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Assessment of Empirical Downburst Models Against Field Measurements of Two Thunderstorm Outflow Events

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ABSTRACT

Downbursts exhibit a strong downdraft of air that descends from a thunderstorm and causes a 'front' of damaging wind on or near to the ground level. They are highly transient, non-synoptic, short duration, and high-intensity wind events. As such, it is important to understand the loads downbursts apply to structures. For this to occur though, a good understanding of the wind fields associated with these events is required. This paper evaluates two existing empirical downburst wind field models (WFMs) against two different recorded wind events. These are, the Lubbock-Reese Rear Flank Downdraft (RFD) event that occurred on the 4th of June 2002 in Lubbock, Texas, and a thunderstorm outflow recorded by the Boulder Atmospheric Observatory (BAO) 300 m tower on 3rd September 2012. The Grey Wolf Optimization (GWO) technique has been applied to investigate and assess the downburst models explicitly. Optimization and simulation results show the importance of assessing downburst WFMs against real wind measurements and considering both downburst wind speed and direction measurement together in this assessment.

1. Introduction

Meteorological wind hazards such as downbursts generate extreme wind gusts of importance to structural design. As such, they have received attention in the wind engineering research community over the last couple of decades, with several full-scale monitoring projects of downburst winds, experimental studies, analytical modelling studies, and numerical simulations of these events undertaken. Simplified analytical downburst wind field models have been empirically developed using full-scale observations or experimentation using downburst-like impinging jet facilities. For example, Oseguera and Bowles (1988) and Vicroy (1991) developed early models based on mathematical models of atmospheric flows that were calibrated using aircraft measurements, while Wood and Kwok (1998), Holmes and Oliver (2000), Chay et al. (2006), Abd-Elaal et al. (2013), Jesson and Sterling (2018) developed models based on experimentation or numerical simulations.

Unfortunately, due to the complexity of downburst field measurements and therefore the limited set of full-scale wind data available for model verification, few studies have extensively justified these models against actual observations. In this paper, two empirical downburst wind field models (WFMs) have been evaluated against wind field measurements from two thunderstorm outflow events. These include the Lubbock-Reese Rear Flank Downdraft (RFD) on the 4th of June 2002 and a thunderstorm outflow measured at the Boulder Atmospheric Observatory (BAO) 300 m tower wind on the 3rd of September 2012. Two coupled impinging jet model-based WFMs (Holmes and Oliver (2000) and Wood and Kwok (1998)) have been tested here, with their ability to replicate both the wind speed and direction of the measured data at multiple locations within each outflow assessed. WFM parameters and estimated storm tracks were optimized using the Grey Wolf Optimization (GWO) (Mirjalili et al., 2014) technique and errors assessed using correlation coefficients. Unlike other WFM verifications, here the ability of models to simultaneously predict both wind speed and direction at multiple locations within the event will be assessed.

2. Data and Methods

Details of the wind data used are provided in Table 1. 1-min mean velocity and wind direction data has been extracted and processed from both datasets for wind events of interest. In the case of the BAO datasets, 1 event out of the 7 events identified by Mason and Schwartz (2018), is studied here. More details of the event identification and extraction procedure are described in that paper. Importantly, the geographic spread of the seven anemometer towers simultaneously sampling during the Lubbock-Reese RFD event will allow an assessment of the ability of WFMs to replicate the surface wind field over an extended region. Similarly, the presence of three anemometers simultaneously sampling velocities through the lowest 300 m of the outflow boundary layer for the BAO event will allow for an assessment of how well the vertical profiles used in WFM can replicate observations.

