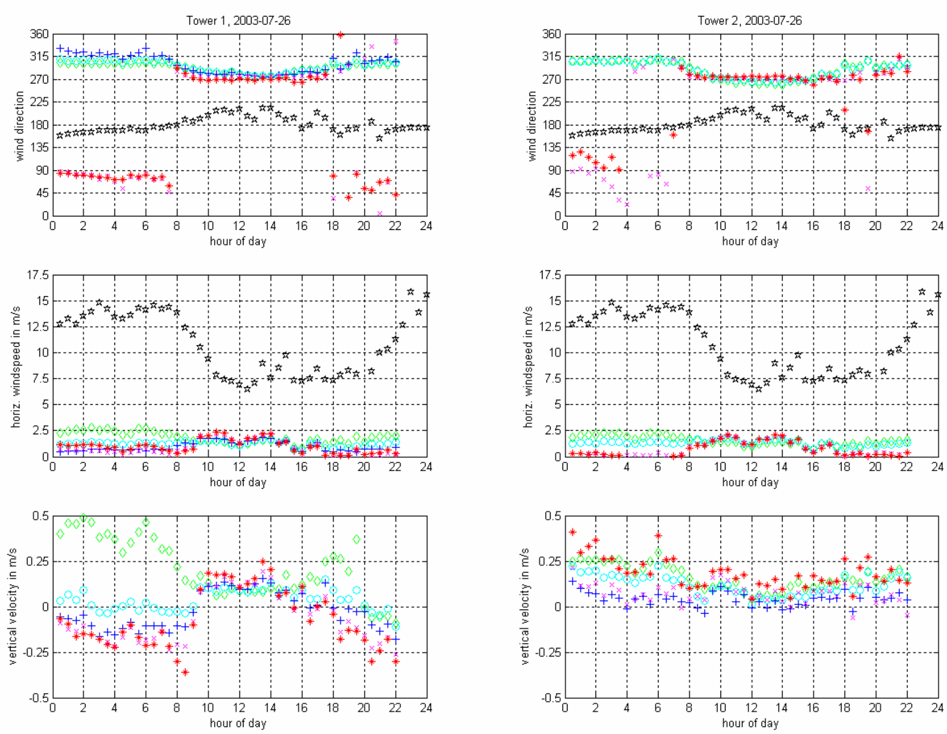

Fig. 6: Same as Fig 3, but for July 26, 2003.

