Analysis of full-scale transient wind event boundary layers at the Boulder Atmospheric Observatory

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ABSTRACT

This paper applies a Self-Organizing Map algorithm to automatically cluster wind events measured on the Boulder Atmospheric Observatory 300 m tower based on their temporal characteristics. Boundary layer velocity profiles are developed for events within each of these clusters and the results compared with a neutral boundary layer profile at the site and the Region A0 velocity profile now specified in AS/NZS1170.2:2021. Results show the most transient events – loosely linked to thunderstorm events – generate boundary layer profiles distinctly different to those in neutral atmospheric conditions, with the resulting profile conservatively enveloped by the prescribed Region A0 profile.

1. Introduction

Many of the strongest wind events are transient in nature. Of particular interest to wind resistant design in non-cyclonic regions are thunderstorm outflows. Despite their importance, there remains limited detailed observations of the near-surface boundary layer during these and other transient wind events. Recent studies have used LiDAR (Canepa *et al.,* 2020) and tall-tower anemometer data (Mason and Schwartz; 2018, Romanic, 2021) to extend our observational understanding of the boundary layer that exists during these events, but much is still to be learned.

In one of these studies, Mason and Schwartz (2018) undertook a preliminary assessment of seven manually identified transient thunderstorm outflows that passed over the Boulder Atmospheric Observatory (BAO) 300 m anemometer tower. They showed that for these events the boundary layer characteristics varied considerably over the duration of storm passage but showed remarkably similar velocity profiles at the time of maximum winds. They also showed that the open terrain (Terrain Category 2) gust velocity profile specified in AS/NZS1170.2 was generally conservative when compared with the 'nose' shaped outflow profiles measured during the thunderstorms (albeit comparing with 1-minute average velocities). In another study, using a profiling LiDAR, Canepa *et al.* (2020) investigated the lowest 250 m of 10 downbursts that occurred over the Northern Mediterranean. They also found that for most events a 'nose' shaped boundary layer velocity profile existed, with this type of profile shape most prominent during the short period prior to and during maximum winds. Typical heights of the maxima in their velocity profiles ranged between 50-180 m. In a further study, Romanic (2021) studied a rare nocturnal outflow event in the Netherlands, which was measured on a 213 m anemometer tower. They show that even when occurring within a stable boundary layer, the thunderstorm downburst still generates velocity profile that exhibits a maximum at an elevation around 100 m. For this case though, the distinctive 'nose' shape was only present for about one minute, but this was during the strongest portion of the outflow so again highlights the strong association of this boundary layer shape with transient outflow events.

This paper extends the work of Mason and Schwartz (2018) and explores the BAO tower data in further detail. Specifically, it will discuss the application of an automated event identification and classification scheme similar to that proposed by Spassiani and Mason (2021), which segregates gust events using a Self-Organizing Map (SOM) algorithm based on their temporal velocity characteristics – i.e. their transience. Boundary layer velocity profiles for events with differing temporal characteristics are then compared with those measured in neutral conditions and differences highlighted. Data from clusters comprised primarily of thunderstorm outflows are then converted to equivalent 0.2-second gust profiles and compared with the Region A0 thunderstorm wind gust profile now prescribed in AS/NZS1170.2: 2021 (Standards Australia, 2021).

2. Boulder Atmospheric Observatory (BAO) 300 m tower

A brief summary of the BAO tower and its surrounds is included in this section. For a more complete description refer to Mason and Schwartz (2018) and references therein. The BAO tower was a 300-metre observational tower located on flat land in the town of Erie, Colorado (USA) between the years 1977 – 2016. Mean velocity, V, direction, ϑ, temperature, T, pressure, P, and precipitation, PR, were available at elevations of z = 10 m, 100 m and 300 m for much of the period 2007 – 2016 at either 30 second or 60 second intervals. Velocity data at z = 10 m and 100 m were measured using an RM Young propellor anemometer, with z = 300 m data measured with a 2D sonic Gill WindObserver II. All data were converted to 60-second block averaged mean values. Only scattered buildings and farmland surround the site with measured z_0 values discussed in Section 3.

