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A Preliminary Study of the Vertical Structure of Convective Outflows Measured at the Boulder Atmospheric Observatory (BAO)

Matthew Mason[1], Andrew Schwartz[2]
[1]*School of Civil Engineering, The University of Queensland, St Lucia, Qld, 4072, Australia.*
matthew.mason@uq.edu.au
[2]*School of Earth and Environmental Sciences, The University of Queensland, St Lucia, Qld, 4072 Australia.*
andrew.schwartz@uq.edu.au

ABSTRACT

Anemometer-derived wind speed profiles measured on the 300 m Boulder Atmospheric Observatory (BAO) instrumented tower during seven thunderstorm outflow events were analysed. Aggregate statistics for these profiles were compared with mean atmospheric boundary layer (ABL) models (Log Law, Deaves and Harris) and gust wind speed profiles specified in AS/NZS1170.2 (ABL), AS/NZS7000 (thunderstorm) and ISO4354 (thunderstorm). Results from this preliminary analysis suggest mean ABL models are conservative when compared with measured (1-min mean) data, but that both ABL and thunderstorm gust profiles specified in current Standards are not.

1. Introduction

It is now well known that convective thunderstorm outflows generate 'design' wind gusts in many parts of the world. Wind engineers have studied these events through laboratory experiments and numerical simulations for the last few decades, but relatively little full-scale observations exist to validate these tests. New Doppler radar, SODAR and LiDAR technologies (Lundquist *et al.*, 2017) show promise for capturing such information, but issues around spatio-temporal averaging remain a hurdle for readily comparing these measurements with more traditional point-based anemometer records or for the analysis of turbulence. Without such validation, however, it will remain difficult to justify explicit incorporation of outflows into general wind-resistant design practice.

The Boulder Atmospheric Observatory (BAO) in Erie, Colorado (USA) operated a 300 m instrumented weather observation tower from 1977 to 2016. Instrumentation on the tower varied throughout its life, but wind sensors were positioned at 10 m, 100 m and 300 m for extended periods of its operation. Instruments logged continuously and captured detailed information on the boundary layer structure of a range of wind events that passed over the site. Included in this, were numerous convective outflows. These data provide a unique opportunity to explore the structure of outflow boundary layers, and provides needed validation for current wind engineering models and understanding.

This paper describes ongoing work to analyse convective outflow events measured at the BAO tower during the period 2007-2016. In particular, it explores velocity profiles for seven (7) events that passed over the tower and compares these with traditional atmospheric boundary layer (ABL) models (Log-law and Deaves and Harris models), a normalised version of the gust wind speed profile specified in AS/NZS1170.2 (Standards Australia, 2011), and outflow velocity profiles specified in AS/NZS7000 (Standards Australia, 2016) and ISO4354 (International Organization for Standardization, 2009).

2. BAO Site and Tower Information

The Boulder Atmospheric Observatory (BAO) was a research facility located in Erie, Colorado (USA) and was operated by the Earth System Research Laboratory within the National Oceanographic and Atmospheric Administration (ESRL/NOAA). It was operational from late 1977 to mid-2016. The core of the BAO facility was a 300 m tower (Figure 1) with atmospheric sensors at a range of elevations used to characterise the lowest part of the atmospheric boundary layer. Instrumentation varied over time, but those measuring temperature, relative humidity and wind speed were present at several levels for much of its operation. A number of remote sensing systems were periodically installed at the site to aid research into their validation (e.g. Lundquist *et al.*, 2017).

