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Measurements of the Static Pressure near the surface in the Atmospheric Boundary Layer

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Measurements have been made of the three components of velocity and of the static pressure in the lowest 10 m of the atmospheric boundary layer. The measurements reported here were made on two occasions: the first with a single 10 m mast and the second with four 6 m masts. One-hour duration measurements at a sampling rate of 10 samples s⁻¹ were processed for statistical properties including an assessment of the mean static pressure, and the time series processed for spectral properties. The mean velocity profile followed the expected boundary-layer log-region. An estimate of the mean static pressure compared to that above the boundary layer has been made and shows a dependency on the RMS (Root Mean Square) of dynamic pressure. The spectra of wind velocity and wind dynamic pressure follow the expected $n^{-5/3}$ power-law decay rate in the inertial subrange, whereas static pressure spectra followed a decay rate close to $n^{-4/3}$ - a result that was not predicted by published theory. Limited comparisons have been made with measurements from wind-tunnel boundary-layer flows, and with one other full-scale experiment. There is evidence from these comparisons that the static pressure spectra has a decay rate close to $n^{-4/3}$ but there is also evidence of Reynolds-number sensitive. These measurements were made as part of a study of wind effects on buildings. The distinct spectral pattern of static pressure compared to that of dynamic pressure is a potential aid to identifying their separate contribution to wind loading and natural ventilation.

Keywords

Boundary layer flow, turbulence, static pressure, spectra.

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31 **I. INTRODUCTION**

32 Vorticity is inherent in all turbulent shear flows, including the atmospheric boundary layer
33 (ABL), and evidence is now available (Hutchins et al. 2012) to show that fluid structures of large
34 scales exist in the ABL. Rotational flow elements that, in boundary layers, are classified as
35 coherent structures or eddies, range in size from millimetres to approaching the boundary-layer
36 thickness, and in the case of atmospheric flows there are cyclonic flows including tornados and
37 hurricanes that exist to a size of $\sim 10^3$ km. These flow structures have a distinctive static pressure
38 pattern. The static pressure in a cyclonic weather system is familiar from forecast maps and is
39 easily measured, but within the ABL the fluid structures contain a complex low-pressure core with
40 smaller structures being embedded within larger ones; it is the static pressure variations in such
41 flows that are the subject of this full-scale experimental study.

42 The term ‘static’ in Bernoullian flow refers to the contribution to total pressure excluding
43 the dynamic pressure. In steady, irrotational flow, the total pressure is constant along a streamline
44 and the static pressure is temporally constant but spatially variable. However, the unsteadiness
45 associated with rotational elements within the flow results in the ‘static’ pressure being depressed
46 and unsteady. Measurement of the static pressure within turbulent laboratory flows poses
47 significant difficulty, particularly in thin boundary layers where a static probe is large in
48 comparison to the boundary-layer thickness. Using a traditional pitot-static probe (Bryer &
49 Pankherst 1971) also requires the probe to be aligned to the instantaneous flow as the static
50 pressure sensed by the probe is sensitive to cross flow. Komerath et al. (1985) developed an
51 alternative method of deriving fluctuating static pressure from the difference between total
52 pressure, measured by a pitot probe, and the dynamic pressure, derived from a hotwire
53 anemometer. The pitot probe is relatively insensitive to misalignment to the instantaneous flow
54 direction in comparison to the static pressure from a pitot-static probe.

55 Measurements made in laboratory boundary-layer flows are often restricted to sensing
56 velocity and occasionally the pressure at the surface (Goody 2004). An exception to this is the
57 work of Tsuji et al. (2007) who used a small static probe: this study measured the static pressure
58 through the boundary layer and also at the surface. Their work included mean static pressure
59 profiles and spectral patterns. They also reviewed earlier work on the measurement of static
60 pressure with an emphasis on spectral properties and comparisons with theoretical expectations.