3. Methods

The first step in this analysis was to determine the local roughness characteristics at the BAO site. This is important for a study like this because if it is shown that conditions are uniform in all directions and across all seasons, then any identified wind events can be reliably compared irrespective of the direction of winds or time of occurrence. To enable this characterization, every one-minute record was assigned a Pasquill stability classification (Golder, 1972) based on its surface-based Richardson Number, which was calculated using 10-minute averaged data from the z = 10 m and 100 m levels when centred on the 1-minute record of interest. All time steps where the 1-minute mean velocity, V_{60} < 10 m/s at z = 10 m were discarded to remove any influence of low wind speed data. Once classified, each 1-minute record was grouped into its stability class and those classified as neutral (Pasquill stability class D) were further sub-divided by their wind direction at z = 10 m and the month of occurrence. Non-dimensional velocity profiles, $V_{60,z}/V_{60,z=10m}$ were plot for all cases and compared.

Once site characteristics and a representative neutral velocity profile were known, wind gust *events* were identified for classification by a SOM algorithm. *Events* were identified by again identifying all points in time where V_{60} > 10 m/s. Once done, the 60-minutes of data before and after that time were extracted. Where multiple time steps within a data block reported V_{60} > 10 m/s, the maximum value was identified and tagged as the *Event Maximum*. The 1-hour period centred on the event maximum was then extracted for classification by the SOM. Spassiani and Mason (2021) describe the application of a multi-variate SOM to classify the meteorological origin of gust events. Here a more simplified univariate (V_{60} at z = 10 m) SOM is used, and events are classified into a 5 x 5 grid, based on the similarity of temporal characteristics of each event. Given this simplified approach, classification is not strictly done based the meteorological origin of each event, but instead on the transience of the boundary layer. However, even though this classification approach does not utilize meteorological variable other than wind speed, Spassiani and Mason (2021) argue that it remains a reasonably robust approach for classifying the meteorological origin of wind data. The link between grid nodes and meteorological phenomena is discussed further in Section 4. Once classified, velocity profile data for each of the SOM nodes were compared with the neutral velocity profile at the site. Given the strongest winds are of primary interest to wind resistant design, the profiles at each *event maximum* as well as the time step before and after were the only ones retained for this comparison.

Finally, measured velocity profiles from nodes most representative of thunderstorm outflows were compared with the gust profile specified for Region A0 in the Standard, AS/NZ1170.2:2021 and the thunderstorm profile in ISO4354 (ISO, 2009). To ensure this comparison was accurate, the V_{60} data from the BAO tower were converted to a 0.2-second gust, $V_{0.2}$, as is used in the Standard. Since no gust or turbulence intensity information is available for each level, theoretical gust factors of 1.39, 1.26, 1.23 were calculated for z = 10 m, 100 m and 300 m, respectively, based upon standard atmospheric boundary layer theory and a surface roughness of z_0 = 0.02 m (see discussion later in paper).

4. Results

Figure 1 shows the non-dimensional boundary layer velocity profiles for 1-minute wind records when classified into either (a) stability classes, or (b) for the neutral profile subset, wind direction bins. Analysis is based on just over 65,000 1-minute records and the median value is used to plot the profile for each stability class. Inspecting the profiles for different stability classes, the procedure set out in Section 3 appears to successfully classify unstable profiles (A – C) and enables their removal for determining surface roughness conditions. Little difference is observed between the neutral (D) and stable (E – G) class profiles, which was initially surprising. However, subsequent investigation found that many of the most stable wind events were already excluded from the analysis due to the requirement that V_{60} > 10 m/s. Irrespective, those classified as E – G were also removed. When fitting a standard log profile to the remaining neutral records, a surface roughness of z_0 = 0.015 m is found. This value is marginally lower than typically expected for open terrain. However, this is due to the fact that 1-minute mean values are used and when redoing this log fitting to 10-minute data a value of approximately z_0 = 0.02 m is found.