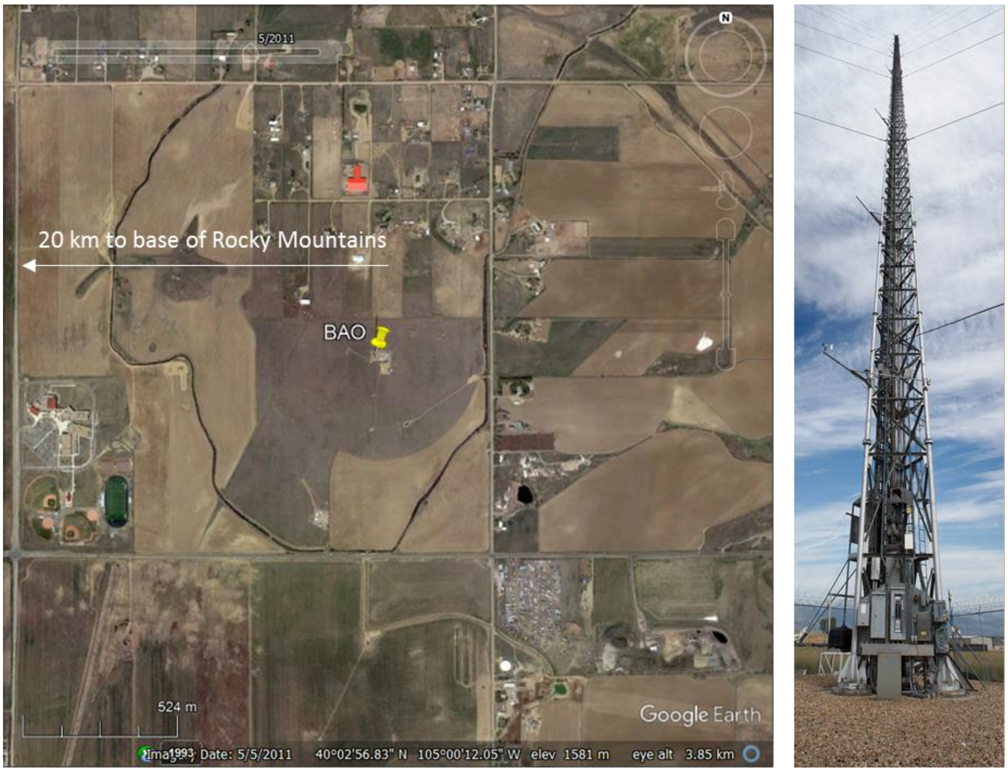


Figure 1. Boulder Atmospheric Observatory (BAO) 300 m tower, (left) local site conditions (2011), and (right) tower itself. Images sourced from Google Earth and NOAA.

This paper discusses measurements made over the nine-year period between June 2007 and July 2016. Wind speed and direction measurements were available at elevations of z = 10 m and 300 m for the entire period, with measurement at z = 100 m introduced in September 2010. Temperature (T) measurements were available for all elevations over the analysis period. Atmospheric pressure (P) and 1-min accumulated precipitation (PR) measurements at the surface were also available for the entire period. Wind speed (V_{60}) and direction (θ) data were available as 1-min mean magnitudes at 10 m and 100 m levels (RM Young propeller anemometer, Model 05105), with 30-second averages available for the 300 m level (2D Sonic Gill WindObserver II). 300 m data were converted to equivalent 1-min mean values to enable instantaneous profile development. No corrections have yet been made to account for any influence instrumentation type may have had on results.

The BAO field site was located approximately 20 km east of the Rocky Mountains. The site and surrounding region is flat and during the period of analysis had only scattered buildings and farmland within 3.5-4 km of the tower. Beyond this distance, some small towns exist and Boulder sits about 15 km west of the site. Given this information, a roughness length of z_0 = 0.02m (open terrain) is assumed reasonable for the site.

3. Methods

To enable analysis of convective outflow events, they first had to be identified and extracted from the data records. For this preliminary study a manual identification procedure was implemented to identify a small number of 'case study' events for initial analysis. A more objective (automated) identification procedure will be developed in future research. In total, seven (7) outflow events were identified, extracted and analysed. The three steps outlined below describes the procedure implemented.