61 The proposal based on Kolmogorov (1941) and often referred to as Kolmogorov's power-law of a
62 -7/3 logarithmic decay failed to explain the limited measurements reviewed in Tsuji et al. (2007)
63 and also failed to fit their more detailed measurements. Both Goody (2004) and Tsuji et al. (2007)
64 showed that static pressure spectra are sensitive to Reynolds number and there is experimental
65 evidence of Reynolds-number sensitivity in vortices associated with recirculating flows around
66 bluff bodies (Lim et al. 2007). This has been observed in both the stable and intermittent vortices
67 generated by a bluff body (Hoxey et al 1998). The evidence of Reynolds-number sensitivity in
68 vortex flows associated with bluff bodies raises questions about similar sensitivity with vortex
69 elements in turbulent boundary-layer flows.

70 Computational methods are being developed to model the ABL. Miles et al. (2004) used
71 large-eddy simulation (LES) to model three ABLs with free convection, forced convection, and
72 stable stratification. Their spectral results for static pressure in the stable boundary layer cast
73 further doubt on the -7/3 decay as their computed spectra have a higher value in the inertial
74 subrange, which from their presentation appears close to -4/3. They also point out that to resolve
75 computational uncertainty "it is probably necessary to measure the pressure spectrum in high
76 Reynolds-number flows to settle this issue".

77 The ABL is of sufficient size to enable a more detailed study of static pressure fluctuations
78 to be made at higher Reynolds number and also at generally higher turbulence levels. The ABL
79 can also accommodate sensors which produce little disturbance to the flow. In the experiments
80 described in this paper, the temporal static pressure to a height of 10 m has been measured using
81 'static' pressure probes (Moran and Hoxey 1979).

82 Two sets of measurements are described in this paper, the first made in 2000 of the vertical
83 profile of velocity and static pressure, and the second made in 2015/16 of both the vertical and
84 horizontal variation in static pressure. The reason for this latter experiment was to explore the
85 spatial variation of static pressure and also to assess the contribution to ventilation driven by static
86 pressure fluctuations on a naturally-ventilated building.

87 Comparisons are made with static pressure measured in the ABL by Albertson et al. (1998),
88 and comparisons are presented with surface pressure fluctuations in boundary-layer flows at
89 relatively low Reynolds number reported by Goody (2004) and Tsuji et al. (2007).

90 Where appropriate, the statistical properties of wind dynamic pressure and of static pressure,
91 including an estimate of mean static pressure, are presented for information, including an

92 assessment of the mean static pressure in the boundary layer based on turbulence intensity, but the
93 primary objective is to detail the spectral properties of static pressure. Since the findings of this
94 did not comply with theoretical prediction, and since an alternative theoretical method was not
95 forthcoming, a simplified vortex model of Eulerian flow, described in Appendix B, was explored
96 to assist in the understanding of the experimental findings.

97

98 **2. MEASUREMENTS OF STATIC PRESSURE IN THE ABL**

99 Two sets of measurements have been made of the static pressure within the ABL on the
100 experimental site at Silsoe, UK. For the measurement of static pressure, static probes were used
101 for above-ground measurements, and at the ground a conventional ground-level tapping hole was
102 used. The probes are insensitive to horizontal flow direction and only slightly sensitive to the
103 vertical component of flow. Wind velocity was measured by 3-component sonic anemometers.

104 .

105 **2.1. Site details and instrumentation**

106 The site at Silsoe (52.00852°N , 0.42378°W) is flat and well exposed to the west for 400 m; to the
107 south there are buildings 250 m away. The immediate surrounding area was cut grass and beyond
108 this the land was cultivated with low level crops or maize stubble at the time measurements were
109 made. The site has been used for many years for the measurement of wind load on buildings which
110 were constructed for that purpose (for example Richards et al 2001). More recently the site has
111 been used for the study of natural ventilation using the 6 m cube (Gough et al 2018). Velocity
112 profile measurements (Hoxey & Richards 1992) show a good fit to a log-law with a typical surface
113 roughness parameter z_0 of 10 mm for winds from the SW to NW; higher z_0 values were measured
114 for winds from S to SW, as found in the 10 m mast measurements reported below.

