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Jesson, M, Lombardo, FT, Sterling, M  and Baker, C (2019) The physical simulation of a transient, downburst-like event – How complex does it need to be? *Journal of Wind Engineering and Industrial Aerodynamics*, 189. pp. 135-150. ISSN 0167-6105

DOI: <https://doi.org/10.1016/j.jweia.2019.03.021>

Publisher: Elsevier BV

Version: Accepted Version

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The physical simulation of a transient, downburst-like event – how complex does it need to be?

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Abstract

There has been much debate of late regarding the physical simulation of downbursts and, in particular, the need to construct large-scale, relatively expensive facilities in order to obtain wind loading data. For the first time, this paper illustrates that, through the use of partial turbulence simulations and quasi-steady analysis, it is possible to capture the both the loading due to the large-scale features present in downburst flows and the local peaks due to smaller scales of turbulence. These findings have considerable implications for future analysis of transient winds.

1 Introduction

Thunderstorm downbursts are transient, non-synoptic wind events which form in storm convection cells. Although generally less well known than other non-synoptic events such as tornadoes, downbursts are the cause of the building design wind speeds in many parts of the world (Chay and Letchford, 2002a).

The rapid cooling of warm, moist air rising in a convection cell, expedited by evaporation of precipitation (Wakimoto and Bringi, 1988), creates a mass of cold, dense air. Thus the motion is reversed and a downdraft is formed, with a ring vortex forming around the edge of the downdraft region (see Vermeire et al (2011) for details). When the downdraft hits the ground a stagnation region forms, driving a radial outflow which carries this vortex (which has a height of ~0.7-1km (Hjelmfelt, 1988)) with it (Fujita, 1981). The combination of the outflow and the ring vortex leads to high wind speeds in the near ground region with, the maximum velocity occurring at a height $z_m = 30-100\text{m}$ above the ground (Fujita and Wakimoto, 1981; Hjelmfelt, 1988). Further flow acceleration has been attributed to the formation of a counter-rotating secondary vortex at the leading edge of the primary (ring) vortex, as seen in numerical simulations (Kim and Hangan, 2007; Mason et al., 2009b). The downburst flow field experienced by a structure, or measured by a fixed anemometer, is further complicated by the translation of the entire downburst as it moves within the parent storm. This translation results in large changes of wind direction as the impingement point moves relative the structure itself, and direction changes are also seen around the time of peak velocity (Lombardo et al., 2018) though these changes take place over timescales of the order of tens of seconds or greater.

Microbursts, as Fujita (1981) terms the most intense downbursts, are relatively small in both temporal and spatial scale, with a downdraft diameter of approximately 1km and a period of extreme wind speed lasting approximately 5 minutes (Fujita, 1981; Holmes et al., 2008). This presents difficulties in recording full-scale events or making full-scale measurements of wind loading on structures during a downburst. Historic projects such as NIMROD and JAWS (Fujita, 1981), and the more recent Thunderstorm Outflow Experiment (Gast and Schroeder, 2003; Holmes et al., 2008)

41 have succeeded in recording a small number of full-scale downbursts. When considering wind
42 loading on structures, the unpredictability of where and when a downburst will strike makes it very
43 difficult to obtain full-scale pressure measurements over a structure – the chances of a single,
44 instrumented building being subject to a downburst are extremely small. Lombardo (2009) has,
45 however, successfully identified a small number of downburst events from historical velocity data
46 recorded at the Texas Tech University Wind Engineering Field Research Laboratory (WERFL), and
47 examined the corresponding pressure data from tappings over the WERFL building (a 9m x 14m x 4m
48 tall, rectangular plan building) – with one case recently detailed in Lombardo et al. (2018)..

49 Although Lombardo et al. have successfully measured downburst wind loading at full-scale, their
50 data is limited to a single type of building and is unavoidably restricted in the range of parameters by
51 the events which have occurred at the field site. Therefore, as with Atmospheric Boundary Layer
52 (ABL) studies, physical simulation is required to determine downburst wind loading on different
53 types and style of structure. A number of physical simulation methods have been applied in order to
54 model downbursts at laboratory-scale: very small-scale density driven flows (e.g. Lundgren et al.,
55 1992); multi-fan wind tunnels (e.g. Butler et al., 2010); slot jets (e.g. Butler and Kareem, 2007; Lin et
56 al., 2007); steady and pulsed impinging jets (e.g. Chay and Letchford, 2002a, 2002b; Choi, 2004;
57 Wood et al., 2001; Zhang et al., 2014, 2013 and Haines et al., 2013; Jesson et al., 2015b, 2015a;
58 Mason et al., 2009a; McConville et al., 2009 respectively). The development of the pulsed jet and
59 slot jet simulators has been driven by the assumption that it is necessary to simulate the transient
60 nature and vortices of a full-scale downburst. The latter has been considered a requirement due to
61 the approximately building-scale primary and secondary vortices which are a feature of many
62 downbursts, with the implicit assumption that the vertical component is non-negligible and must be
63 simulated. Surprisingly, despite the efforts made to generate these vortices and their vertical
64 velocity, these studies have tended to focus solely on the radial (horizontal) velocity component for
65 validation of the wind field.

66 The development of these simulators has permitted wind loading on a variety of model-scale
67 structures to be measured. Direct measurements of loading on pressure tapped building models
68 have been made (e.g. Chay and Letchford, 2002b, 2002a; Jesson et al., 2015b, 2015a; Mason et al.,
69 2009a). Additionally, the physical simulation data has been used to validate CFD simulations which
70 have then been applied to calculate loading on, and failure of, power transmission lines exposed to
71 downbursts (e.g. Aboshosha and El Damatty, 2015; Shehata et al., 2005). Although such projects
72 provide valuable loading data, the number of types of structures for which data is currently available
73 is limited. The complexity of the simulators makes them expensive and the experimental process
74 slow, while the small scale (1:1600 in the work of Jesson et al., for example) limits the
75 measurements which can be made, the size and detailing of the models and precision of probe
76 placement. As a consequence, current design codes either have no provision for downburst loading,
77 or simply apply a factor to ABL loading pressure coefficients.

78 This paper determines whether such complex physical simulations are required for downburst wind
79 loading studies. Data from full-scale downburst events is analysed, focussing on the length scales of
80 the large- and small-scale structures of the wind field and the vertical velocity component at building
81 height. This introduction is followed by a discussion of pertinent theory (Section 2), the methodology
82 applied (Section 3), and in Section 4 by a presentation and discussion of the results. The paper
83 concludes with a summary of the important implications of this work.

84 2 Background

85 2.1 Non-Stationary Analysis

86 In the case of statistically stationary winds, the turbulence intensity of a velocity component, I_x
87 (where $x = u, v, w$, and u, v and w are the instantaneous, raw streamwise, lateral and vertical
88 velocity components respectively), is generally defined as the ratio of the standard deviation of the
89 component, σ_x , to the mean streamwise velocity, U (Holmes, 2001):

$$I_x = \frac{\sigma_x}{U} \quad (1)$$

90 Downburst wind fields are statistically highly non-stationary, and as a consequence, this definition is
91 problematic as neither σ_x nor U are clearly defined in the case of a non-stationary time-series. While
92 there is currently no standard method for doing so, a time-varying streamwise turbulence intensity
93 may be calculated by decomposing the streamwise velocity time-series into a time-varying mean,
94 $U(t)$, and a residual fluctuating component, $u'(t) = u(t) - U(t)$ (similarly for v' and w'). This
95 decomposition has previously been achieved through two methods. The first is through defining
96 $U(t)$ as a simple, N -point moving average (Holmes et al., 2008). In previous studies N has been
97 taken as a value which is judged "reasonable" based on the resulting $U(t)$ and $u'(t)$ time-series
98 capturing the main flow features and having a near-zero mean respectively (Holmes et al., 2008).
99 However, the effective cut-off frequency, f_c , of a moving average filter applied to a time-series
100 sampled at rate f_s , with averaging over a period $\Delta t = f_s N$ may be estimated as (Asghari Mooneghi
101 et al., 2016):

$$f_c \cong \frac{0.45}{\Delta t} \quad (2)$$

102 if $f_s \gg f_c$.

103 The second method is wavelet decomposition (Jesson et al., 2015b; Wang, 2007; Wang and Kareem,
104 2004; a similar approach has been applied by Chen and Letchford, 2005). Wavelet analysis uses the
105 convolution of scaled and translated versions of a parent wavelet to determine the time-varying
106 power spectral density of a time-series. The parent wavelet can have a variety of forms, but must be
107 defined by a zero-mean function which is localised in time and frequency (Torrence and Compo,
108 1998).

109 The Continuous Wavelet Transform (CWT) algorithm (Torrence and Compo, 1998) outputs a 2-D
110 matrix of wavelet coefficients, each corresponding to a wavelet scale and time. The scales may be
111 converted to a pseudo-frequencies through multiplication by an appropriate velocity scalar. In what
112 follows, the pseudo-frequency is referred to simply as frequency for convenience. In order to
113 decompose the time-series, those coefficients corresponding to frequencies above (or below) the
114 required cut-off frequency are set to zero and the inverse CWT algorithm (Erickson, 2016) applied to
115 give the low-frequency (or high-frequency) component.

116 Once the signal has been decomposed into $U(t)$ and $u'(t)$ the time-varying $I_u(t)$ is calculated as:

$$I_u(t) = \frac{\overline{\sigma_{u,T}(t)}}{\overline{U_T(t)}} \quad (3)$$

117 where overbar and subscript T indicate the time-mean over an interval of T seconds around time t
118 (Holmes et al., 2008; Wang et al., 2013).

119 In application to downburst flows, a second issue with the definition of turbulence intensity in (1)
 120 arises. Implicit in (1) (and consequently (3)) is the assumption that mean velocities in the lateral and
 121 vertical directions are negligible, i.e. that the mean flow speed may be approximated as U , and the
 122 flow has a clearly defined streamwise direction. This will not be the case for a downburst flow field,
 123 which is frequently modelled as a combination of large-scale vortices (e.g. Fujita, 1985; Mason et al.,
 124 2009b). In order to account for these additional non-negligible components, (3) has been amended
 125 to:

$$I_x(t) = \frac{\overline{\sigma_{x,T}}(t)}{S_T(t)} \quad (4)$$

126 where $S(t)$ is the instantaneous wind speed:

$$S(t) = \sqrt{u^2(t) + v^2(t) + w^2(t)} \quad (5)$$

127 Clearly this change will have negligible effect if $v(t)$ and $w(t)$ are approximately zero-mean.

128 2.2 Quasi-Steady Theory

129 Quasi-steady (QS) theory assumes that the pressure at a point on the building envelope is
 130 proportional to a dynamic pressure, $\frac{1}{2}\rho U_{ref}^2$, calculated from a reference wind speed, U_{ref} , and the
 131 air density, ρ (Letchford et al., 1993). The constant of proportionality is the pressure coefficient, C_p ,
 132 with the differential pressure, Δp (pressure relative to a reference pressure), given by:

$$\Delta p = C_p \frac{1}{2} \rho U_{ref}^2 \quad (6)$$

133 For ABL flow, time variation of the pressure field due to turbulence is incorporated through the use
 134 of instantaneous wind speed, $U_{ref}(t)$:

$$\Delta p(t) = \frac{1}{2} \rho C_p U_{ref}^2(t) \quad (7)$$

135 C_p varies over the building envelope (Figure 1) thereby accounting for, for example, regions of flow
 136 separation (in which $C_p < 0$) on the roof and leeward face, and high pressure regions on windward
 137 faces (where $C_p > 0$). It is clear that as the angle of the incoming wind (the azimuth, θ) varies then
 138 these regions change location on the building. Consequently C_p at a particular point is a function of
 139 θ and, similarly, C_p is dependent on the angle of the wind to the horizontal, the elevation, β . Hence
 140 $C_p = C_p(\theta, \beta)$ (Wu and Kopp, 2018, 2016) and is inherently time-varying since u , v and w vary with
 141 time:

$$\theta = \tan^{-1} \left(\frac{v(t)}{u(t)} \right) \quad (8)$$

$$\beta = \tan^{-1} \left(\frac{w(t)}{\sqrt{u^2(t) + v^2(t)}} \right) \quad (9)$$

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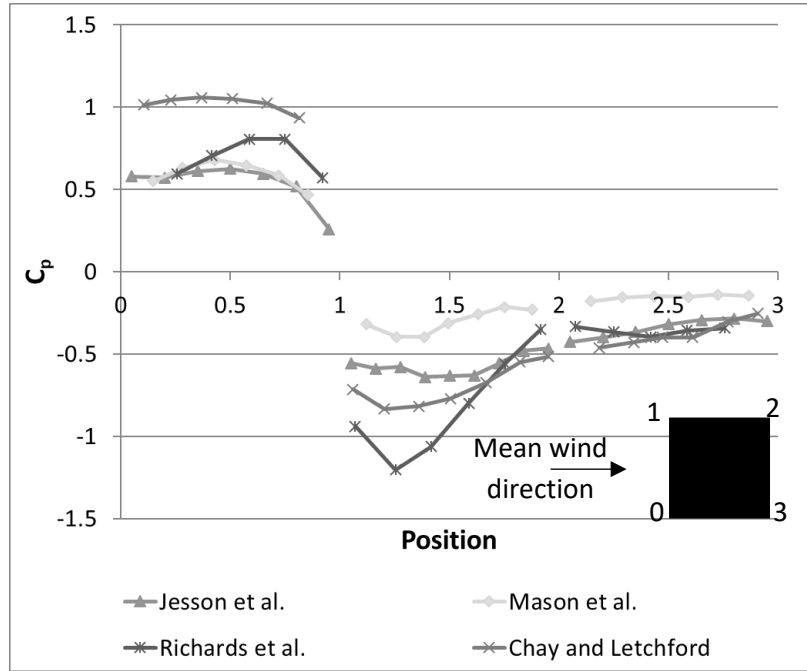


Figure 1 C_p along the centreline of a cubic building with azimuth $\theta = 0^\circ$. Adapted from Jesson et al. (2015b). Original data from downburst simulations (Jesson et al. (2015b), Mason et al. (2009a), Chay and Letchford (2002a)) and full-scale ABL flow (Richards et al. (2001)).