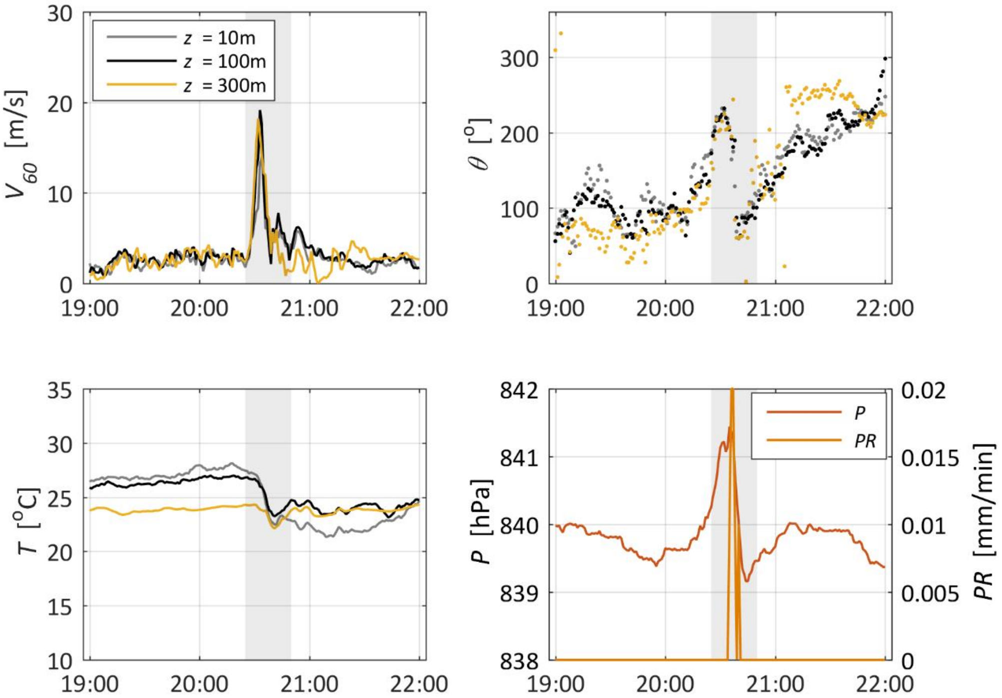
1. Identify all days where $V_{60} > 15$ m/s was recorded at $z = 10$ m,
2. Keep all days that matched those in an existing ESRL/NOAA archive of severe wind gusts recorded in Boulder, CO and were attributed to thunderstorm activity (https://www.esrl.noaa.gov/psd/boulder/wind.html),
3. Using reflectivity radar archives, confirm convective storm activity in the area of the BAO site at the time of recorded winds.

In at least two cases, multiple outflow events were recorded on the same day. In these instances, each have been extracted and analysed separately (event if point 1 was not satisfied). An example of an identified outflow event is shown in Figure 2. Figure 2 (a) shows a 3-hour time history of measurements at all three anemometer levels (V_{60}, θ, T) and P and PR measurements at the surface. The period extracted for analysis is highlighted in grey. For this event, many 'classic' wet microburst signatures are evident. These include a rapid drop in T and increase in V_{60} as the outflow front arrives, a nearly 180^{o} shift in θ, and a spike in P and PR as the downdraft moves over the top of the tower. Figure 2 (b) shows radar reflectivity at the time of peak winds, with the BAO site and storm motion vector indicated. Use of such radar information not only allows convective activity to be confirmed, but also enables storm translation speed and direction, and site distance from outflow origin to be estimated. While not explored in this paper, these parameters will be useful for understanding the evolution of outflow profiles with time and distance travelled away from their parent thunderstorm. Once event case studies were identified and extracted, vertical profiles of V_{60} were developed for each minute of record. Storm event envelope profiles (i.e. peak wind speed at each elevation for the extracted event period) were also developed. Profiles were normalised by the 10 m wind speed, $V_{60,z=10m}$, (1-minute or enveloped values) for plotting and comparison.

