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OBSERVATION OF THE URBAN WIND ISLAND EFFECT

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ABSTRACT

Urban wind island effect (UWI) is defined as a phenomenon in which boundary layer mean wind speeds in an urban area are noticeably higher than its neighboring rural areas. Unlike urban heat island effect which has been extensively studied, the UWI was only recently observed in a modeling study. Here we study existence of the UWI over Indianapolis, Indiana using wind profile measurements from two Doppler wind lidars (DWL) that were deployed in climatologically upwind and downwind of the city. Under certain atmospheric conditions higher wind speeds and turbulence were observed at the downwind site over the entire urban boundary layer outside the urban canopy layer.

1. INTRODUCTION

More than half of the world population now lives in urban areas and increasingly in denser cities. By 2050, it is projected that two-third of the world population will be dwelling in urban areas [1]. Landscape changes with development of urban areas creates micro climate over these urban areas. With more people living in urban areas these micro climates disproportionately affect higher number of people. The urban heat island effect, where a higher temperature is observed over urban areas compared to their rural surroundings [2], is one such example. This effect has been widely studied and it is known to be caused by change is surface properties, such as heat capacity, roughness etc., over urban areas.

Similarly, under certain conditions wind speeds can also be higher over urban areas compared to their neighboring rural surroundings, a phenomenon named the urban wind island effect (UWI) [3]. Using a conceptual bulk model of atmospheric boundary layer, Droste et al. (2018) showed that for certain atmospheric conditions, boundary layer mean wind speeds over a city can be higher than its surrounding rural areas. They found a combination of differences in atmospheric boundary layer growth, surface roughness and ageostrophic wind between city and rural areas causes the UWI in the afternoons. Considering that increase in surface roughness over urban areas is expected to reduce wind speeds, occurrence of the UWI in the model is a surprising finding.

Understanding the UWI is very important for urban air quality and transport of pollutants from cities. In this study we investigate existence of the UWI over Indianapolis, Indiana by comparing wind speeds measured by two Doppler wind lidars (DWL) located upwind and downwind of the city. We compare mean wind speeds in the urban canopy layer (UCL) and in the urban boundary layer (UBL) between the two sites under difference wind direction regimes. We explore individual case studies to identify conditions that might favor development of the UWI.

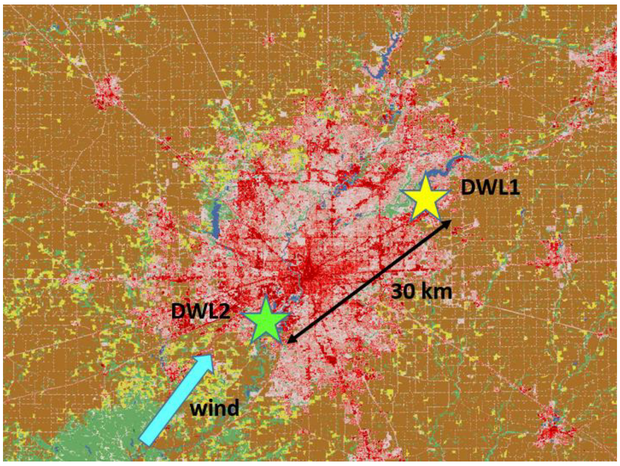

Figure 1: Land usage map from the 2011 National Land Cover Database [4] showing locations of the two Doppler wind lidars in Indianapolis, IN. Cyan arrow shows the predominant wind direction. Major land uses are developed areas (red, darker indicating denser development), and cultivated crops (light brown).

2. OBSERVATIONS

A coherent DWL (DWL1; HALO Photonics Stream Line XR) has been making measurements of mean horizontal wind profiles and mixing layer heights in the suburban area of Indianapolis, IN as part of the Indianapolis Flux Experiment (INFLUX) [5] for quantification of greenhouse gas emissions from the urban area. Location of this DWL is shown as yellow star in Figure 1.

The lidar has been operating with a repeating 20 min scan cycle which consists of conical scans at 3, 10, 35.3, and 60° elevation angles (EA); vertical slice scans to the south and east; a zenith stare (lasting 10 min during the day, 4 min at night); and quasi-horizontal stares at 20° EA to the south and east at night. The scan cycle was optimized for retrieval of horizontal wind profiles, atmospheric turbulence properties and mixing layer height.

Horizontal wind profiles are retrieved using the velocity-azimuthal display (VAD) technique [6]. Mixing layer height is retrieved using an automated composite fuzzy logic technique which combines information from various scan types to determine a unified measurement of the mixing height and its uncertainty [7].

A second coherent DWL (DWL2; Leosphere Windcube 200S) was deployed climatologically upwind of the city for a three-month period in Fall 2017 to study the urban influence on winds and boundary layer. Location of DWL2 is shown as green star in Figure 1. The DWL2 was operated with the same scan settings, and horizontal wind profiles, atmospheric turbulence properties and mixing layer height was retrieved using the same methods as the DWL1.