158 For practical application, i.e. calculation of wind loading under expected wind fields, C_p must be
159 quantified for the type of building and the expected range of θ and β . This is generally achieved
160 through physical simulations in which Δp and U_{ref} are measured simultaneously and θ and β are
161 varied by rotation and tilting of the building model (e.g. Letchford and Marwood, 1997; Richards and
162 Hoxey, 2004). From such tests it has been found that if v and w are assumed to be small relative to
163 u then the variation in C_p with angle may be represented by a simple, linear expansion (Letchford et
164 al., 1993):

$$C_p(\theta, \beta) = C_p(\bar{\theta}, \bar{\beta}) + \left(\frac{v}{U}\right) \frac{dC_p}{d\theta} + \left(\frac{w}{U}\right) \frac{dC_p}{d\beta} \quad (10)$$

165 where overbars (angles) and capitals (velocities) indicate time-mean values. Conversely, Richards et
166 al. (1995) show that for larger v (w was not considered) the pressure coefficient data for a tapping
167 at the leading roof edge of a building is periodic in θ and so a fitted Fourier series gives a good
168 approximation:

$$C_p(\theta) = \sum_{k=0}^N a_k \cos(k\theta) + b_k \sin(k\theta) \quad (11)$$

169 where a_k and b_k are the fitted Fourier coefficients. As any such function $C_p(\theta)$ is necessarily
170 periodic over the range $-\pi \leq \theta < \pi$, it should be possible to determine an equivalent Fourier series
171 for any tapping position.

172 In the discussion which follows it is assumed that experiments may be designed to measure C_p for all
173 required combinations of θ and β .

174 2.3 Partial Turbulence Simulation

175 Richards and Hoxey (2004) note “that a quasi-steady model cannot be expected to account for every
176 effect”, and it is recognised that peak wind pressures are influenced by both large-scale turbulence
177 (accounted for by quasi-steady theory) and small-scale turbulence in the incoming wind field which
178 interacts with building generated turbulence and shear layers (Asghari Mooneghi et al., 2016); the
179 effects of the latter cannot be modelled by quasi-steady theory, a limitation which is accepted for
180 ABL simulations. Asghari Mooneghi et al. (2016) considered the relevance of these two scales of
181 turbulence in wind tunnel modelling of a low-rise building. In contrast to the modelling of high-rise
182 buildings, which typically requires model scales smaller than 1:300, modelling low-rise buildings at a
183 practical size requires large model scales. At these larger model scales, the large-scale turbulence of
184 ABL flow cannot be simulated within a standard wind tunnel (Asghari Mooneghi et al., 2016; Wu and
185 Kopp, 2018). This limitation can be mitigated through “Partial Turbulence Simulation” (PTS), in
186 which the contribution of small-scale turbulence is quantified through wind tunnel experiments in
187 which these small-scales are correctly simulated, with a quasi-steady approach used to account for
188 the large-scale turbulence in post processing (Asghari Mooneghi et al., 2016). Comparison with full-
189 scale data showed that peak pressure coefficients “agreed well enough” (Asghari Mooneghi et al.,
190 2016), with the largest errors being around 20% and generally much lower. Asghari Mooneghi et al.
191 make an assumption which is problematic when directly applying their method to a transient event -
192 the streamwise high frequency turbulence intensity, I_{uH} :

$$I_{uH} = \frac{\sigma_{uH}}{U + u_L} \quad (12)$$

193 is assumed constant (subscripts L and H signify low and high frequency components, i.e. small- and
194 large-scale turbulence, respectively). As has been shown (e.g. Holmes et al., 2007; Jesson et al.,
195 2015b) this is not the case for downbursts. However, the main application of this assumption is in
196 the determination of the boundary frequency between large- and small-scales, which includes the
197 somewhat arbitrary ratio of 1:10 for the building height to the cut-off length scale. Wu and Kopp
198 (2018) further investigated the PTS approach in a set of wind tunnel tests investigating upstream
199 roughness/turbulence effects, again focussing on the roof of a low-rise building, with $13\% \leq I_u \leq$
200 27% and azimuths $0^\circ \leq \theta \leq 90^\circ$. Elevation variation was purely due to turbulence in the flow (i.e.
201 their models were not tilted). Building surface pressures were measured simultaneously with wind
202 velocity at one roof height above the leading edge of their building model. Through examination of
203 the coherence between quasi-steady predictions and measured pressure coefficient, Wu and Kopp
204 determined that $5H$, where H is the building height, was an appropriate cut-off scale for low-rise
205 buildings.

206 Both Asghari Mooneghi et al. (2016) and Wu and Kopp (2018) define the boundary frequency
207 between small and large-scale turbulence in terms of the building height. It should be noted that (as
208 stated by the former) the matching of this frequency at model and full-scale is based on some
209 representative length rather than the height specifically, with the height considered appropriate for
210 low-rise buildings.

212 3 Methodology

213 In the current paper, the requirement for transient physical simulations of downburst wind fields is
 214 assessed by examination of two factors:

- 215 1) The extent to which the transient flow field can be modelled using a quasi-steady approach,
 216 with small-scale turbulence being a zero-mean time-series, the effects of which can be
 217 accounted for in a similar manner to the PTS approach.
- 218 2) The importance of the vertical component of velocity (as discussed later, the lateral
 219 component is assumed negligible), which is predicted to exist due to the ring and secondary
 220 vortices of a “standard” downburst.

221 The data analysed are full-scale, horizontal and vertical wind speed data recorded at the Texas Tech
 222 University Wind Engineering Research Field Laboratory (WERFL) field site during five transient wind
 223 events identified as downbursts. Details of the site and transient wind detection are given by
 224 Lombardo et al. (2014). Briefly, the original WERFL, which was equipped with a 50m anemometer
 225 tower, was moved to a new site with a 200m tower in early 2006. The data were recorded by a
 226 network of anemometers at WERFL, with anemometers at height above ground, z , ranging from 1m
 227 to 200m. Data are not available for all events at all heights; details are given in Table 1. All
 228 anemometers were sampled at 30Hz. Both sites are classified as “open terrain” with z_0
 229 approximately 0.015m. Additionally, a single stationary record of ABL flow from the same site has
 230 been processed in the same manner as a baseline.

231 **Table 1 Anemometer heights for the recorded full-scale events**

Date → z (m) ↓	Stationary	19 June 2003	21 May 2008	19 June 2008	13 August 2008	08 March 2010
200	x		x	x	x	x
158	x		x	x	x	x
75	x					x
49		x				
47	x					x
21		x				
17	x					x
10	x	x	x	x	x	x
4	x	x	x	x	x	x
2		x	x	x	x	
1			x	x	x	

232 The anemometers record horizontal and vertical wind speeds, rather than 3-D velocities. Henceforth
 233 it is assumed that, as the downburst flow is driven by a localised impingement point which results in
 234 high-speed radial winds, the flow may be treated as a 2-D flow with only streamwise and vertical
 235 components and negligible lateral velocity, i.e. $v(t) \equiv 0$. It should be noted, however, that the
 236 streamwise direction is not fixed and may vary over timescales of minutes due to storm translation,
 237 as discussed in Section 1.

238 Wavelet decomposition (depicted in a flow chart in the Appendix for clarity) has been performed
 239 using the Morlet wavelet, $\psi_0(\eta)$, where η is a dimensionless “time”. This is a modulated sinusoid
 240 defined as (Torrence and Compo, 1998):

$$\psi_0(\eta) = \pi^{-\frac{1}{4}} e^{i\omega_0\eta} e^{-\frac{\eta^2}{2}} \quad (13)$$

241 and was chosen due to its relationship to the sinusoids of the Fourier transform for a stationary
 242 time-series. ω_0 is the non-dimensional frequency. The cut-off frequency was based on the $5H$ limit
 243 of Wu and Kopp (2018), with a building heights of $H = 6m$ giving a cut-off scale of $30m$. Data up to
 244 a height of $z = 200m$ has been analysed, well above the height of a low-rise building. These data
 245 are put into context in the discussion of application in Section 5.2. An additional building height of
 246 $30m$ (corresponding to the upper end of the “low-rise” limit specified for downbursts by Jesson et
 247 al. (2015a)) has also been applied in a small number of cases to demonstrate its impact. Differences
 248 between this limit and the $10H$ limit of Asghari Mooneghi et al. (2016) were examined but found to
 249 be negligible (as demonstrated in Section 4). The Fourier periods returned by the CWT algorithm
 250 were converted to length scales through scaling by a representative streamwise wind speed, u_R :

$$u_R = u_{min30} + \frac{1}{2}(u_{max30} - u_{min30}) \quad (14)$$

251 where u_{max30} and u_{min30} are the maximum and minimum of $u_{30}(t)$ ($u(t)$ smoothed with a 30
 252 second moving average. This moving average period was deemed to adequately smooth extremes. It
 253 is accepted that a different period, and indeed a different definition of u_R , may be applied. The aim
 254 of this process is, however, simply to obtain a representative speed for the conversion of the Fourier
 255 periods to approximate length scales, and so this method is considered appropriate). The first length
 256 scale exceeding $5H$ was identified, and taken to be the cut-off scale, corresponding to the cut-off
 257 frequency.

258 It is noted that the applicability of this $5H$ limit has not been proven for buildings as tall as $30m$, but
 259 it seems reasonable to assume that, if anything, the factor of 5 would be reduced in this case as the
 260 ratio of height to breadth and length increases. Consequently, retaining this relationship represents
 261 an extreme case in which medium-scale turbulence is included as “small” rather than “large”. From
 262 this decomposition, the time-varying turbulence intensity and the form of the residual (high
 263 frequency) velocity are examined.

264 For comparison, decomposition has also been performed using a moving average decomposition. In
 265 this case, the moving average period was determined via (2) by setting f_c as used for the wavelet
 266 decomposition.

267 u_R was also used to define the period of highest wind speeds (“peak period”), taken as the period
 268 around the time of the maximum of $u_{30}(t)$ for which $u_{30}(t) \geq u_R$.

269 Integral length scales have been calculated as the integral of the autocorrelation function, $A_x(\tau)$
 270 ($x = u, w$; τ is the time offset) for the range $0 \leq \tau \leq \tau_0$ (τ_0 is the first value for which $A_x(\tau) \leq 0$),
 271 scaled by u_R :

$$A_x(\tau) = \frac{1}{\sigma_x^2} \int_{t=0}^{t=T} x(t)x(t-\tau) dt \quad (15)$$

272

$$L_x = u_R \int_{\tau=0}^{\tau=\tau_0} A_x(\tau) d\tau \quad (16)$$

273

274 To investigate the vertical component of velocity, (9) was applied to the low-frequency time-series
275 (similar results are obtained from the unfiltered time-series) to calculate the elevation angle time-
276 series, $\beta(t)$. The wind speed measurements, $S(t)$, were split into bins based on the corresponding
277 $\beta(t)$, with 5 degree bin widths, and the maximum wind speed from each bin identified to produce
278 an elevation-based, maximum speed wind rose, used in Section 4.2.2. The duration of periods of
279 “High-Speed, Large-Elevation” (HSLE) velocities were determined through cross-referencing the wind
280 speed and elevation angle time-series. Continuous periods during which the wind had both a speed
281 and elevation angle from the horizontal exceeding threshold values were identified, and the
282 duration of each such section (the “HSLE Duration”) calculated. A parametric study of the HSLE
283 Duration was carried out, with a small range of speed and elevation thresholds. Due to the variability
284 of the maximum wind speed, S_{max} , from event to event, the speed thresholds were set relative to
285 this maximum, at $S_{max}/4$, $S_{max}/3$ and $S_{max}/2$. These factors were chosen as the smallest of these,
286 $S_{max}/4$, would represent a wind speed of approximately $17ms^{-1}$ (approaching gale force) for an
287 extreme microburst such as that recorded at Andrews Air Force Base (Fujita, 1985), and the others
288 are convenient scalings. Elevation thresholds of 30° and 45° were used, based on an initial analysis
289 of the elevation angles which occurred.