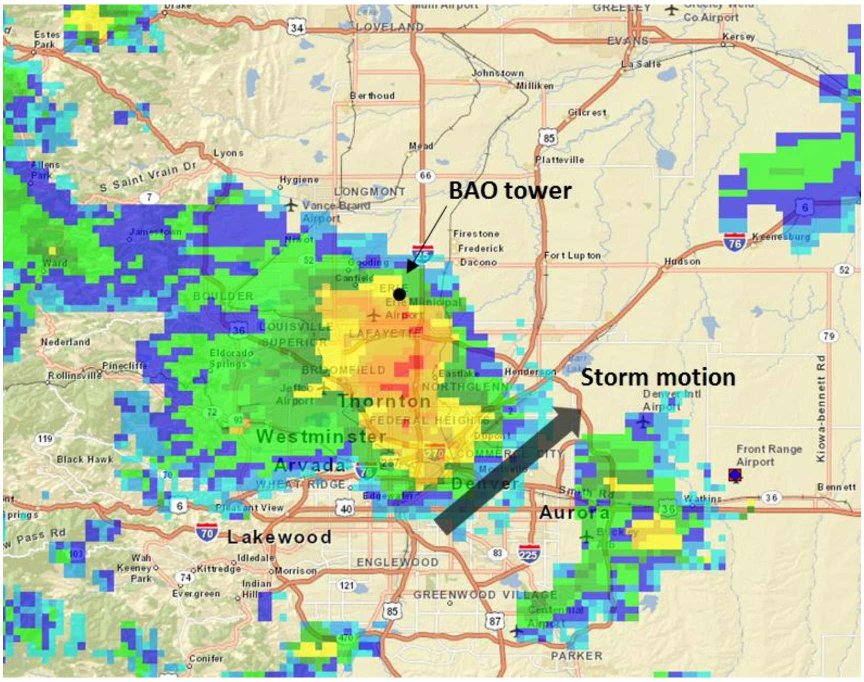
4. Results and Discussion

Figure 3 shows normalised ($V_{60}/V_{60,z=10m}$) wind speed profiles for the 10 July, 2011 case study event detailed in Figure 2. Profiles of 1-minute data as well as the median of these profiles are shown. The profile at the time of peak $z = 10$ m wind is also highlighted to detail the outflow structure at the time of peak 'surface' winds. Considerable scatter is evident between the 1-minute profiles, but some general observations can be made. Firstly, wind speeds at 100 m almost always remained at or above those at 10 m. This is supported by a median $V_{60}/V_{60,z=10m}$ value of 1.13. At 300 m, normalised speeds are more variable, and at many times are less than those at 10 m. The median normalised wind speed, however, remains above 1 suggesting that more often than not it is greater than at the surface. At the time of peak 10 m winds, the profile shape follows the oft assumed low-level (or wall) jet profile shape. Given data were available at only three levels it is unclear whether the true peak resides above or below the $z = 100$ m level, but such observations do serve to validate current thinking about the boundary layer within these events.

Extending the analysis to all extracted events, Figure 4 shows normalised wind speed profiles for each case at the time of maximum 10 m winds (a) and for the envelope of storm maximum winds (b). The median and mean profiles for the seven cases are also shown. Unlike for the profiles measured throughout an event (i.e. Figure 3), both plots show a high level of consistency between storms. This is, to some degree, surprising given the distance between the tower and parent storms varied by up to 20 km between events. A priori one may expect such a difference to influence the lowest part of the boundary layer shape, but these preliminary observations may suggest otherwise (at least near the time of peak outflow intensity). Further research is require to explore such relationships. Both mean and median 10 m peak and enveloped profiles show wind speeds at 100 m to be greater than those at 300 m. The low level peak is, however, more prominent in the peak profile.



(a) One minute mean wind speed (V_{60}), wind direction (θ) and temperature (T) recorded at z = 10 m, 100 m and 300 m, as well as pressure (P) and precipitation rate (PR) measured at the surface. Shaded region indicates data extracted for event analysis.



(b) Radar reflectivity at 20:30 UTC. Direction of storm motion also indicated. Data sourced from NOAA (https://gis.ncdc.noaa.gov/maps/ncei/radar).

Figure 2. Recorded data for an outflow event on 10 July, 2011.