3. RESULTS

3.1 Composite Analysis

We segregated individual measurement days into 4 groups based on the predominant wind direction that day (sector 1: 0-89°, sector 2: 90-179°, sector 3: 180-269° and sector 4: 270-359°). The mean horizontal wind speed inside the UCL (lowest 100 m layer) and inside the UBL (400-700 m layer) measured every 20 minutes at the two sites each day were then compared. The tallest building in Indianapolis is 247 m [8]. Thus, the lowest 100 m layer is very likely within the UCL and the layer between 400-700 m is outside the UCL but very likely within the urban atmospheric boundary layer (UBL here on).

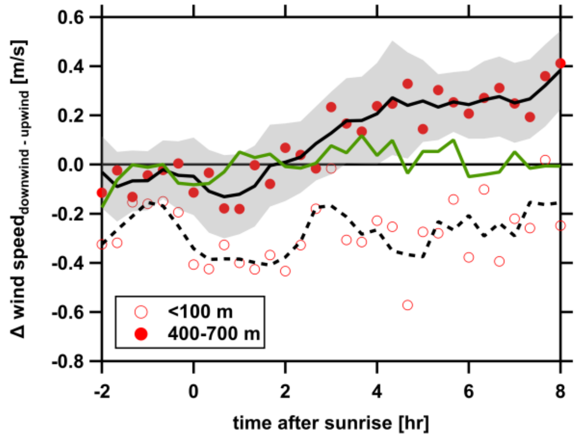

Figure 2: Mean difference in horizontal wind speed inside the UCL (red open circles), and inside the UBL (red closed circles) for wind direction = 180-269° (N = 41). The black dashed and solid lines are hourly averaged (3 points) running mean to the red open and closed circles respectively and included for visual aid. The grey shading represents the standard error of the mean. The green line is same as the black solid line for wind direction = 90-179° (N = 16).

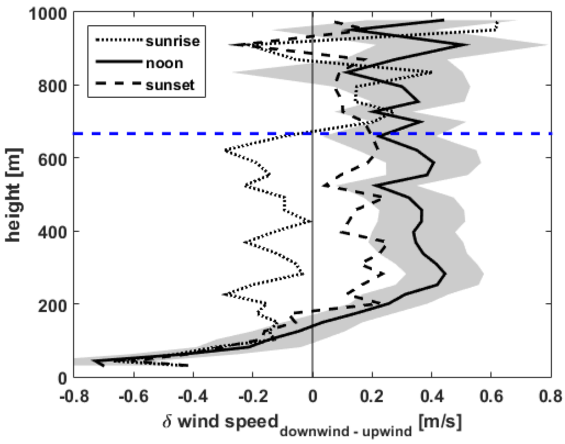

Figure 3: Vertical profile of mean difference in wind speed between the two DWL measurements at sunrise (dotted), solar noon (solid) and sunset (dashed). The grey shading represents the standard error of the mean. The blue dashed line shows the mean mixing layer height for the days included in the analysis.

The mean horizontal wind speed difference between the two lidar measurements (DWL1-DWL2) in the UCL and UBL as a function of time after the sunrise for sector 2 and 3 are shown in Figure 2. When the wind was blowing from sector 3, DWL2 was located upwind of the city and was not affected by the city whereas DWL1 was located downwind of the city and was affected by the city. Thus, sector 3 provided cases for studying the UWI. When wind was blowing from sector 2, both DWLs were not affected by the city and thus, provided a null hypothesis cases. For sector 3, within the UCL, the mean wind speeds were lower downwind of the city throughout the course of the day. This was very likely due to increased surface roughness of the urban area slowing down the wind. Inside the UBL, wind speeds were comparable between the two sites up to the first two hours after the sunrise. Two hours after the sunrise, the mean wind speeds became higher in the downwind site and stayed higher for the rest of the day. This is consistent with the observation by Droste et al. (2018). In contrast, for sector 2, when both the sites were not affected by the city, there was no difference in wind speeds in the UBL between the two sites (Figure 2 green line).

Figure 3 shows the vertical profiles of mean difference in wind speeds at sunrise, solar noon and sunset for sector 3. The higher wind speeds at the downwind site were observed through the entire UBL outside the UCL at solar noon and sunset but not at sunrise. In contrast, wind speed is higher upwind of the city over the entire UCL.

3.2 Case Study

Individual case studies provide an opportunity to further explore the causes for UWI. Figure 4 shows an example of time-height cross section of horizontal wind speed profiles measured by the two DWLs on 26 September 2017 when wind was blowing from sector 3. The differences between wind speed profiles at the two sites are also shown in Figure 4. Both the sites showed very similar overall wind speed indicating both the sites experienced the same general wind flow. Although individual profile differences were noisy, we can see that early in the morning the wind speed differences were negative inside the mixed layer i.e. the downwind site experienced lower wind speeds. This could be due to wind speed was being used to generate turbulence for eroding night time inversion layer and mixing layer height growth at the downwind site (see Figure 5). Indeed, the mixing layer height started to grow earlier at the downwind site.