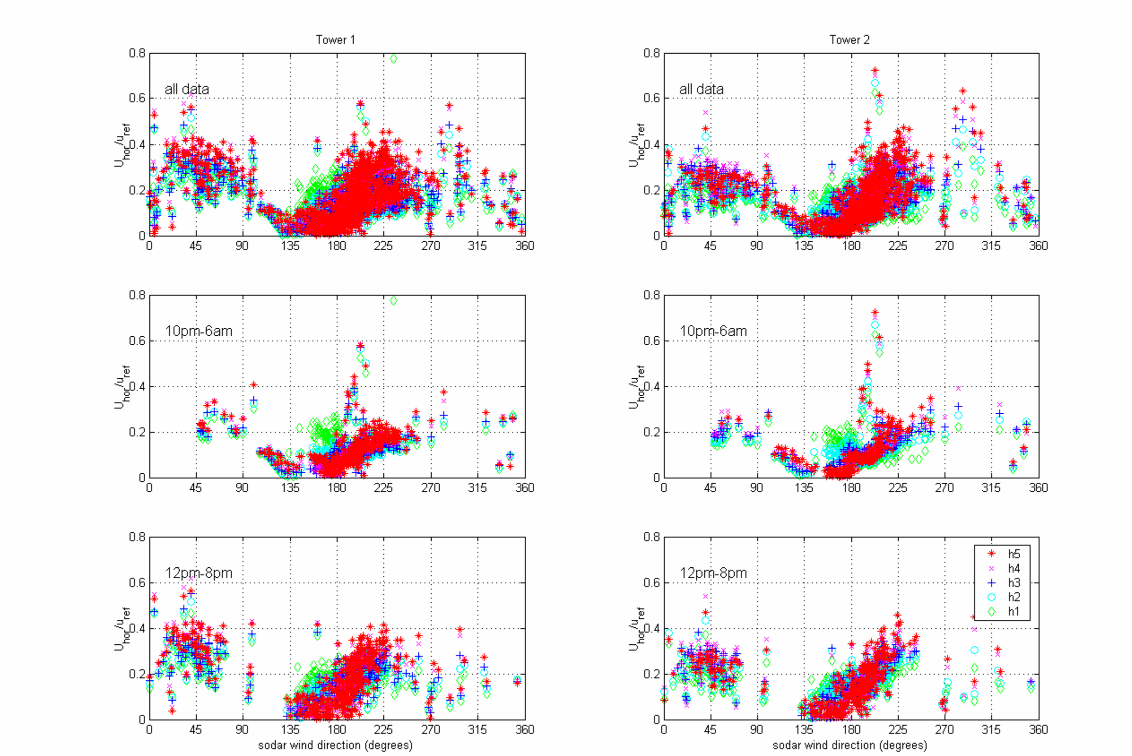

Fig. 7: Variation of horizontal wind speed with the upwind wind direction measured at the 250 m-PNNL sodar reference level. The diagrams refer to all data (top), nighttime data (middle) and afternoon data (bottom) measured at the five sonic levels (red: h5, pink: h4, blue: h3, turquoise: h2, green: h1) on tower 1 (left diagrams) and 2 (right diagrams) during July 2003. All data correspond to 30min averages.

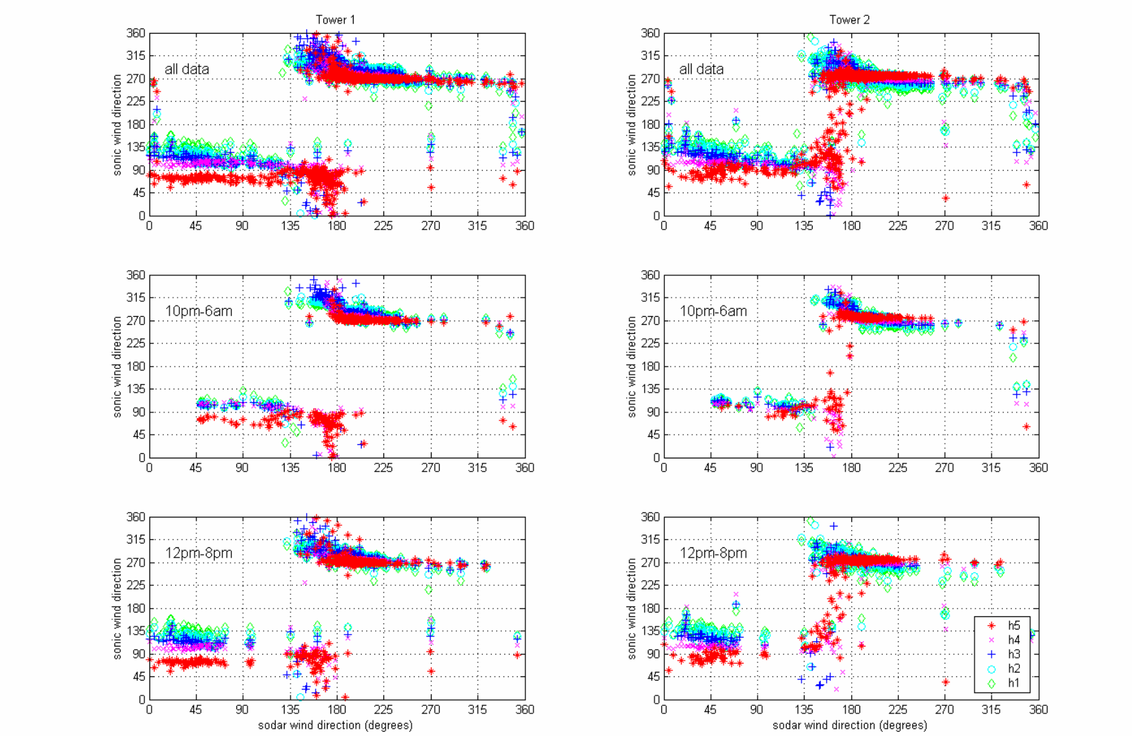

Fig. 8: Same as Fig 7, but for wind direction inside the canyon.