290 **4 Results and Analysis**

291 *4.1 Stationary Data*

292 The stationary data (Figure 2) follow the standard log-law profile, with increasing mean speed with
293 height (Figure 3). Turbulence intensity, I_u , is relatively low (17% at $z = 4m$) but consistent with the
294 site terrain ($z_0 \cong 0.015$ (Lombardo et al., 2014)) and the corresponding ESDU profiles (ESDU, 2001),
295 and decreases with altitude as expected (Figure 3).

296 The time-varying I_u also decreases with height (not shown) and is generally below the stationary I_u
297 value (Figure 4). This is consistent with the decomposition approach, in which the larger scales of
298 turbulence are incorporated in the time-varying mean. By definition, the time-varying I_u depends on
299 the building height due to the $5H$ scale boundary. As building height increases the cut-off scale is
300 increased, resulting in more Fourier Periods included in $u'(t)$ and a larger $\sigma_{u'}$, and vice-versa. The
301 time-varying I_u is therefore increased for $H = 30m$ (Figure 4(b)). The wavelet decomposition and
302 moving average decomposition follow the same trends, with differences at extreme values (Figure
303 5). It is clear that, unlike the stationary I_u (which is seen as an absolute characteristic of the wind
304 field), the time-varying I_u must be treated with caution, particularly when making comparisons
305 across applications.

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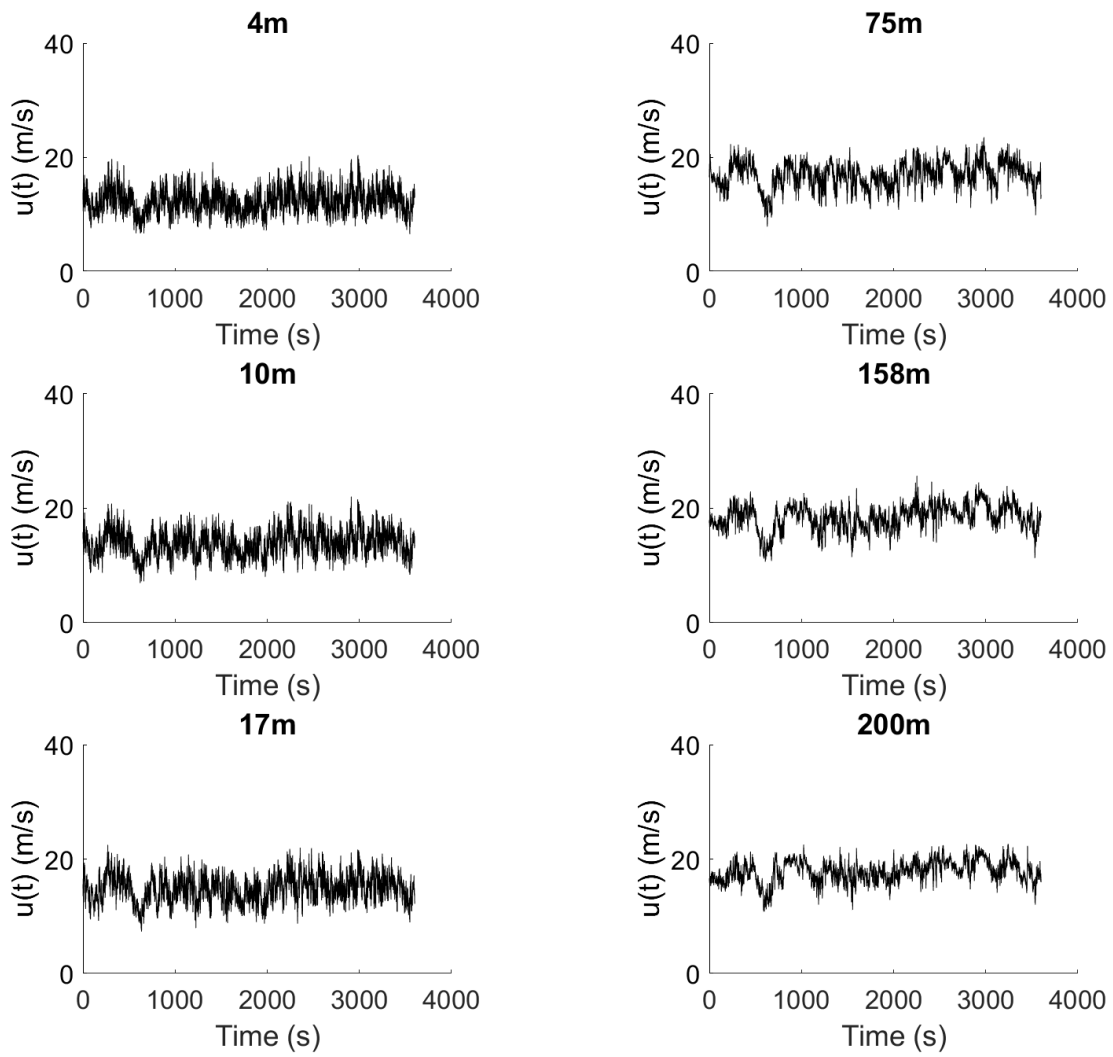


Figure 2 Streamwise velocity data for ABL flow at the test site

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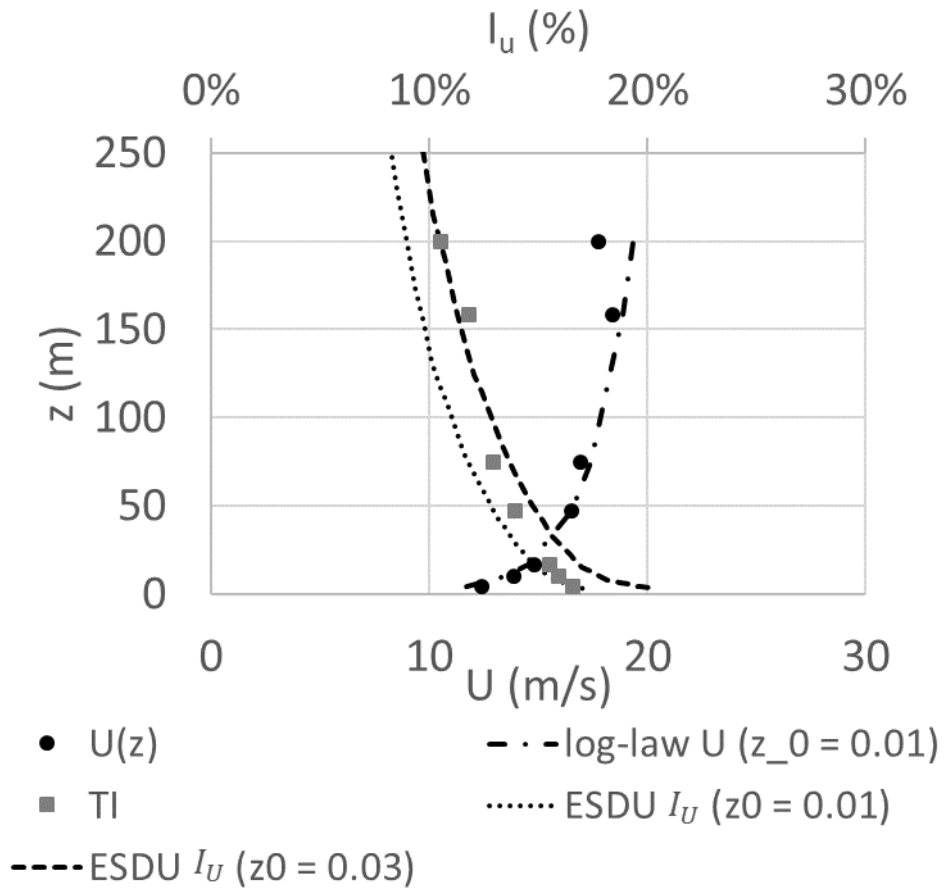
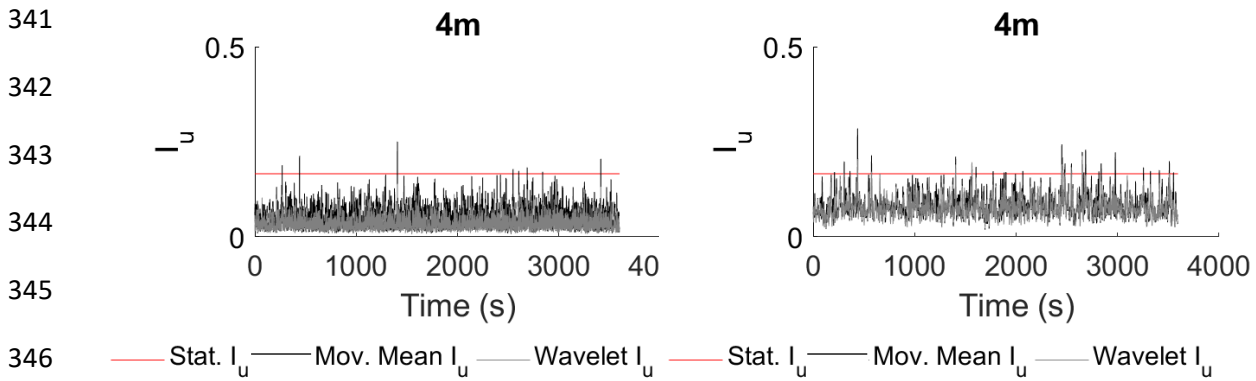
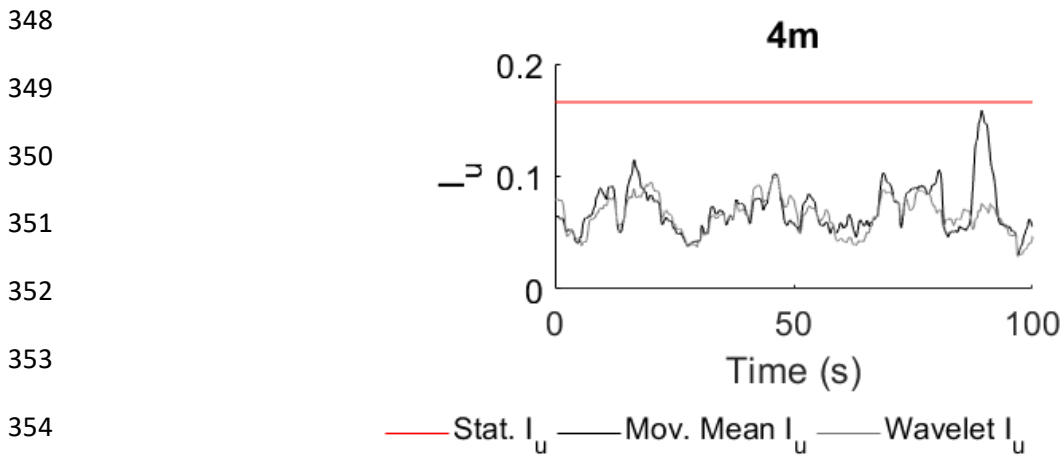


Figure 3 Mean wind speed and turbulence intensities for the stationary data

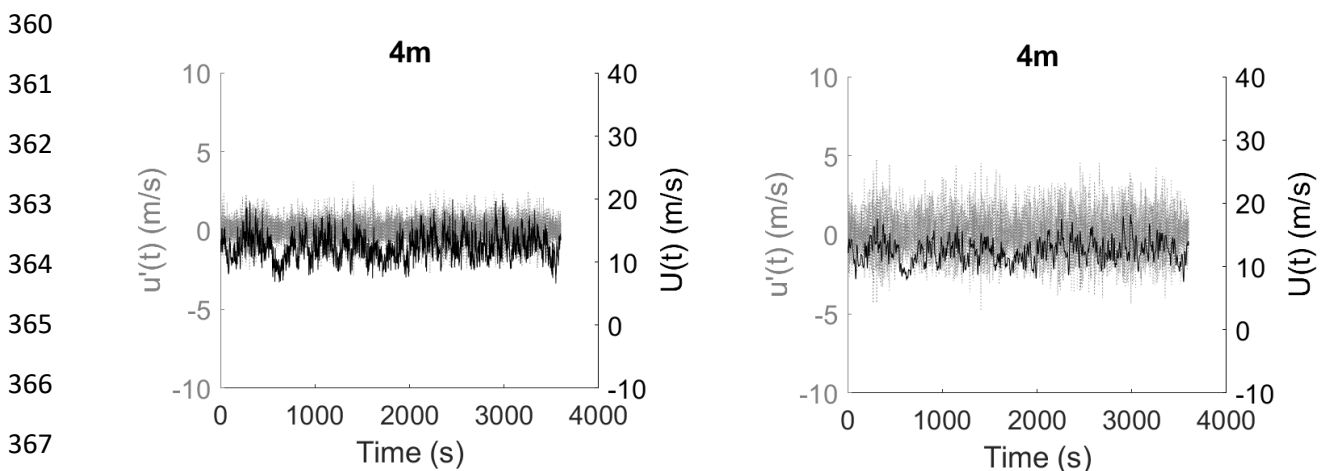


347 **Figure 4** Turbulence Intensity of the stationary signal at $z = 4m$ with (a) $H = 6m$ and (b) $H = 30m$



355 **Figure 5** Sub-section of the turbulence Intensity of the stationary signal at $z = 4m$ with $H = 30m$

356 The effect of this change of cut-off frequency is also apparent in the high- and low-frequency
 357 decomposition (Figure 6). For the higher building ($H = 30m$) the low-frequency wind speed, $U(t)$,
 358 is smoothed in comparison with the low-rise case ($H = 6m$), while the root-mean-square (RMS)
 359 high-frequency wind speed, $u'(t)$, increases.