Table.1 Description of observation wind datasets

Data archive name	***No. of anemometer and their position***	***Available data***	***Event date***
Lubbock-Reese Rear Flank Downdraft (RFD)	11 anemometers spread over 7 towers positioned 263m apart, spanning a total distance of 1578m. Tower 1 (3m), tower 3 (10m), tower 4 (15, 10, 6, 4, 3m), tower 5 (10, 6,4m), tower 6 (10m), tower 7 (3m)	30 minutes of wind speed and direction data at each anemometer sampled at 2 Hz.	4th June 2002
Boulder Atmospheric Observatory (BAO) 300 m tower	3 anemometers at 10, 100, 300 m on a single tower	Mean wind speed and direction data are recorded every minute.	3rd September 2012

To enable the three-dimensional (3D) characteristics of downbursts to be simulated, WFMs describing the radial distribution of winds and the vertical profiles of those winds had to be coupled. Table 2 shows the two combined models assessed here, with Holmes and Oliver (2000) used to define the horizontal distribution of winds in both models and Wood and Kwok (1998) used to describe the vertical profiles of wind speed in one and a power law function (typically used for standard atmospheric boundary layers) used in the other. Both models have been coded and simulated in MATLAB. Model equations and parameters are explained in their respective papers and for brevity not repeated here. The same space and time-intensity function has been applied in both models in an attempt to simulate the dynamic nature of these events.

Table.2 Selected downburst WFMs

Downburst WFMs	***Coupled model name***
Holmes and Oliver (2000) (radial velocity profiles) + Wood and Kwok (1998)(vertical profiles)	HW
Holmes and Oliver (2000) (radial velocity profiles) + standard atmospheric boundary layer (ABL) power law profile	HABL

An optimization technique has been applied to compare the recorded and predicted velocity and direction profiles of the downburst models. Errors in predictions of both these parameters at each anemometer are combined together and assessed using three different objective functions.

Objectives 1 and 2 compare the velocity and direction profile errors separately, and objective 3 combines objective 1 and 2 errors together into a single objective by using the weighted sum method (WSM). Here, the WSM objective function is solved by considering equal weights (0.50) to normalised versions of both wind speed and direction errors, with normalisations based on the errors found for objective function 1 and 2. To determine how well each model/parameter combination fits the observed data, a correlation coefficient has been calculated. To optimize the fit variables, Grey Wolf Optimizer (GWO) technique has been investigated in this paper. This technique is used to determine how well each could fit the models to the data with the least computational time. Details of this technique are explained by Mirjalili et al. (2014).

As an example of the inputs required for each model, Table 3 shows the variables of the downburst WFMs required to be optimized, along with their selected optimization ranges. Since only velocity and direction data are available for both extracted downburst events, procedures for determining optimization ranges have been developed based on the data itself (e.g., when determining, where event tracks began), or based on historically observed downburst characteristics (e.g., size of the events, $\mathrm{r}_{\max}$) and trial and error. A minimum number of 100 iterations have been generated here for each problem by using the GWO technique.

Table 3. Optimize design variables and their limits for HW and HABL models

Variable name	***Optimisation range***	***Model***	***Description***
x_c , y_c (m)	Using assumption	HW, HABL	Model domain coordinates for initial storm location
V_{max} (m/s)	$1 \leq V_{max} \leq 40$	HW, HABL	Maximum velocity
V_{tx}, V_{ty}(m/s)	$-20 \leq V_t \leq 20$	HW, HABL	Moving velocity in x and y axis
$r_{max}\ (m)$	$500 \leq r_{max} \leq 2200$	HW, HABL	Radius of V_{max}
$T\ (s)$	$120 \leq T \leq Total\ time\ period\ (t)$	HW, HABL	Effective decay time scale
t_{max} (s)	$2\%\ of\ t \leq t_{max} \leq (2 \times t)$	HW, HABL	Maximum storm intensity time
$z_{max}\ (m)$	$10 \leq z_{max} \leq 400$	HW	Elevation of V_{max} occur
C_3	$1 \leq C_3 \leq 6$	HW	Height constant
α	$0.01 \leq \alpha \leq 1$	HABL	Power law coefficient

3. Results and Discussion

Figure 1 shows the optimized time domain plots of both models for the 3 objective cases using the Lubbock-Reese RFD recorded data at 10 m height on towers 4 and 6, which are separated by 526 m (Figure 2), as examples of predicted horizontal winds. An 18-minute time period was used at both towers for these optimizations, as this was deemed to be the period where outflow winds, exclusively, were being measured by the weather stations. It is noticed that the time domain curves are relatively similar for both tower cases, which is largely a result of the two towers being relatively near to each other with respect to the size of the outflow.