115 For the measurement of static pressure, static probes (Moran and Hoxey 1979 and reviewed
116 in Appendix A) were used for above-ground measurements. These cylindrical, axis-symmetric
117 probes (165 mm in height by 28 mm in head diameter) are mounted vertically and consequently
118 their performance is insensitive to horizontal flow direction; they are also suitable for use in rain.
119 The design of the probe is a scaled-down version of a static probe for use in atmospheric flows
120 first proposed by Marshall (1976). Alternative designs of static probe have been developed for
121 turbulent flow, for example Nishiyama and Bedard (1991) who also include the probe used here
122 in their review.

123 The probes developed at Silsoe Research Institute were first used on full-scale buildings to
124 replace surface roof tappings which were susceptible to being blocked. The probes were initially
125 calibrated by mounting them at a height of 3 m above a ground tap on an exposed, cut-grass site.
126 This full-scale calibration procedure was followed by wind-tunnel comparisons in low-turbulence
127 flow, and a consistent pressure coefficient difference of +0.07 was observed. For the measurements
128 of static pressure in the ABL, the probes were calibrated in a low-turbulence wind tunnel and set
129 to agree with the static pressure at a wall tap at the probe position in the working section of the
130 wind-tunnel in the conventional manner for calibrating static probes. It was apparent from the
131 consistent difference between these two calibration methods that the probes were sensitive to the
132 static pressure field associated with turbulent flow in the ABL, and that by implication it is the
133 eddies in turbulent flow that were responsible. At this time (in the 1980's), the authors were not
134 aware of any other measurements in the ABL. It was not until Albertson et al published their
135 findings in 1998, using a different probe based on two horizontal flat plates, that these observations
136 were corroborated. Details of the probe design used in the current study, and its sensitivity to air
137 speed and pitch are described in Appendix A. All the probes used in these experiments were
138 individually calibrated in a low-turbulent wind-tunnel flow within an overall estimate of error of
139 $\pm 1\frac{1}{2}\%$ of wind dynamic pressure.

140 The probes have a sensing head of 28 mm in diameter, giving a potential response to eddies
141 of this size and larger. Static pressure was also sensed at the ground with a conventional ground-
142 level tapping hole of 9 mm diameter with a potential response to eddies of this size. In the
143 experiments described here, it is the 6 mm internal diameter tubing connecting the sensors to the
144 transducers that limits frequency response. The shortest tube lengths used were 1 m, giving a flat
145 response to ~ 70 Hz, and the longest tube of 15 m gives a flat response to ~ 5 Hz. Individual
146 differential pressure transducers (Honeywell Differential Pressure Sensor 163PC01075 $\pm 2\frac{1}{2}$
147 inches of H_2O , ± 635 Pa) were used for each sensor. The pressure transducers have a flat response
148 to over 50 Hz but again this is limited by the tubing. The conversion from analogue to digital gave
149 a pressure resolution of 0.026 Pa/count.

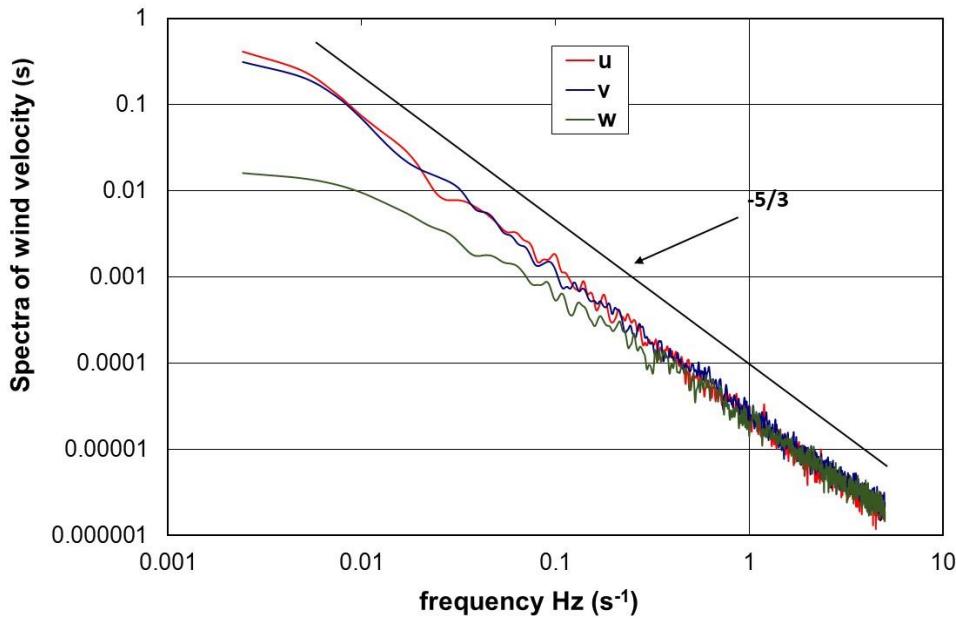
150 The backing pressure for all the measurements was from a ground tapping which consisted
151 of a 100 mm aluminum can buried in the ground flush to the surface with a 9 mm tapping hole.
152 The pressure from this tapping was conveyed by 6 mm internal diameter tube and was
153 pneumatically averaged using a restrictor/volume combination with a response of ~ 100 s. This