368 **Figure 6** Wavelet decomposition of the stationary signal with (left) $H = 6m$ and (right) $H = 30m$.

369

370 4.2 *Transient Events*

371 4.2.1 *Horizontal Wind Speed*

372 It is recognised that there is a large variation in the velocity field between different downburst
373 events (e.g. Choi, 2004; Hjelmfelt, 1988; Lombardo, 2009; Zhang et al., 2018). This is further
374 evidenced by the events recorded for the current study (Figure 7). Four events show a clear
375 acceleration in the horizontal wind speed, though the rate of acceleration and duration of the high
376 wind speeds differ from event to event. For each event, the horizontal wind speed time-series are
377 qualitatively the same across all measured heights (Figure 8).

378 With the exception of a small number of cases, the data of 13th August 2008 event are
379 representative of all downburst events analysed. Data from this event are presented as
380 representative of all events, with data from other events included only where important differences
381 occur, or similarities are to be clearly demonstrated.

382 Wavelet decomposition, with the cut-off frequency/scale determined by the $5H$ relationship, splits
383 the wind speed time-series into a slowly fluctuating component, which follows the large-scale
384 features of the flow field, and a rapidly fluctuating component (Figure 9). Importantly, although the
385 magnitude of the latter varies with time, this variation is slow in relation to the frequencies making
386 up the component, i.e. it is effectively a modulation of a stationary signal. (This representation of the
387 stochastic part of the flow has been applied in numerical simulations of downbursts, e.g. Chen and
388 Letchford, 2007; Kwon and Kareem, 2009; Solari, 2016). It is not unreasonable to conclude,
389 therefore, that the peak wind loading due to this high-frequency part of the downburst wind field
390 (for which, under the PTS assumption, the quasi-steady approach is not suitable), can be quantified
391 experimentally using steady, suitably turbulent flow and the same statistical methods previously
392 applied for ABL flow.

393 There is a general trend of an increase in the magnitude of the residual, high-frequency component
394 as the low-frequency component increases (Figure 9). This is particularly evident for those events
395 with a low initial wind speed and clear increase during the downburst itself. The magnitude of the
396 high-frequency component reduces with altitude (Figure 10), and this manifests itself as a reduction
397 in time-varying turbulence intensity (Figure 11), as seen for ABL flows. Following Holmes et al.
398 (2008), the mean turbulence intensity during the peak period (defined in Section 2) has been
399 calculated. From Figure 11 it is evident that there are issues with this calculation. Firstly, the peak
400 period is not necessarily the same across heights. Refinement of the definition may aid with this, but
401 in the example shown the wind speed exhibits a double peak at low altitudes, while at higher
402 altitudes these peaks are merged (though this is specific to this particular event, which has a longer
403 peak duration than others). Secondly, the turbulence intensity is not constant across the peak
404 period, and this variation is not consistent across events or altitude, beyond a tendency to increase
405 at the start and end of the peak period, attributable to the lower $S(t)$ at these times. The reduction
406 with height of the turbulence intensity during the peak period is evident, falling from between 13%
407 and 18% at $z = 1m$ to 1% at $z = 200m$ (Figure 12). The rapid reduction in I_u with height may be
408 due to the relatively short development length (and thus thinness) of the local boundary layer which
409 develops with the downburst outflow. Integral length scales of turbulence for the high-frequency
410 component reduce with building height (Figure 13), consistent with the reduction in the cut-off
411 scale. Some spread is seen from event-to-event, particularly at low altitudes. At $z \geq 10m$, L_u is

412 consistent with the stationary case, indicating that if an ABL tunnel is able to adequately simulate
413 the required scales for ABL flow then it can also do so for a downburst-like flow. The maximum
414 integral length scales seen are approximately $10m$, two orders of magnitude smaller than both the
415 downdraft diameter ($\sim 1000m$) or the ring vortex diameter (estimated as $700m$ to $1100m$
416 (Hjelmfelt, 1988)). The issue of how to correctly determine the scaling of downburst simulations is
417 an open one, with one of these two parameters commonly used as a length scale, though with
418 limited justification. Replacing pulsed/impinging jet simulations with a quasi-steady/PTS approach
419 removes the requirement for such simulations and renders these scaling arguments redundant.

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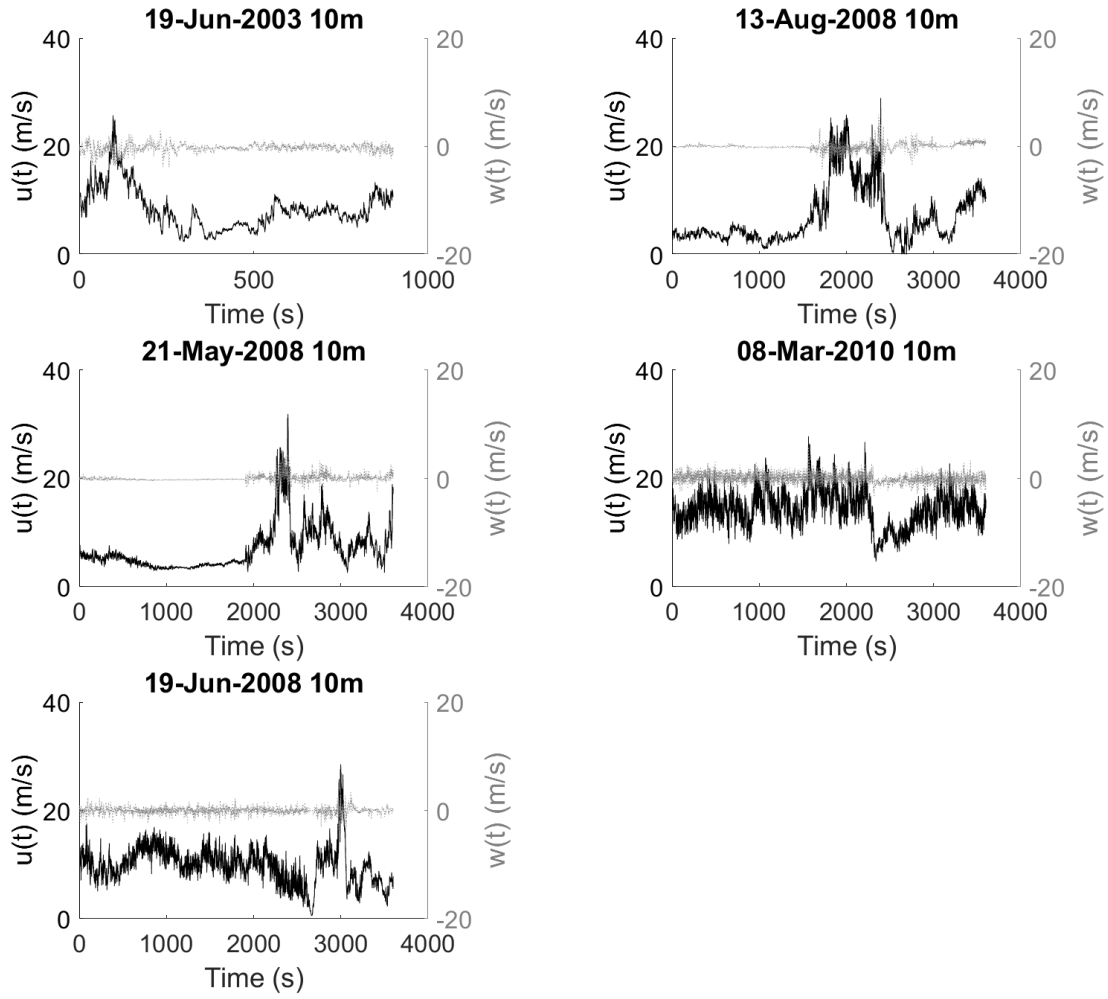


Figure 7 Velocity time-series at 10m for five downburst events.
 $t = 0$ is the start of the 1 hour period during which the event was detected.

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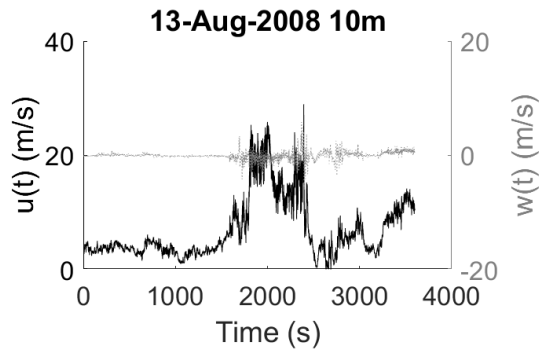
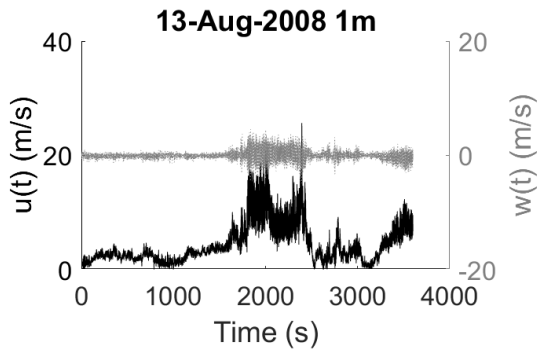
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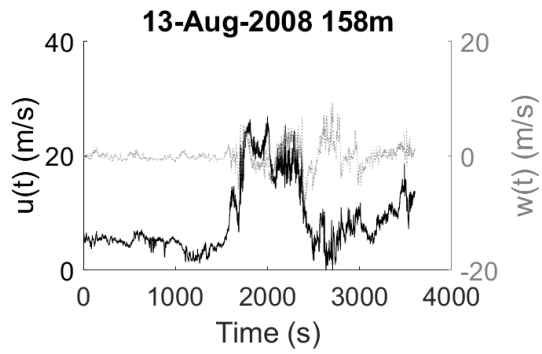
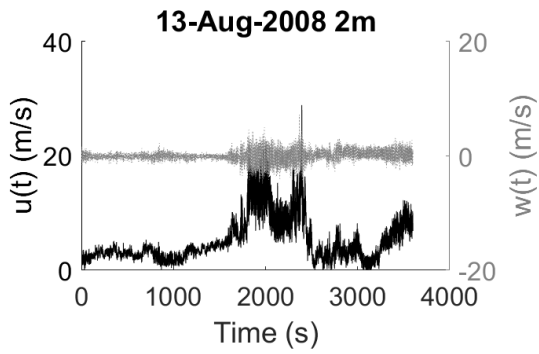
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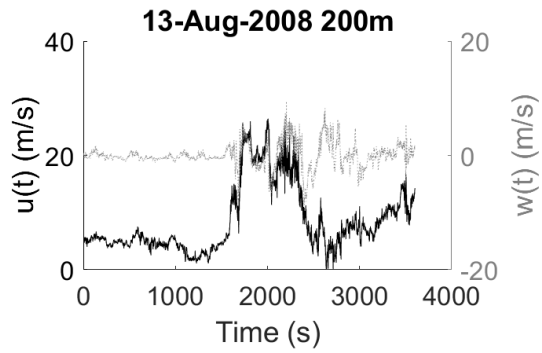
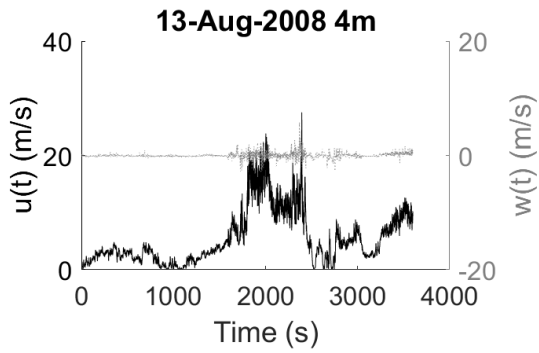
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Figure 8 Velocity time-series for the 13th August 2008 event at a different heights above the ground