Inspecting objective 1 (i.e. optimizing against velocity data) results in more detail, Figure 1 (a to d) indicates a reasonable matching between observed and optimized horizontal velocity profiles (particularly during the peak of the event) for both models and for both tower cases. Over the full-time history, the correlation coefficient in all cases was greater than 86%. However, when inspecting the predicted direction for these simulations it is clear that the direction profiles do not match in any of these cases. In fact, they have the storm travelling in the wrong direction (see in Figure 2). Inspecting objective 2 results (i.e. optimizing against direction), the direction predictions are shown to be much improved, with both model cases correlated more than 90%. However, now the predicted velocity profiles do not match the recorded RFD velocity data well and consistently overestimate in all cases. Inspecting objective 3 (i.e. optimized against wind speed and direction data) results, both models illustrate relatively good agreement in terms of matching both the recorded and predicted wind speed and direction profiles. The correlation between observed and optimized velocity and direction profiles for both models are approximately 85%, and 90% respectively.

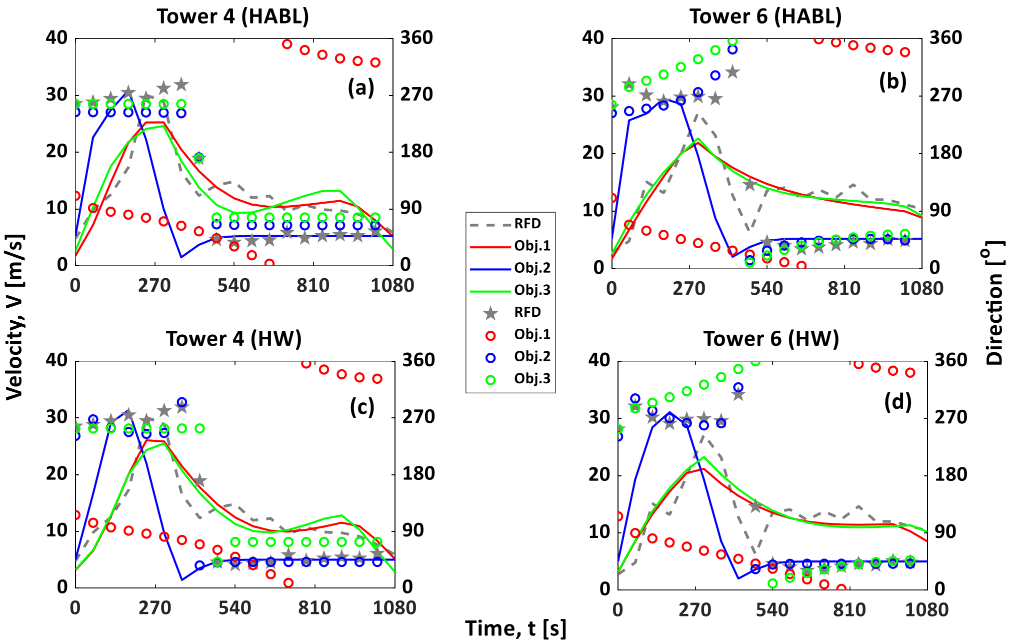

Figure 1. Time-domain profiles after optimization for HABL model (a, b), and HW model (c, d) using RFD wind events [Here, lines and markers represent wind velocity and direction respectively].