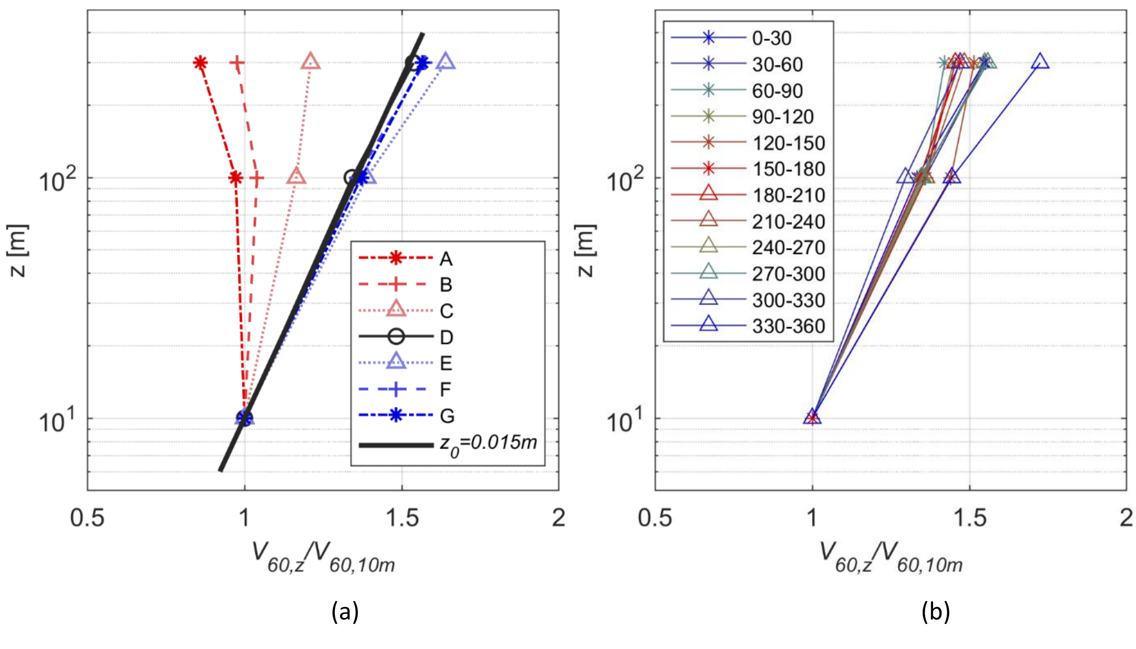

Figure 1. Measured boundary layer velocity profiles by (a) stability classes, and (b) neutral (Pasquill class D) by wind direction.

The directional profiles shown in Figure 1 (b) show similar results for most bins and therefore suggest relatively uniform roughness in all directions. A similar analysis based on the month of occurrence (not shown) also shows relatively consistent profiles throughout the year, albeit with a slight preference for profiles tending towards stable in the winter and unstable in the warmer months. Considering these observations, subsequent analysis is carried out independent of wind direction or time of occurrence and the Pasquill class D profile in Figure 1 (a) was used as representative of neutral winds at the BAO site.

Following the *event* identification procedure set out in Section 3, 1,424 events were identified for classification by the SOM. Prior to this, all 60-minute event time histories were non-dimensionalised by dividing the record by the *event maximum* value to yield the parameter λ. Doing this ensured that events were classified based solely on their shape rather than their magnitude. Results of the SOM classification into the specified 5 x 5 = 25 nodes is shown in Figure 2. Node number and the relative percentage of the total number of events sorted into each node is shown.