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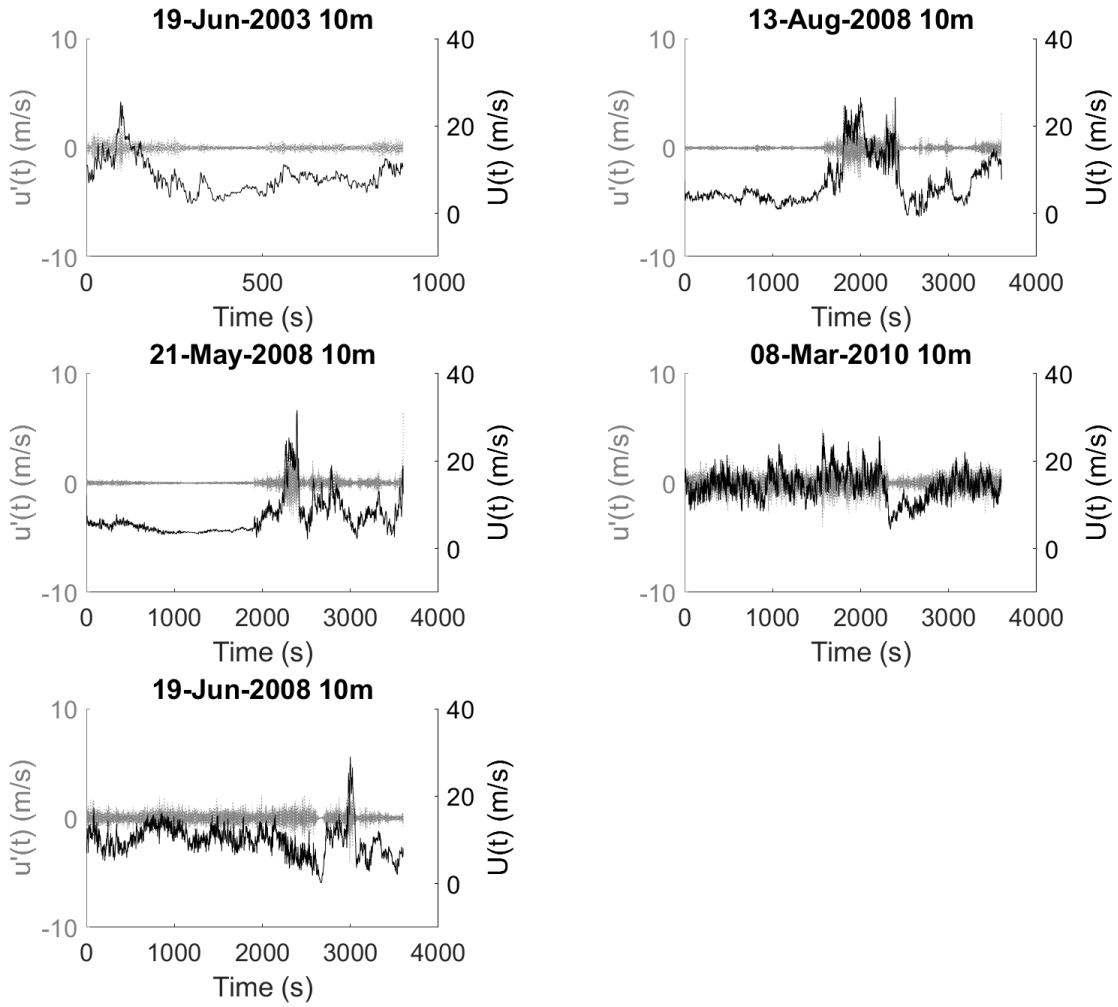


Figure 9 Wavelet decomposition of the horizontal wind speed at 10m for five downburst events

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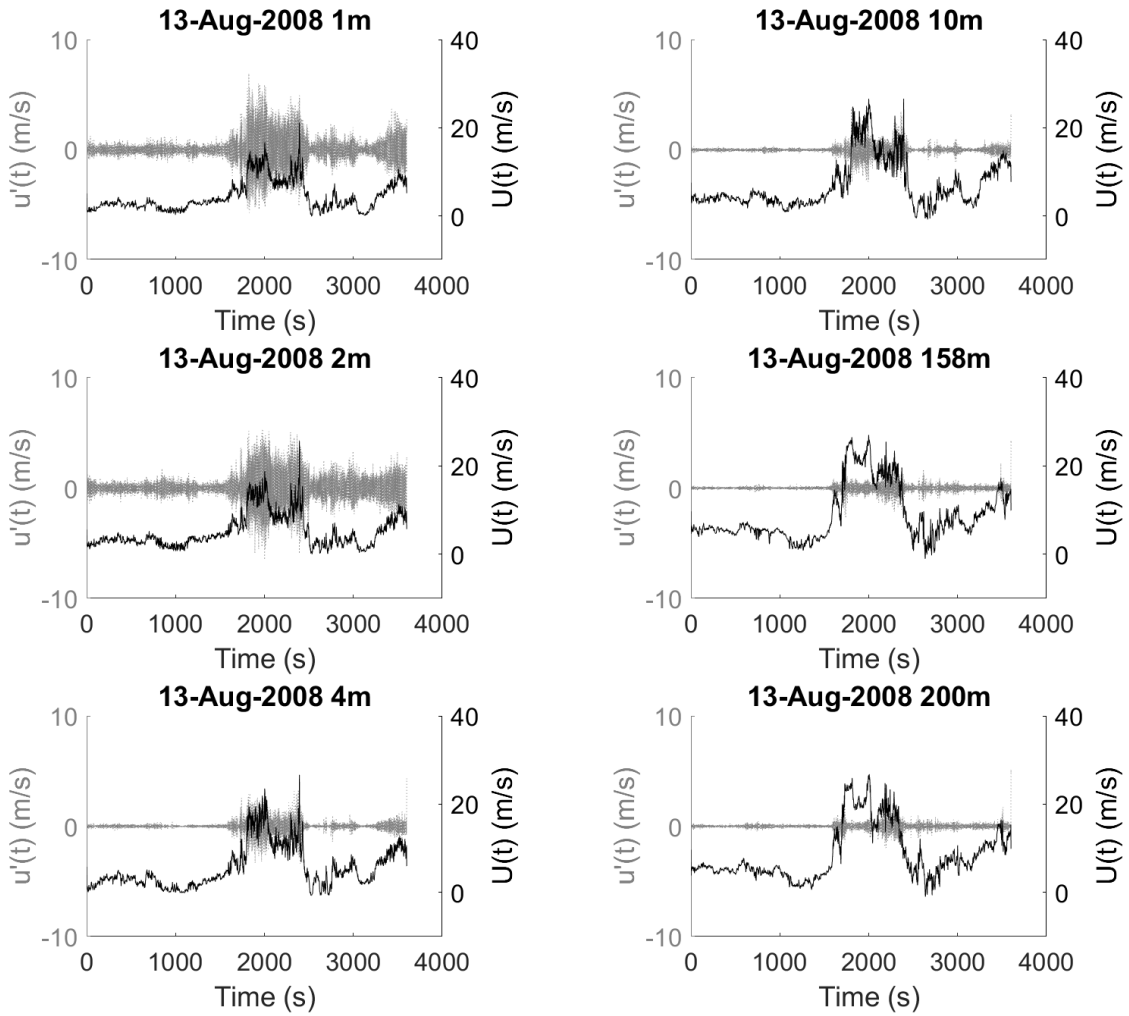


Figure 10 Wavelet decomposition of the horizontal wind speed for the 13th August 2008 event at all measured heights

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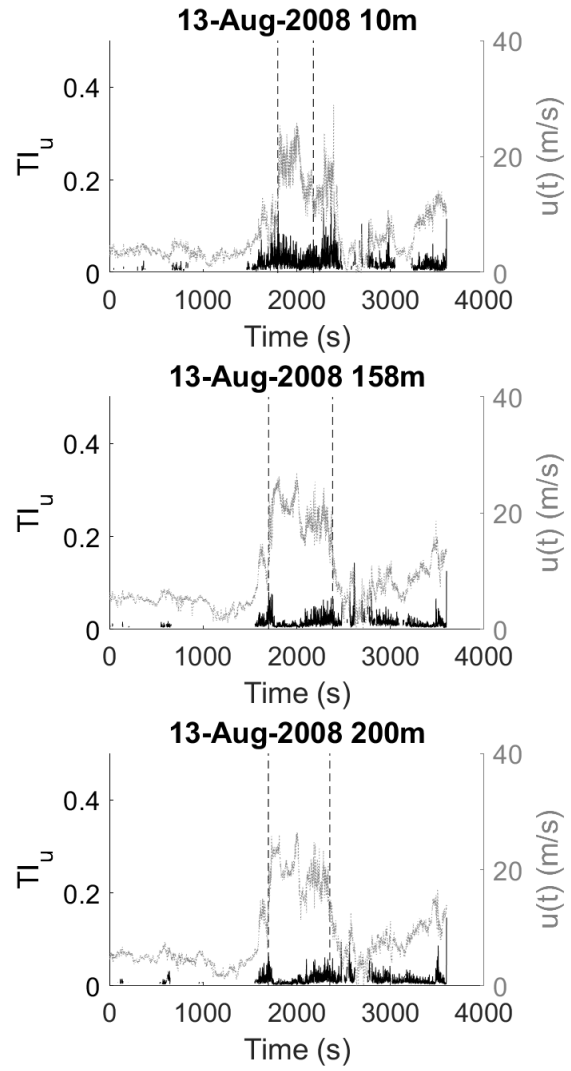
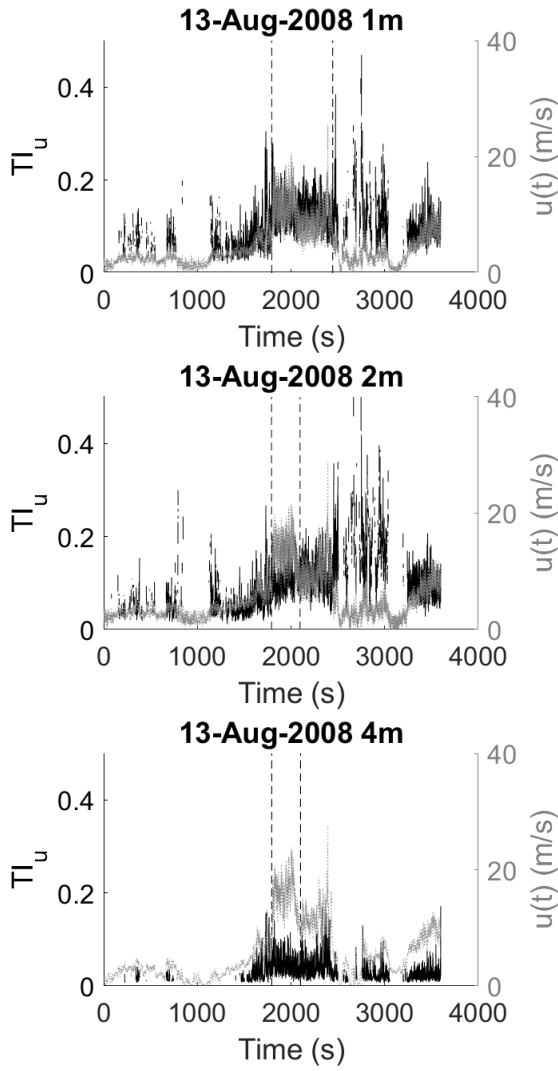
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Figure 11 Wavelet turbulence intensity of the horizontal wind speed for the 13th August 2008 event at all measured heights (for clarity, turbulence intensity is only shown where $u(t) > U$, the overall mean horizontal wind speed). Vertical lines indicate the peak period.