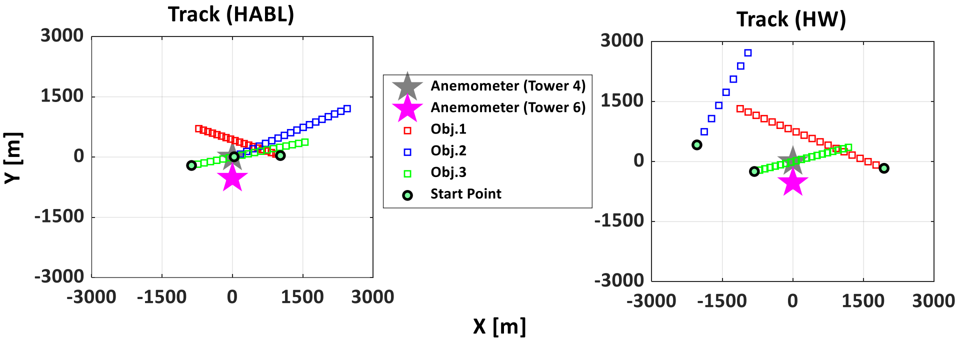

Figure 2. Track plots for the Lubbock-Reese RFD wind event.

Figure 2 illustrates the predicted storm tracks for both the HABL and HW model when using the 3 objective solutions, which indicates variable predicted storm behavior for many of the cases. In fact, when fitting to the velocity alone (objective 1), the storm is predicted to track from east to west, which is opposite to the other two objective cases and is in direct contradiction of what is seen in the radar imagery for the event (GAST, 2003). This clearly shows potential errors that may arise when not considering all available information about the wind field within an optimization. Similarly, inspecting results for objective 2, while direction is reasonably well predicted with the optimized model, wind speed is poorly predicted. This is the case for both models and at both stations shown. Objective 3 fitting does a much better job at finding a solution that predicts both the wind speed and direction observations reasonably well, but also does not find a solution that matches throughout the entire time history shown. This is particularly evident at Tower 6, where neither the peak of the event or the drop-in wind speed that is measured as the storm moves over the tower array fit with any great accuracy. This fitting is even worse when moving to towers further from Tower 4 (i.e. where the center of the model track crosses the tower array). This, we hypothesize to be due to the idealized nature of the wind field models utilized not being able to capture the true physical characteristics of this event. In particular, given a fixed r_{max} is used, the storm effectively maintains the same physical size throughout the event. Given most RFD events have diverging fronts (which can contain the strongest winds), this may not be appropriate. Also, inspecting the radar imagery shown in (GAST, 2003), it is evident that the outflow is not divergent around a circular downdraft, so forcing this assumption within the wind field models may also be inappropriate.