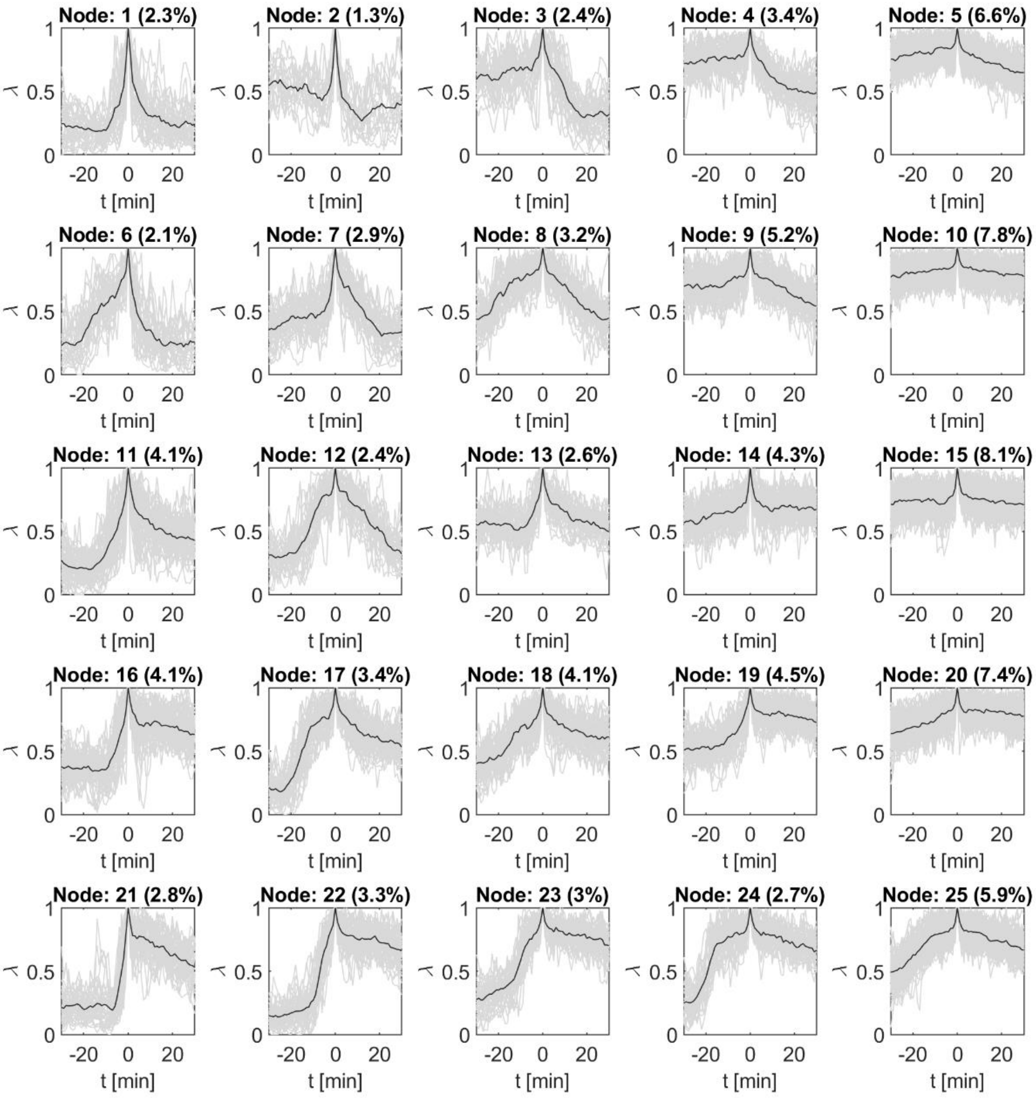

Figure 2. Mean (black) and individual event (grey) non-dimensionalised velocity time history for events classified into each node.