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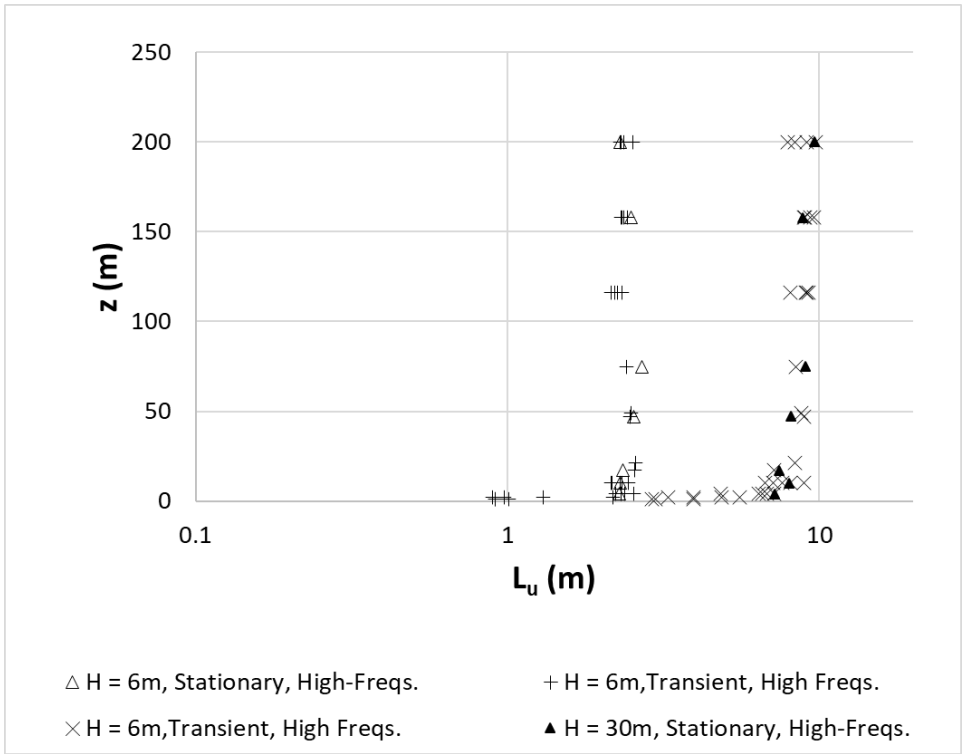
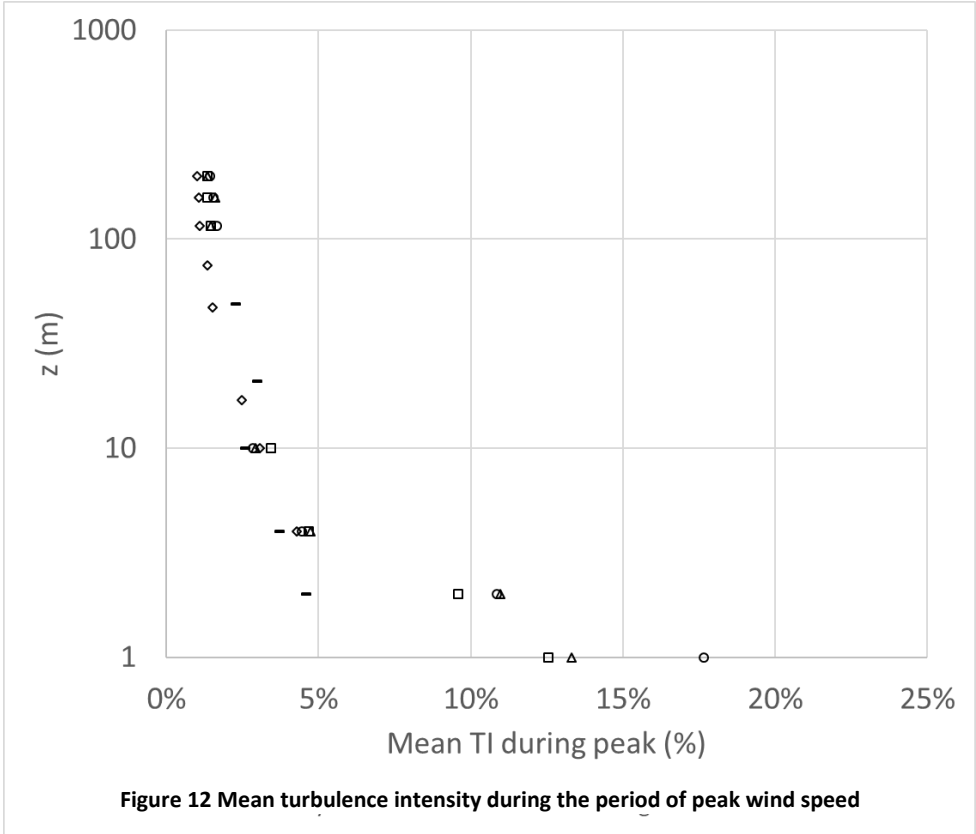
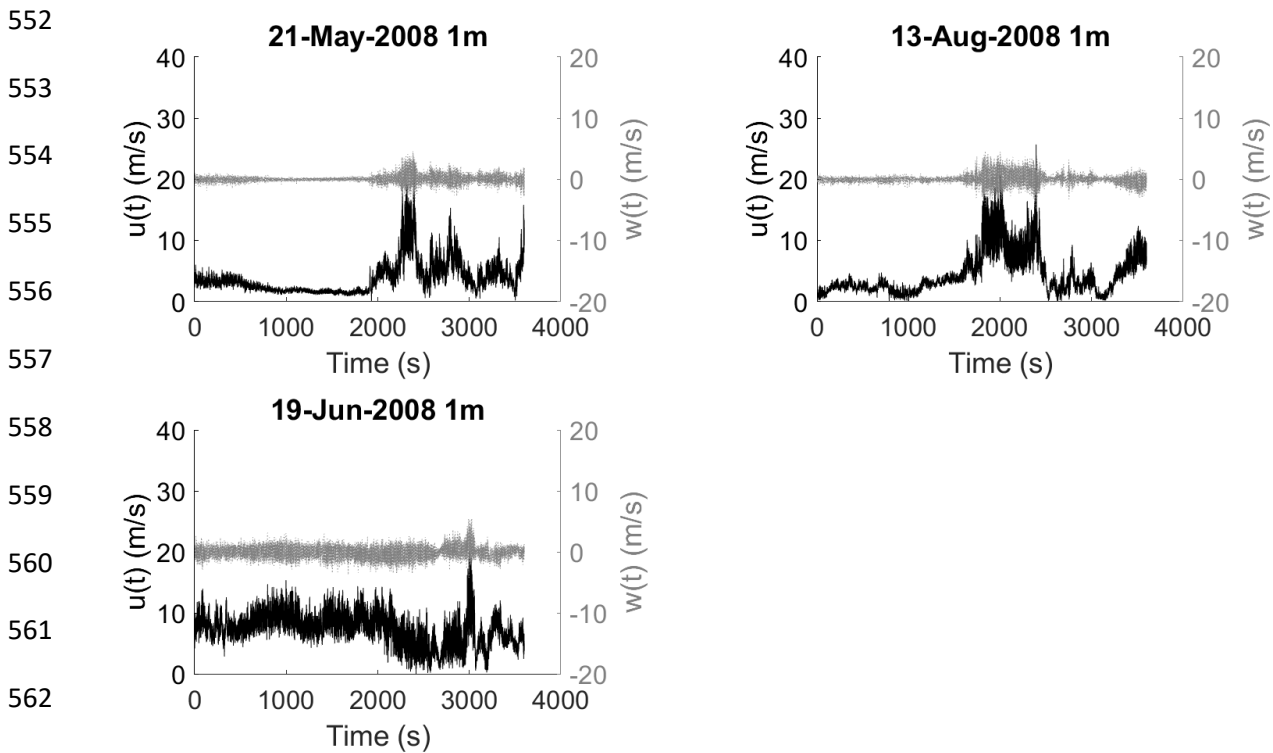


Figure 13 Integral length scales of turbulence for the high-frequency decomposition component

539 4.2.2 Vertical Component of Velocity

540 At low altitudes (< 10m; Figure 14) the magnitude of $w(t)$ increases during the peak period, reaching
541 10m/s. This mirrors the behaviour seen from event to event before the downburst, where $|w(t)|$ is
542 approximately proportional to $u(t)$. As altitude increases, this period of increased vertical velocity
543 extends to the deceleration phase of $u(t)$; maximum magnitude remains approximately unchanged
544 (Figure 7), but the very small-scale turbulence (generated from ground roughness) has reduced. At
545 the highest altitudes measured ($z > 116m$), $w(t)$ reaches 12m/s (21st May 2008 event) during the
546 peak period and, in the case of the 13th August 2008 event, reaches 8m/s during the low horizontal
547 speed region following the peak period (Figure 15).

548 Decomposition of the vertical wind speed illustrates this change with altitude from small-scale
549 turbulence to larger scale effects. At low altitudes the low-frequency term is approximately zero,
550 with some small ($\sim 1m/s$) fluctuations appearing at $z = 10m$. At the high altitudes, low-frequency
551 fluctuations dominate.



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564 **Figure 14 Wind speed time-histories at $z=1m$, all recorded events**

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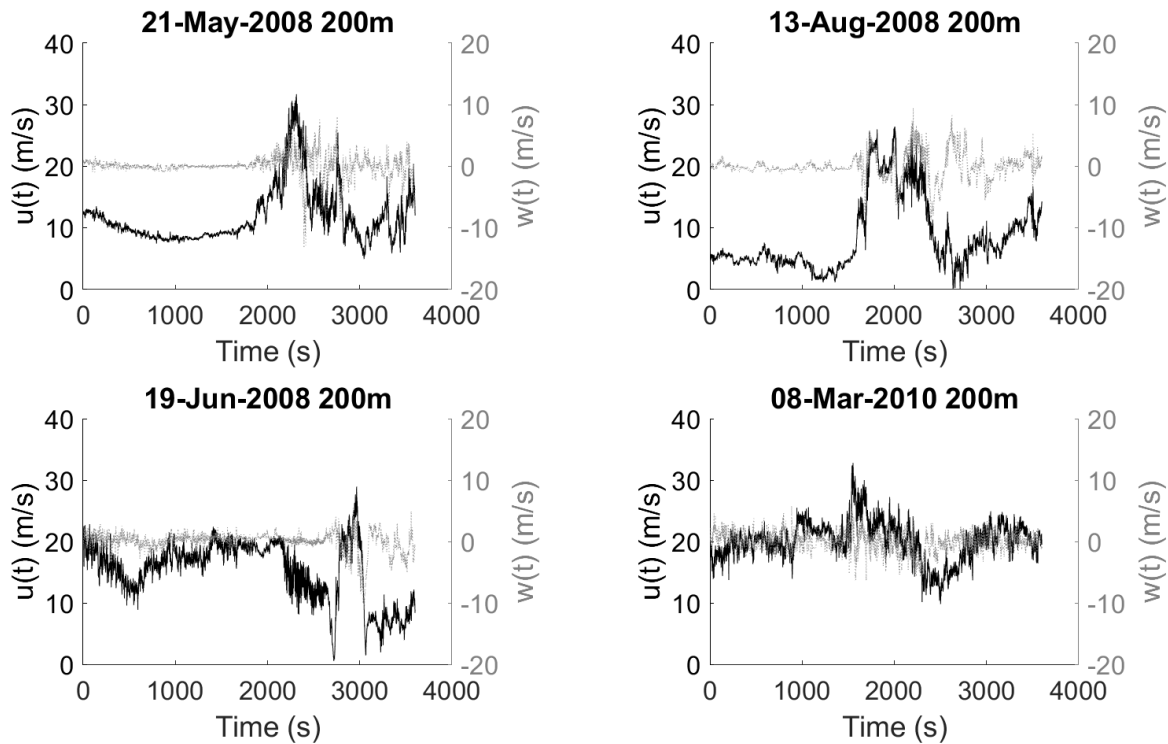


Figure 15 Wind speed histories at $z=200m$, all recorded events

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To date, validation of physical simulations of downburst flow fields has compared only the horizontal wind speed to full-scale data, with the vertical component being neglected. The variation from event to event is large. During the 8th March 2010 event (Figure 16) the elevation angle was within $\pm 30^\circ$ of horizontal at all heights. Generally, the range of angles is greater at low altitudes (Figure 17), though for the extreme elevation angles the magnitude is low ($< \sim 4m/s$), reduces at $z = 4m$ to $z = 10m$ (e.g. 13th August 2008 event, Figure 18) and then increases at high altitudes. Importantly, wind speeds $S(t) \cong 10m/s$ are seen for both upward ($\beta(t) \cong 280^\circ$, 13th August 2008, $z = 158m$, Figure 18) and downward ($\beta(t) \cong 80^\circ$, 19th June 2008, $z = 200m$, not shown) wind directions.

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Figure 16 to Figure 18 were created from the low-frequency time-series and thus these extreme angle-speed combinations lie within those scales which are hypothesised to be modelable using the quasi-steady approach. Equivalent figures using the raw velocity data show similar elevation-wind speed characteristics, and neither give a clear insight into how long these high-speed, large-angle periods last; for this it is necessary to analyse the HSLE Duration data, defined in Section 3. Below 49m HSLE periods are only detected for the lowest thresholds ($S > S_{max}/4$, $\beta > 30^\circ$ from horizontal), and for short durations (0.5 seconds or less). For 49m and higher (Figure 19) these periods of HSLE winds span the scales, with a minimum duration of 0.03s (equivalent to the sampling rate) but maximum durations in the tens of seconds at higher altitudes and thresholds of $S > S_{max}/3$ and $S > S_{max}/4$. If the speed threshold is set to $S > S_{max}/2$ or the elevation threshold is 45° then all HSLE periods are less than 3 seconds, the typical gust duration used for ABL flows. It is evident that low-rise and high-rise structures experience very different wind vectors during a downburst event. From this analysis it may be seen that low-rise and high-rise buildings experience very different wind fields during a downburst. The practical implications of these differences are discussed in the following section.

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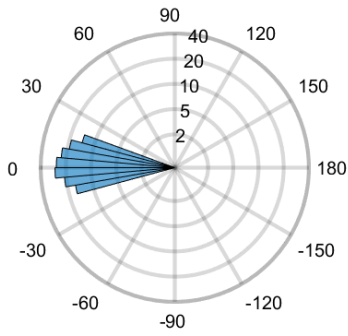
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602 It should be noted that the location of the anemometers relative to the downdraft impingement
603 point is unknown for the data presented in this paper, and almost certainly varies between events.
604 The fact that the above analysis is consistent across events indicates that, in terms of evaluating the
605 decomposition into low- and high-frequency components, this difference in relative position is
606 unimportant. Further, while there may be structural differences in the flow fields which cannot be
607 identified due to this limitation, in none of the cases examined do the data refute the assertion that
608 a quasi-steady/PTS approach is suitable. While some of the events (e.g. 8th March 2010) have
609 relatively low elevation angles, it is possible that (if measured at other relative positions) more
610 extreme angles would occur; the data from those events for which extreme elevation angles is
611 sufficient to show that further experiments to measure wind loading at such angles are necessary.