154 backing pressure was connected to each of the pressure transducers via a manifold. There are
155 practical difficulties in finding a suitable backing pressure as small changes in temperature and
156 atmospheric pressure will affect the air in the volume (a large earthenware bottle) which will
157 become apparent in the low frequency part of the static pressure spectrum. Low frequency
158 fluctuations in pressure occur in windy conditions and cannot be eliminated, but for the
159 measurements reported here there were near constant temperature conditions which minimize this
160 effect.

161 Symmetrical head three-component ultrasonic anemometers (3-D Wind Master Sonic
162 Anemometer manufactured by Gill Instruments) were used to measure the three components of air
163 velocity and also the speed of sound: as the speed of sound relates to air temperature, the instrument
164 was used to calculate heat flux. The anemometer has a path length of 150 mm which attenuates
165 response to eddies smaller than two to three times this path length. The anemometer was used as
166 the timing device for the data recording, in this case set to 10 samples s^{-1} . The frequency response
167 will depend on air velocity; for flows below $3 m s^{-1}$ ($20 \times$ path length), response to 10 Hz with
168 attenuation can be expected. In the measurements reported here, streamwise wind speed was above
169 $5 ms^{-1}$ with no significant attenuation in the measurements, although the opposite effect on spectra
170 of aliasing is likely to affect the frequencies below the Nyquist frequency.

171 The spectral analysis of the static pressure measurements is restricted to curve fitting over
172 that part of the inertial subrange for which measurements were made. To identify the extent of the
173 inertial subrange (defined as the frequency range where the spectrum of velocity has a logarithmic
174 decay of $-5/3$) the spectra of the three components of velocity (u' , v' and w') are shown in figure
175 1. This is for an average of two non-overlapping records of 4096 data points at 10 samples s^{-1} . This
176 figure confirms an inertial subrange from approximately 0.005 Hz to 5 Hz and it may extend to
177 both lower and higher frequencies, but record length and instrumentation response were
178 insufficient to establish this. Logarithmic curve fitting over the full range will be used for all
179 analysis in this paper. Unpublished measurements with hot wire anemometers mounted at a height
180 of 1 m beside a sonic anemometer on the Silsoe site have shown that the inertial subrange extends
181 well beyond 50 Hz, but the sonic anemometer measurements are not reliable above the Nyquist
182 frequency of 5 Hz. The energy spectrum of wind dynamic pressure has the same logarithmic
183 spectral decay of $-5/3$ as that of velocity, since velocity has to be squared (and multiplied by air
184 density) to give an energy spectrum. The wind dynamic pressure spectrum is used in the analysis

185 that follows for comparison with static pressure spectra as they are dimensionally consistent. This
186 requires that pressure energy spectra are computed by Fast Fourier Transform (FFT) and not via
187 the autocorrelation method, as this effectively squares the input quantity.