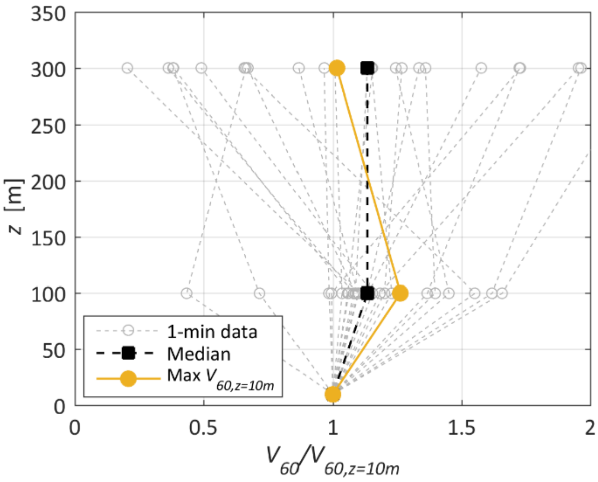
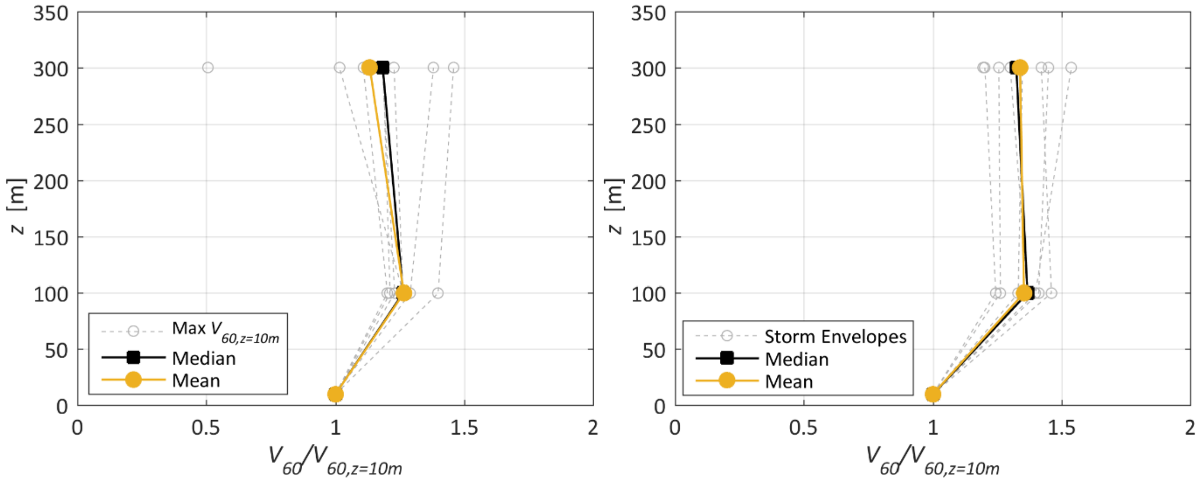


Figure 3. Normalised wind speed profiles for the extracted period of the 10 July, 2011 event.



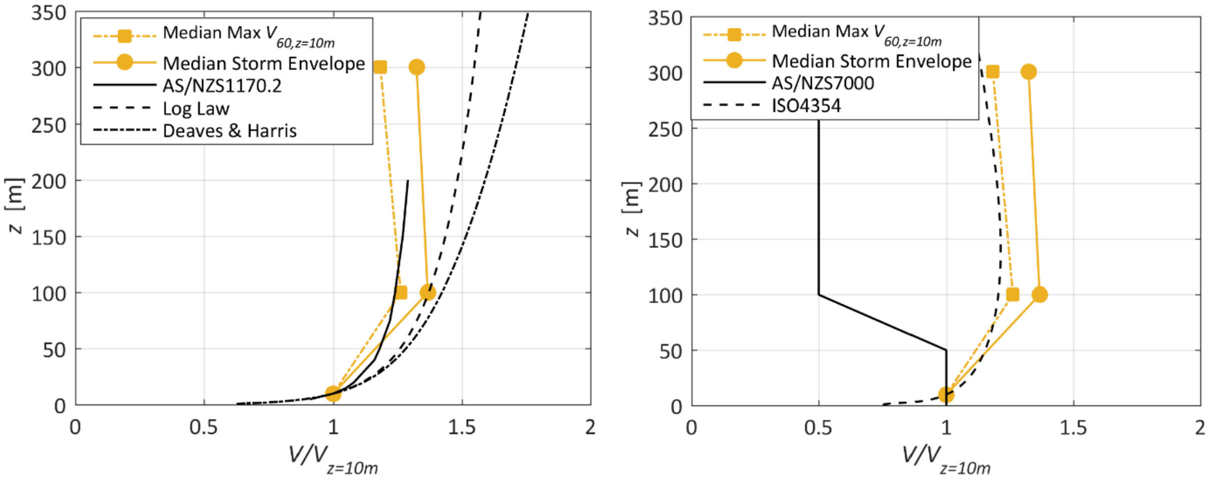
(a)