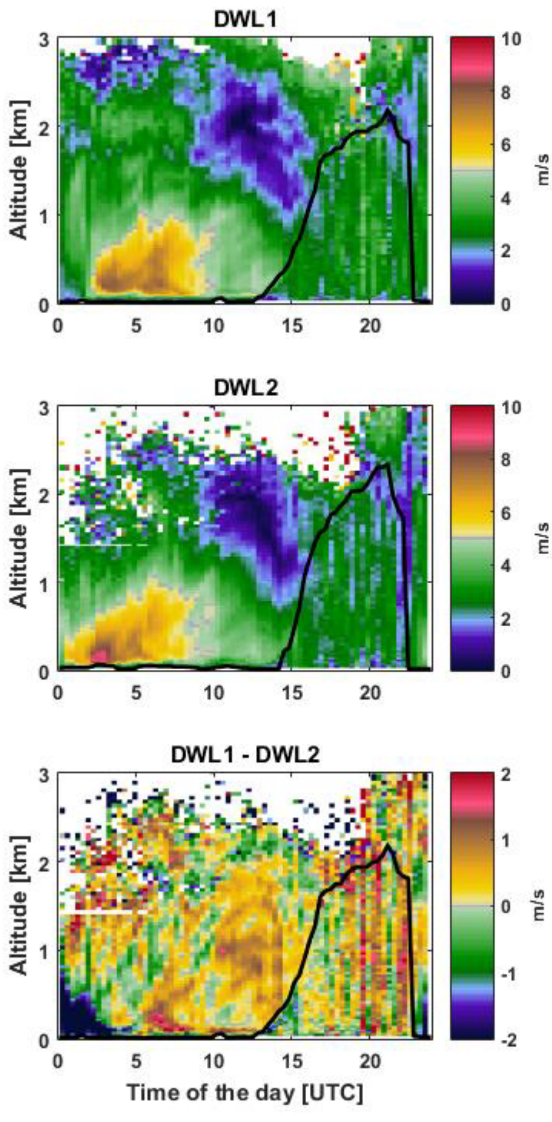

Figure 4: Time-height cross section showing horizontal wind speed profiles measured by DWL1 (top), and DWL2 (middle) on 26 September 2017. The black solid lines represent the measured mixing layer height at the two sites. The bottom panel shows the difference between the top two panels.

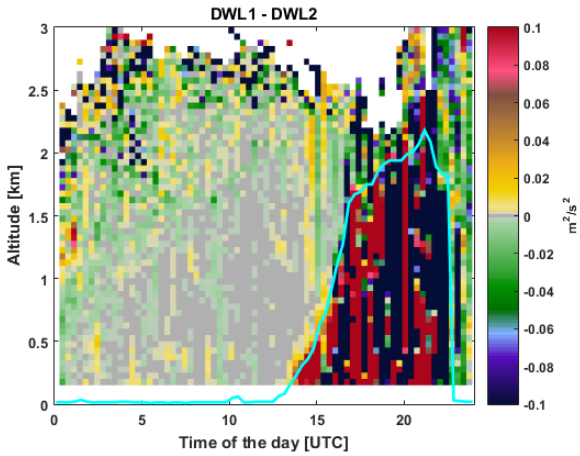

Figure 5: Time-height cross-section showing the difference in vertical velocity variance between two sites on 26 September 2017. The cyan solid like represent mixing layer height measured by DWL1.

As seen in the Figure 2, around 2 hours after the sunrise, wind speeds were generally higher in the downwind location. This higher wind speed coincided with higher turbulence inside the UBL during the mixing layer height growth phase and lower turbulence during the decay phase. Figure 5 shows difference in vertical velocity variance between the two sites on 26 September 2017. This enhanced mixing in the UBL at the downwind site during the mixing layer growth phase facilitates entrainment of free tropospheric air and this very likely resulted in higher wind speed. Droste et al. (2018) also identified enhanced turbulence in the urban area as one of the causes for UWI.

4. CONCLUSIONS

Horizontal wind profile measurements by DWLs at an upwind and a downwind location of Indianapolis, Indiana showed existence of an UWI effect i.e. mean horizontal wind speed inside the boundary layer is higher in the urban areas than the surrounding rural areas. This higher wind speeds at the downwind site was observed over the entire UBL and it was found to occur with increased turbulence. Enhanced turbulence aids mixing of free tropospheric air and this very likely results in UWI. Inside the UCL, wind speeds were lower in the downwind site. This is consistent with our conventional understanding of winds over urban areas i.e. increase surface roughness over urban areas results in lower wind speeds. In a control experiment where neither of the DWLs were affected by the city, there was no difference in mean horizontal wind speeds between the two sites.

Future work to understand UWI would involve measurements of horizontal wind profiles, atmospheric turbulence properties, and mixing layer height over rural-urban areas using airborne and/or mobile Doppler wind lidars to continuously monitor the progression of UWI effect across urban areas.

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