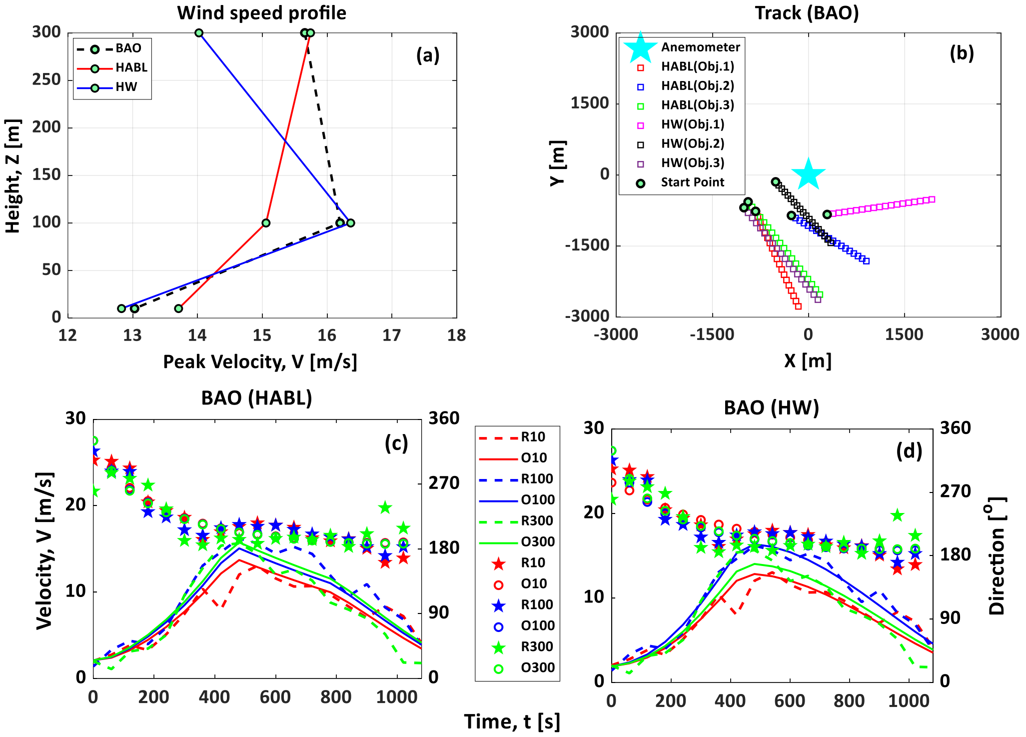

Figure 3. Wind profiles of peak optimized winds at multiple levels (a), track plot (b), time-domain plots of HABL (c) and HW (d) models using objective 3 solutions of BAO wind events [In figures (c and d), lines and markers represent wind velocity and direction respectively].

Moving to the BAO event, Figure 3 shows the measured and simulated velocity profiles, track plot and optimized time domain plots of both models using objective 3 solutions when considering fitting at all three elevations (i.e. 10,100,300 m) with the GWO optimization method. Figure 3 (a) shows the envelope velocity profile, being the peak 1-minute winds predicted at a given elevation over the entire observation or simulation period. Both modelled profiles differ from each other with their shapes governed by the vertical velocity profiles the model functions impose. At 10m height, the optimized peak values of the HABL model are slightly larger than observed at that anemometer, but the HW model is able to match this peak value with accuracy. Looking at 100 m, as expected the wind speed profile shape is larger than the 10 m wind speed in both model cases. At this height, the HABL model optimized peak value are smaller than the observed peak value, with the HW again matching the observed data well. At 300 m, the opposite is true and the HABL model matches the observed data well, with the HW model underpredicting it. Considering the velocity profiles imposed by both the Wood and Kwok (1998) model and that of a power law, these observations are not surprising. They do, however, highlight the fact that neither a steady impinging jet or standard boundary layer profile appropriately match the envelope outflow boundary layer in this case.

Similar to the RFD wind event, objective 3 calculations produce the best overall model fits to the observed data. Both velocity and direction time histories for HABL (Figure 3 (c)) and HW models (Figure 3 (d)) fit the BAO wind event reasonably well and generally for at least two heights. However, it is evident from these records that relationship between velocities at different elevations can change throughout the event, so for a model to fit this well, it will require the versatility to adjust the profile shape with time. Overall, optimized direction profiles are reasonably well predicted at each level for both model cases. The correlation of observed and optimized BAO velocity events at multiple levels was 90% for both models, but the direction correlation was reduced to around 80%.

4. Conclusions

The importance of fitting wind field models to both wind speed and direction time histories has been highlighted, with inaccurate storm behavior (e.g. storm tracks) predicted when not considering both. For the Lubbock-Reese RFD event, both models tested did a reasonable job replicating the wind field at one or two anemometers, but struggled to fit to all spatially dispersed locations. Inaccuracies were also found in the vertical profiles predicted by both models for the BAO example event. This occurred because in the case shown the boundary layer profile switches between something resembling an ABL (or even uniform profile) to something more consistent with the generally expected nose shaped downburst profile part way through the event. These observations highlight the need for versatility within downburst models and exemplifies the complexity that real events exhibit and which these models must incorporate.

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