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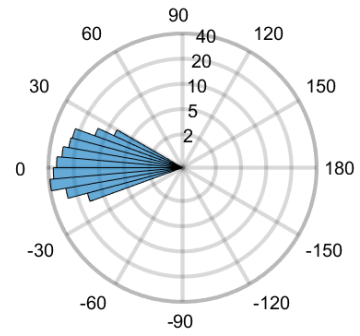
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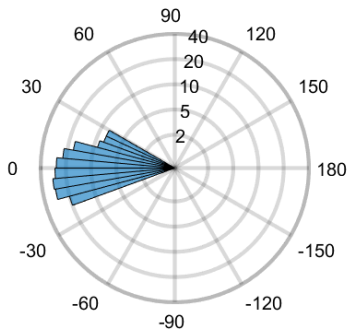
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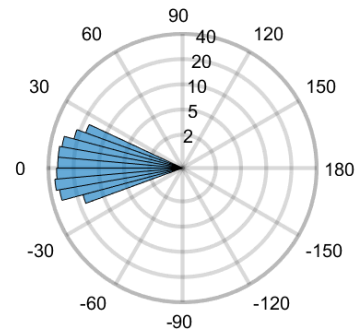
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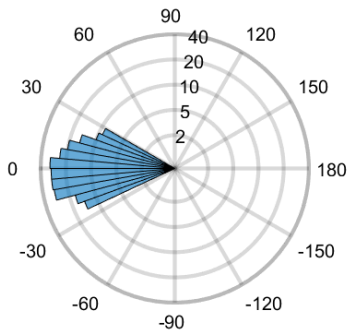
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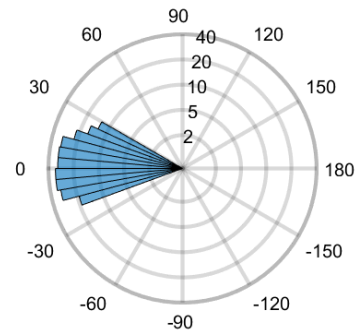
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08-Mar-2010 200m



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Figure 16 Maximum wind speed by elevation angle for the 8th March 2010 event (radial scale m/s and logarithmic)

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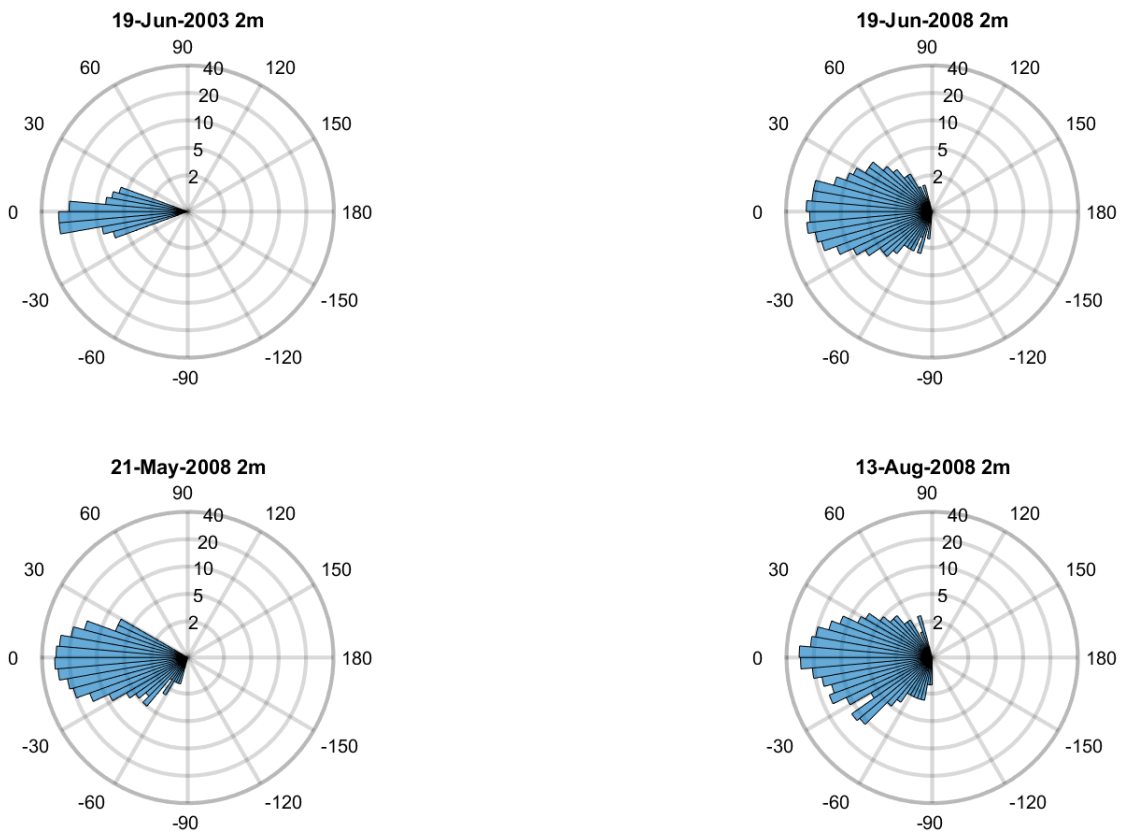


Figure 17 Maximum wind speed by elevation angle at $z = 2m$ (radial scale m/s and logarithmic)

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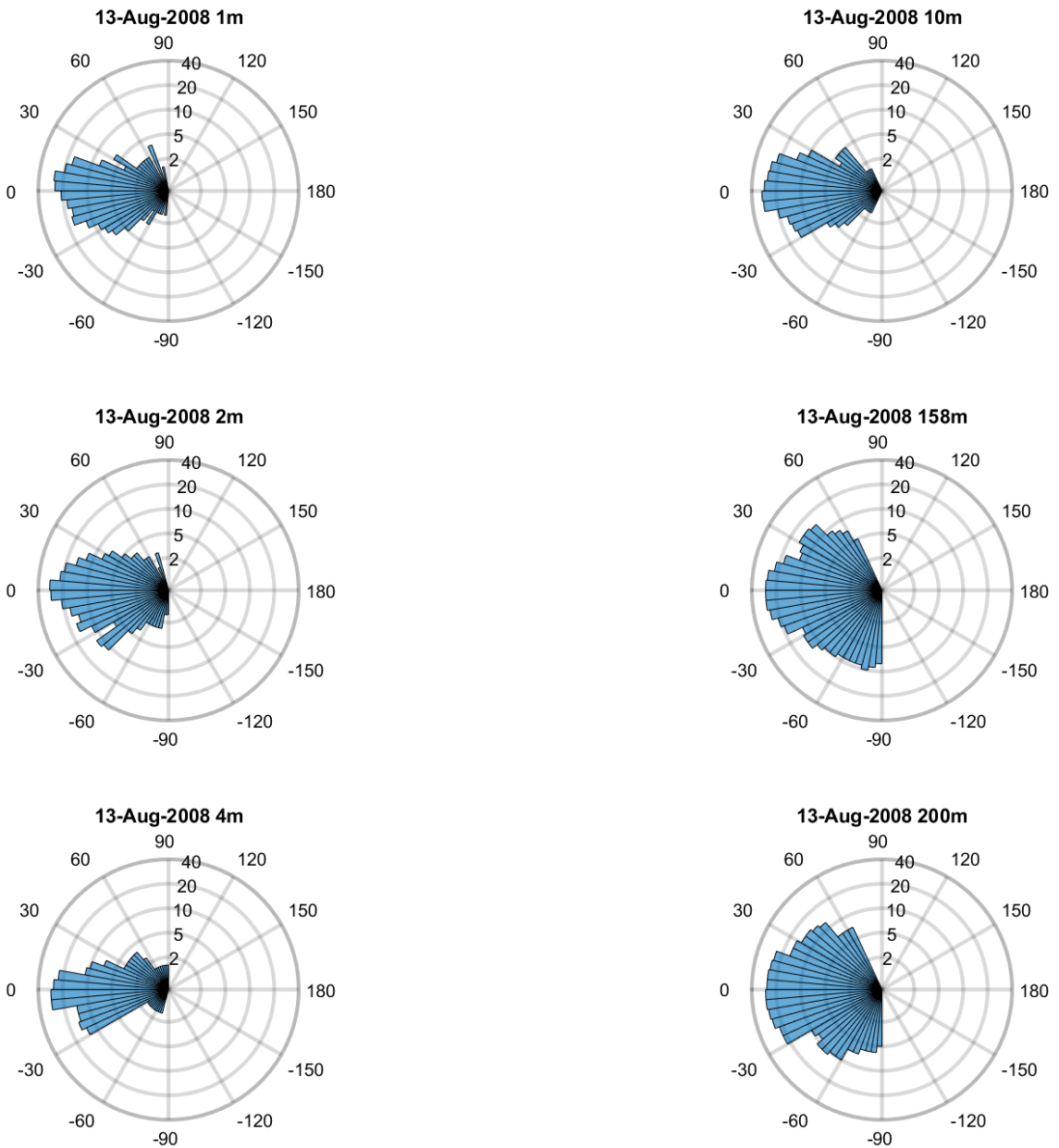


Figure 18 Maximum wind speed by elevation angle for the 13th August 2008 event (radial scale m/s and logarithmic)

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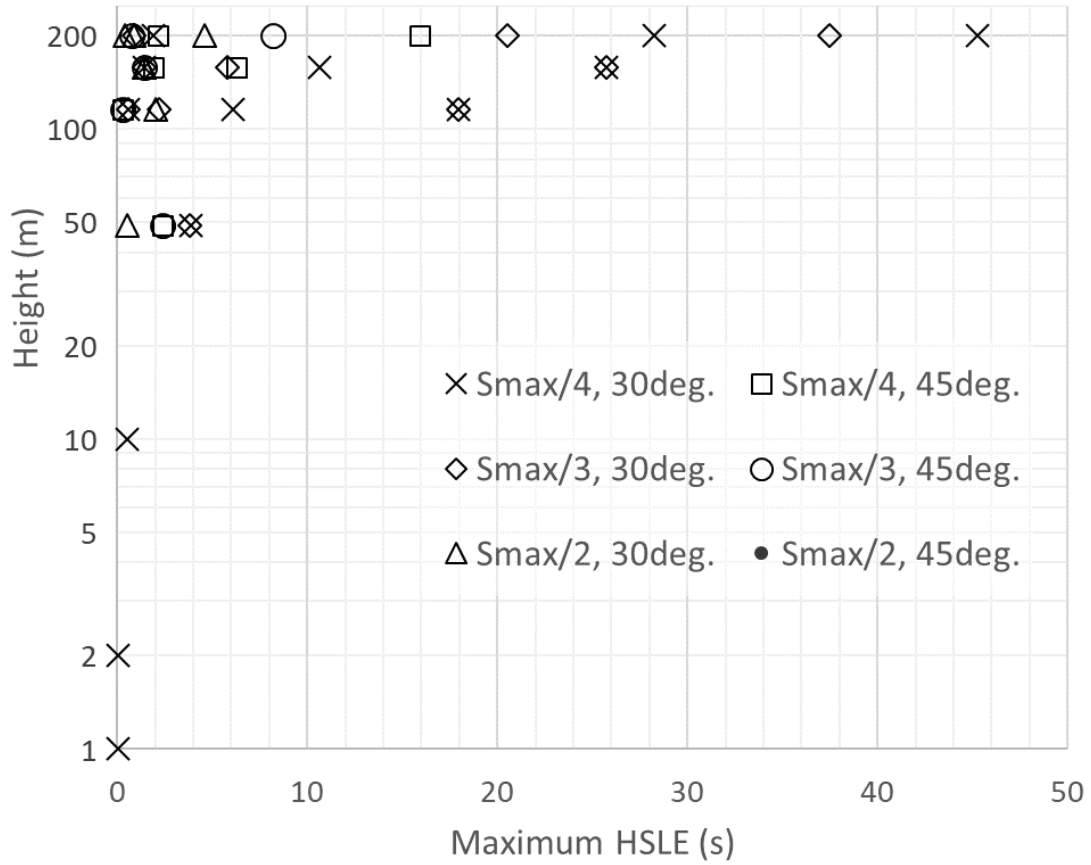


Figure 19 Maximum duration of high-speed, large-elevation events by height above ground

686 5 Application

687 For both low-rise and high-rise buildings, it is necessary to measure peak C_p values at a greater
688 range of elevation angles and turbulence intensities, I_u , than is generally undertaken. This may be
689 achieved using experimental methods similar to those detailed by Wu and Kopp (2018), and
690 elevation angles spanning the range $-60^\circ \leq \beta \leq 60^\circ$ combined with $I_u(z_{fs} = 2m) \cong 10\%$
691 (subscript fs signifies full-scale equivalent) and $I_u(z_{fs} = 10m) \cong 3\%$ (see Figure 12). It should be
692 emphasised that the I_u values presented in this paper are from the wavelet decomposition, and a
693 similar process must be applied to evaluate this parameter for the wind tunnel. The process for
694 obtaining the C_p values is outlined in Figure 20.