(b)

Figure 4. Normalised wind speed profiles for (a) the time of event maximum 10 m wind speed, $V_{60,z=10m}$, and (b) envelope of event maximum winds at each height.

Given the importance of convective outflows in defining the extreme wind climate in many regions of the world, it is important to investigate how they can be explicitly incorporated into design practice. An initial step in this process is to compare measured profile data with models and codes/standards currently used in engineering practice. To this end, Figure 5 (a) compares the median profiles shown in Figure 4 with traditional ABL representations based on the Log-Law model, Deaves and Harris (DH) model (Cook, 1997) and the Australia/New Zealand wind loading Standard, AS/NZS1170.2 (Standards Australia, 2011). Figure 5 (b) compares these same data with outflow profiles currently specified in AS/NZS7000 (Standards Australia, 2016) and ISO4354 (International Organization for Standardization, 2009). The two models shown in Figure 5 (a) are *mean* wind speed profiles, while all others are *gust* wind speed profiles. Recorded 1-minute data lies somewhere between the two.

Figure 5 (a) shows that when using a roughness length of z_0 = 0.02m, both the Log Law and DH models are conservative when compared with the median envelope and peak profiles. This is more so the case for *z* = 300 m, where they both overestimate normalised wind speeds by *O* 10-40%. AS/NZS1170.2 appears to be less conservative, and in fact underestimates the enveloped profile at *z* = 100 m. A key reason for this is thought to be linked to differing wind speed averaging times (i.e. shorter averaging durations will tend towards flatter profiles), and further research is required to ensure any such comparison (and any conclusions drawn from these) are based on comparing like with like. Comparisons shown in Figure 5 (b) show the ISO4354 profile to reasonably replicate the median 1-min peak 10 m wind speed profile, but underestimates the envelope. Part of the reason for this may again be linked to wind speed averaging times and further research is again required to ensure adequate comparisons can be made. The AS/NZS7000 profile is un-conservative against both measured profiles.



(a)

(b)

Figure 5. Comparison between median of envelope and peak profiles at the time of maximum 10 m winds, for all analysed events and (a) general atmospheric boundary layer standards and modes, and (b) standardised outflow profile shapes.

5. Conclusions

A preliminary analysis of seven outflow events measured on the 300 m BAO tower has been undertaken. Vertical profiles of horizontal wind speeds were developed to investigate the boundary layer structure throughout each event. These profiles were normalised and compared with both ABL model and ABL and thunderstorm profiles specified in a range of wind-resistant design Standards. Current mean ABL profiles were found to be conservative when compared with the 1-min data presented in this paper, but gust profiles (both ABL and thunderstorm) were shown to be un-conservative for the same data.

Future research will refine the simple event selection procedure presented here. It will also investigate the role of storm parameters (e.g. storm relative position) in defining the boundary layer structure. Improved methods for comparing these measured data with mean and gust profiles in design Standards will also be explored.

References

Cook, N., 1997. The Deaves and harris ABL model applied to heterogeneous terrain. *J. Wind Eng. Ind. Aero.* 66:197-214.

International Organization for Standardization (2009), “Wind actions on structures”, International Standard, ISO4354:2009.

Lundquist, J. *et al.*, 2017. Assessing state-of-the-art capabilities for probing the atmospheric boundary layer: The XPIA field campaign. *Bull. Amer. Meteor. Soc.* 98:289-314.

Standards Australia, (2011), "Structural design actions. Part 2 Wind actions", Australian/New Zealand Standard, AS/NZS 1170.2:2011.

Standards Australia, (2016), "Overhead line design", Australian/New Zealand Standard, AS/NZS 7000:2016.