Some distinct groupings are evident in the SOM. For example, the top left of the grid shows clusters of highly transient events, with nodes 1 clustering events that sharply rise to a maximum and then fell away, all within around 10 – 15 minutes. The right hand side of the SOM clusters more stationary signals, with nodes 10 and 15 clustering events where the maximum velocity is (close to) reached repeatedly throughout the 1-hour period. While the SOM doesn't classify the meteorological origin of a gust, the velocity time history shape can be used to diagnose what type of meteorological events is most likely to have caused the measured winds. Node 1, again, is a good example of near-surface velocity time history expected from a small-scale microburst. Other examples could be nodes 21 and 22 where a sharp rise in velocity is observed over a few minutes with a slow decrease in velocity over half an hour or more. This type of signal is synonymous with a large-scale frontal passage. While a full classification of the meteorology of each node is beyond the scope of this paper, the nodes associated with the thunderstorm generated wind events discussed in Mason and Schwartz (2018) were identified to give a preliminary indication of which nodes may be associated with this type of wind event. Nearly half of the Mason and Schwartz (2018) events were assigned to node 1, with the others split between node 6, 11, 12 and 21.

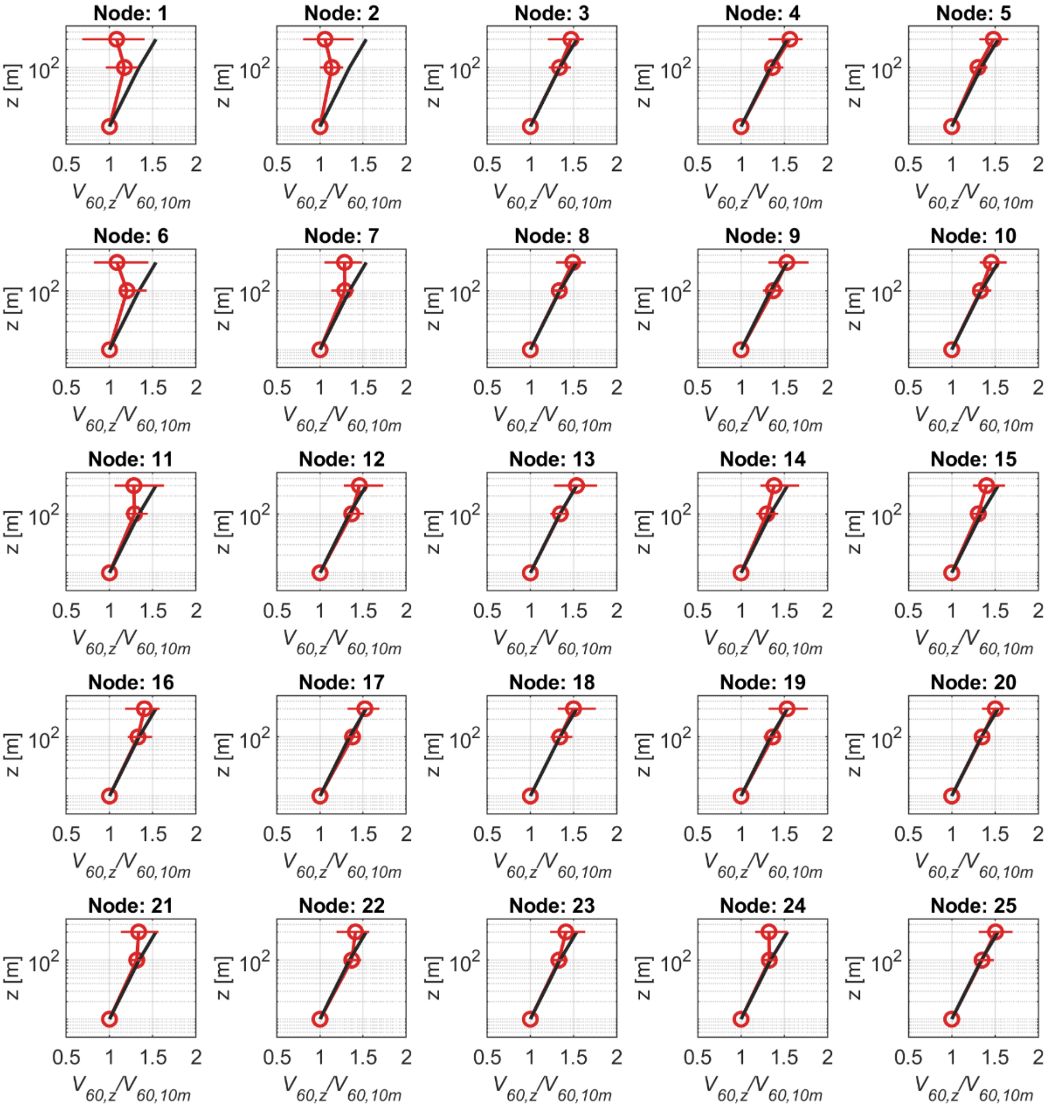

Figure 3. Measured boundary layer velocity profiles for each node. Red circles indicate the median value at each level with horizontal lines indicating the inter-quartile range. Neutral profile shown in black.

Non-dimensionalised velocity profiles were developed for each node using the profiles at and around the time of *event maximum* for each event classified into that node. Figure 3 shows these profiles for each node, where the circles indicate the median value and the horizontal lines the 25th and 75th percentile bounds