188
189 FIGURE 1 Spectra of the 3-components of velocity measured at a height of 6 m. The spectral density for
190 all the components have been divided by the integrated spectrum of the streamwise component.
191

192 **2.2. Single 10-m Mast**

193 The first measurements, in March 2000, were of the static pressure on the site at Silsoe, at 1, 3, 6
194 and 10 m above ground. The static probes were mounted vertically on brackets horizontally off-
195 set by 1 m from a 10m mast. The pressures from the static probes were measured against a backing
196 pressure from the pneumatically-averaged pressure (time constant ≈ 100 s) from a tapping hole in
197 the ground. Three-component sonic anemometers were also mounted at 1, 3, 6 and 10 m above
198 ground on the same mast, but horizontally off-set to avoid interference with the static probes and
199 the mast. Synchronised measurements of static pressure and of wind velocity from the sonic
200 anemometers were collected at 10 samples s^{-1} for 60-min records (36,000 data points) and
201 processed as four 15-min records. Four pressure transducers were positioned on the mast each with
202 a 1 m length of 6 mm diameter tube connected to a static probe.

203 The one-hour of measurements reported here were made on the 29th March 2000
204 commencing at 09.58 GMT (sun rise 05.48 GMT). The measured heat flux, derived from the sonic

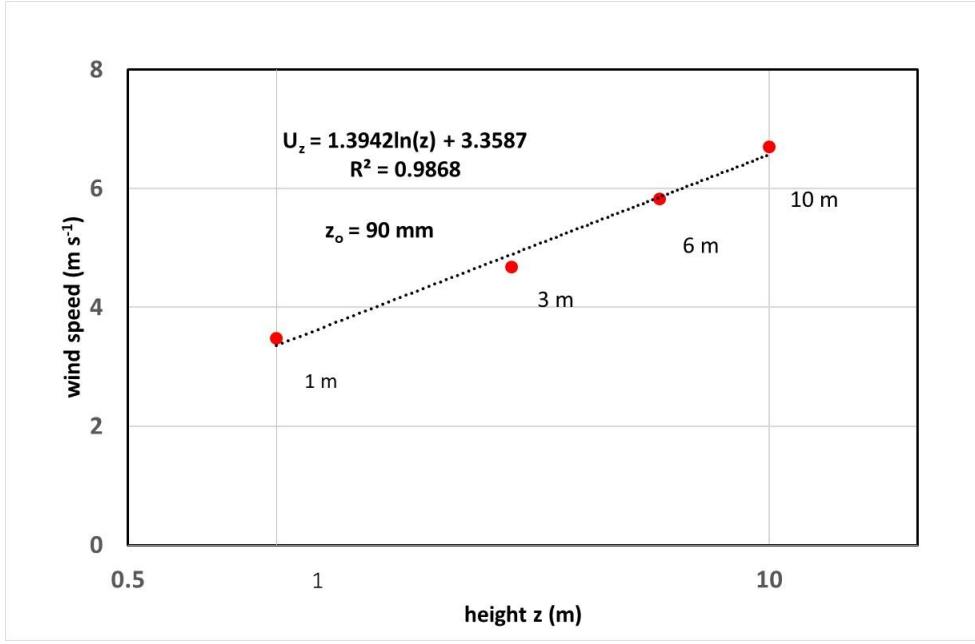
205 anemometers, and z/L where L is the Obukhov length, are given in table 1. These values of z/L are
 206 indicative of near-neutral atmospheric stability.

z (m)	$\overline{w'\theta'}$ (ms^{-1}K)	z/L
1	-0.0029	0.0002
3	-0.0005	0.0001
6	0.0035	-0.0016
10	0.0279	-0.0202

207

208 TABLE 1. Heat flux and atmospheric stability measured at the four heights
 209

210 The streamwise mean-velocity profile, derived from the sonic anemometers, is shown in
 211 figure 2. This is well represented by a log-law of the form $U_z = \frac{u_*}{K} \ln(z) + \text{constant}$, where U_z
 212 is the velocity at height z , u_* is the frictional velocity and κ is the von Karman constant. Defining
 213 a roughness length z_0 where $U_{z0} = 0$ gives $U_z = \frac{u_*}{K} \ln\left(\frac{z}{z_0}\right)$. Extrapolating from a least-squares curve
 214 fit gives $z_0 = 90$ mm and hence $u_{*/K} = 1.39 \text{ m s}^{-1}$ ($u_* = 0.57 \text{ m s}^{-1}$ with $\kappa = 0.41$). The mean
 215 velocity (U_z), turbulence intensities ($I_u = \text{RMS}(u)/U$, $I_v = \text{RMS}(v)/U$ and $I_z = \text{RMS}(w)/U$) and a
 216 velocity u_τ from the local Reynolds stress ($u_\tau = (-\overline{u'w'})^{1/2}$) derived from the sonic anemometers
 217 for the average of the four records, are given in table 2.