695 Due to the differences in the flow experienced by low-rise and high-rise buildings, each must be
696 treated differently:

697 5.1 Low-Rise Buildings

698 The winds experienced by a low-rise building have durations similar to those of a typical ABL gust. In
699 comparison to the scale of the large-scale vortex structures of a downburst ($\sim 1000m$), a low-rise
700 building is small in height, and it is reasonable to assume that the flow direction is, in a mean sense,
701 uniform over the building. Results from the tests outlined above may therefore be applied directly.
702 The workflow is illustrated in Figure 21.

703 5.2 High-Rise Buildings

704 At heights above approximately $50m$, high-rise buildings may be subject to sustained, high speed
705 winds at large elevation angles. It is suggested that the regions above and below $50m$ are treated
706 separately for the evaluation of both local (component) loads and overall loading, with calculations
707 reflecting the differences in wind speed, elevation angle and duration of the extremes of these.

708 In the measurement of the pressure coefficients, the use of building height, H , as the defining length
709 is arguably inappropriate; for a building of height $200m$ the $5H$ cut-off scale is approximately the
710 scale of the downdraft and ring vortex. The along-wind length may be a more appropriate
711 representative length.

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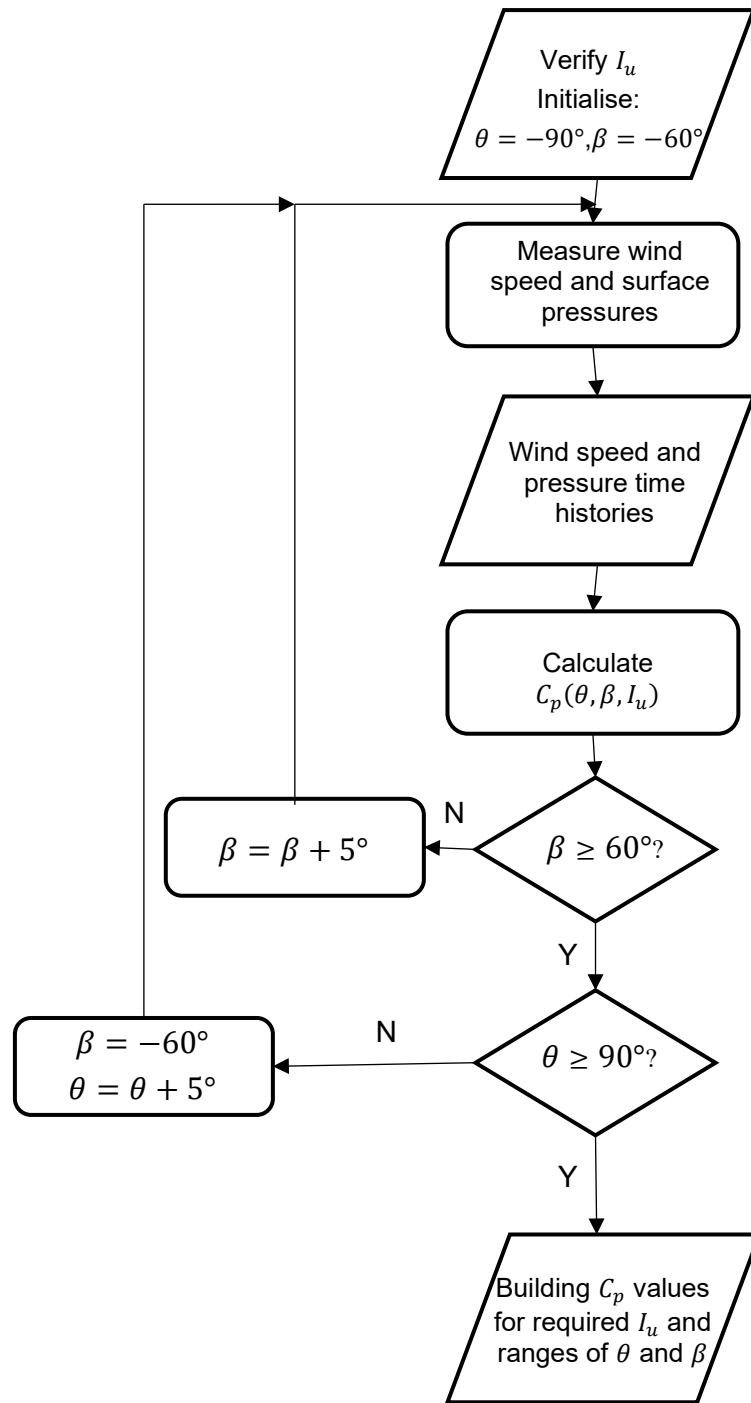


Figure 20 Process flow chart for measurement of peak C_p values

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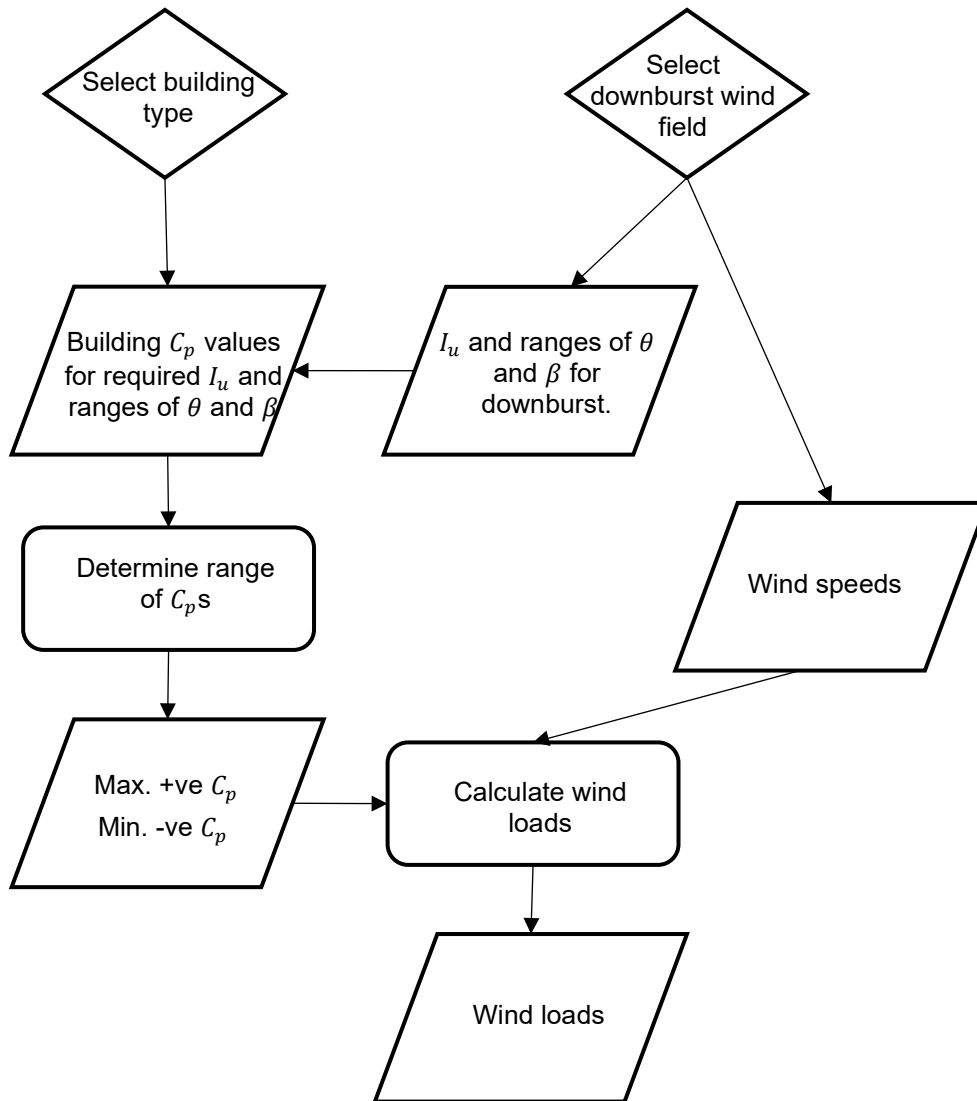


Figure 21 Wind loading calculation process flowchart

767 **6 Conclusions**

768 This novel research has examined the near surface wind field arising from full-scale thunderstorm
769 downbursts. Aspects of Partial Turbulence Simulation have been applied to estimate a turbulence
770 scale above which wind loading may be estimated by application of the quasi-steady theory, and
771 below which wind tunnel tests are required to determine pressure coefficients. Horizontal and
772 vertical velocity time-series were decomposed into high- and low-frequency components as defined
773 by this scale. From this analysis it is concluded that:

- 774 1. Event-to-event variability of downbursts applies not only to the horizontal wind speed, but
775 also to the large-scale variation of the vertical wind speed, and how this changes with
776 respect to the peak horizontal field;
- 777 2. The main vortex structures of a downburst are large-scale by the above definition;
- 778 3. Although the magnitude of the high-frequency component varies with time, this variation is
779 slow in relation to the frequencies making up the component, i.e. it is effectively a
780 modulation of a stationary signal. The aerodynamic effects of the high-frequency
781 components may, therefore, be estimated from steady wind tunnel simulations with
782 appropriate turbulence;
- 783 4. Wind loading calculations for low-rise and high-rise buildings require different techniques,
784 with the latter being somewhat more complex due to the variation of the flow field over the
785 building height. In both cases, the suggested methodology for determining local pressure
786 coefficients may be applied.

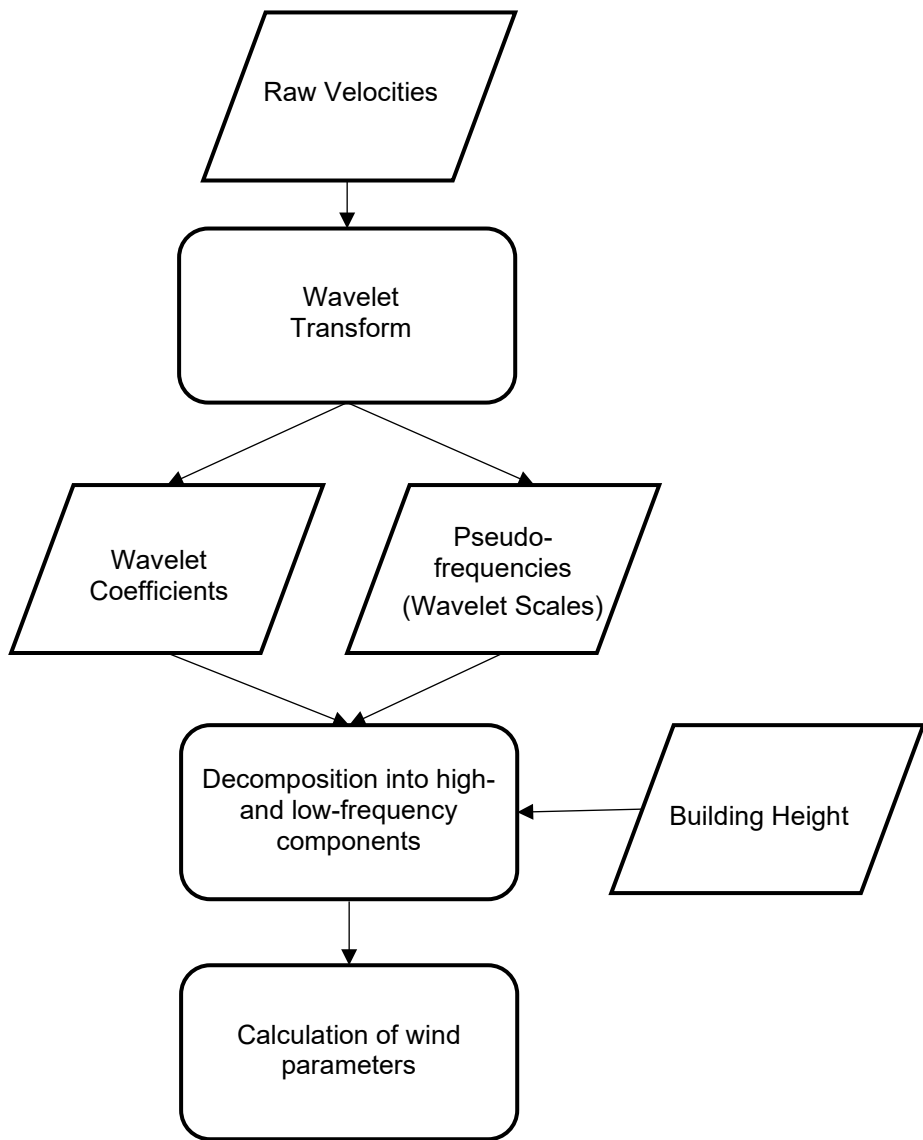
787 The above suggests that it is unnecessary to model the transient features of the wind field in
788 physical simulations. This novel finding has considerable implications for the development of the
789 subject, namely that bespoke, large-scale physical simulators are not required for such conditions.

790 **Acknowledgements**

791 The authors would like to thank the UK Engineering and Physical Science Research Council, which
792 funded the University of Birmingham's original research on downbursts under grant number
793 EP/J008281/1.

794

795 **Appendix**



813 **Figure 22 The wavelet decomposition process**

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