of data at that elevation. While the majority of nodes display profiles very similar to the neutral profile identified in Figure 1 and shown on each of the node plots, considerable variation from the neutral profile is observed for nodes with the most highly transient time histories, i.e. nodes 1, 2 and 6. Nearby nodes, 7, 11 and 21 also show dissimilarities at the 300 m level, but remain relatively consistent with the neutral profile at 10 m and 100 m levels.

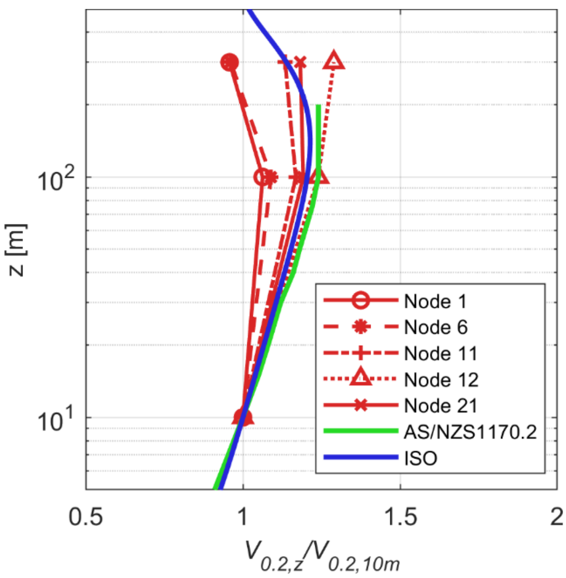

Figure 4. Comparison between estimated (median) gust velocity profiles at 'thunderstorm' nodes and the thunderstorm generated gust profiles specified in AS/NZS1170.2:2021 and ISO4354.

Extracting the median profiles for each of the nodes identified to have at least one of the Mason and schwartz (2018) thunderstorms, 1-minute velocities were converted to 0.2-second gust values, re-normalised and compared with the Region A0 velocity profile from AS/NZS1170.2:2021 and the thunderstorm profile from ISO4354:2009 in Figure 4. Results show the A0 profile to conservatively envelopes each of the node profiles below 100 m, with only one exceeding it in the upper elevations. Interestingly, the more transient the event, the higher the conservatism appears to be.

4. Conclusions

Wind events with near-surface (z = 10 m) velocities greater than 10 m/s measured at the Boulder Atmospheric Observatory (BAO) 300 m tower between 2007 and 2016 were identified and classified based on the transient characteristics of their velocity time history using a Self-Organizing Map (SOM). Comparing the median boundary layer velocity profiles for each of the sorted map nodes showed that despite differing temporal characteristics, most events displayed a profile similar to neutral conditions. However, for the few nodes associated with the most highly transient wind events, this was not the case and distinctly different profiles were observed.

References

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