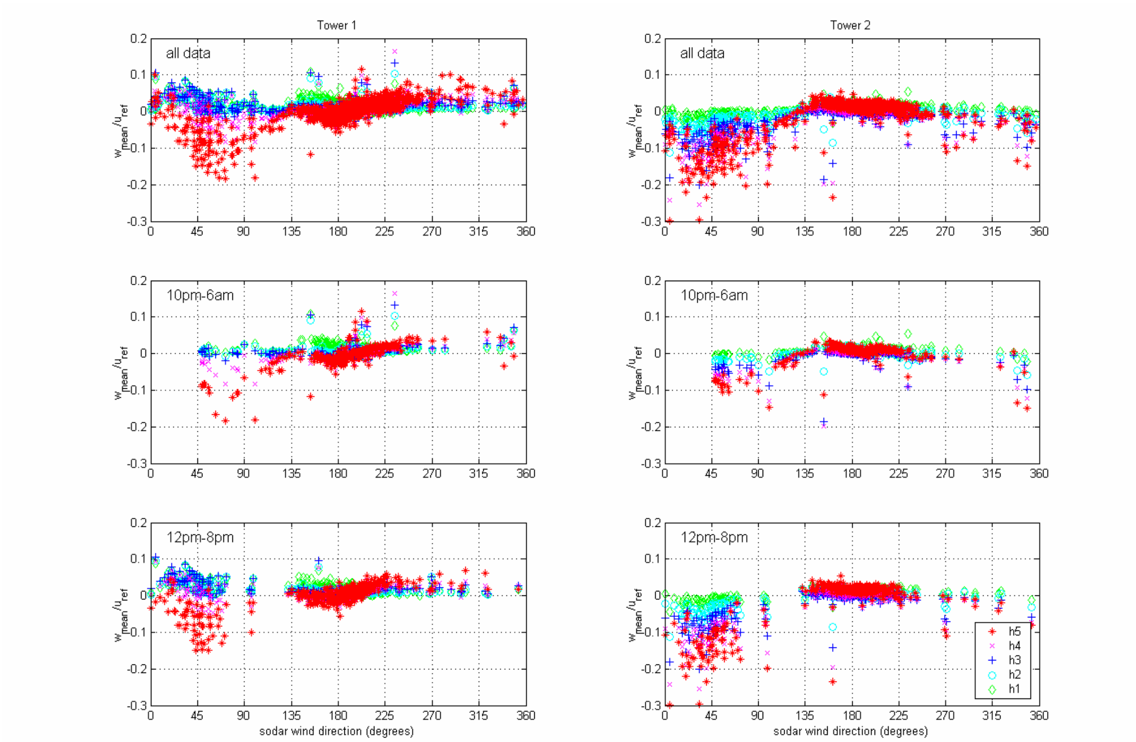

Fig. 9: Same as Fig 7, but for vertical wind component (w).

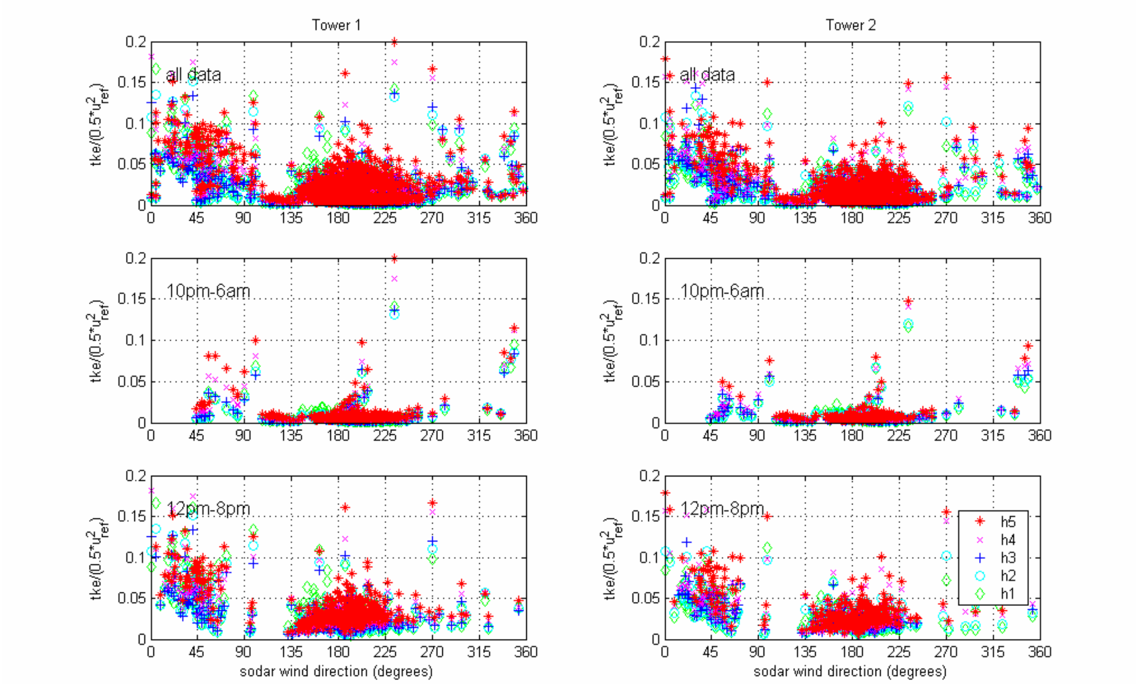

Fig. 10: Same as Fig 7, but for turbulence kinetic energy (tke).