218
219
220

FIGURE 2. One-hour mean velocity profile with least squares estimate of U_z and z_0 .

z (m)	U_z (m s^{-1})	I_u	I_v	I_w	u_τ (m s^{-1})	$\frac{u_\tau}{U_z}$
1	3.48	0.44	0.40	0.23	0.25	0.071
3	4.68	0.34	0.27	0.21	0.50	0.107
6	5.82	0.30	0.24	0.16	0.65	0.112
10	6.70	0.28	0.22	0.13	0.71	0.106

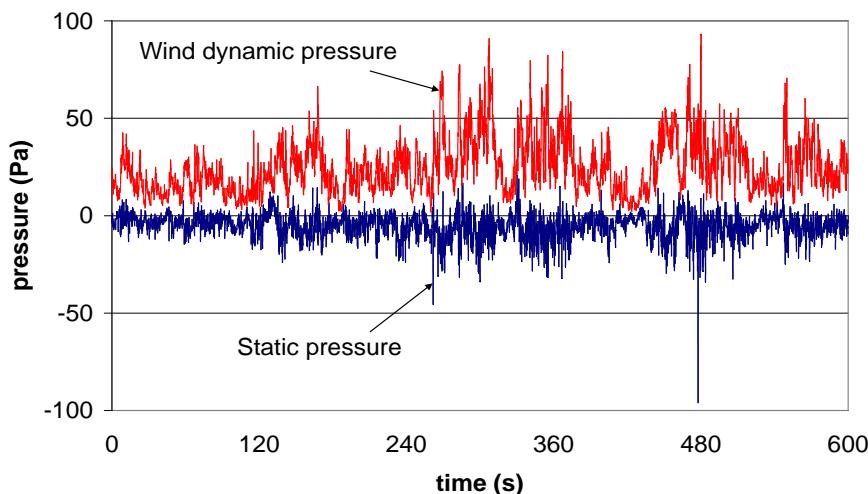
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224

TABLE 2. Velocity-profile statistics (mean streamwise velocity (U_z), turbulence intensities (I) and a velocity from the local Reynolds stress (u_τ)) derived from the four sonic anemometers: average of four 15-min records.

225 The turbulence intensities are high compared with previous measurements on the site (I_u
226 0.18, I_v 0.15, I_w 0.08 at $z = 6$ m, Richards et al., 2000) and relate to the high roughness length (z_0)
227 which occurs for winds on this site from the south. The statistics are from 15-min records and the
228 inherent non-stationarity of the flow means that the standard deviation of the velocity components
229 are sensitive to, and increase with, record length. The frictional velocity u_τ derived from the
230 product of u' and w' is not reliable at low height as there is insufficient frequency response from
231 the 10 Hz sonic anemometer. At a height of 1 m, a significant proportion of the stress may not be
232 measured (Richards et al., 2000). The assessment of frictional velocity (u_τ) from the sonic

233 anemometers (table 2) is thus considered to be reasonably consistent with the assessment of
234 frictional velocity of $u_* = 0.57 \text{ m s}^{-1}$ obtained from the velocity profile.

235 An example of the dynamic pressure, derived from the three-component sonic anemometer,
236 and of the 'static' pressure measured at a height of 6 m in the ABL is shown in figure 3. (Note:
237 'true' zero for static pressure is not known; the static pressure data shown are with reference to a
238 long-term static pressure average at ground level). There is interaction between the two quantities
239 as both respond to eddies in the shear flow but there is a complex correlation as the dynamic
240 pressure can be above or below that of the mean flow, whereas the static pressure is mainly
241 negative. The 'spikes' in the record are associated with an eddy vortex centre passing very close
242 to the sensor at the time of sampling. With a mean flow of 5 m s^{-1} , the static pressure is being
243 sampled every 0.5 m of the flow, and with many eddies smaller than this the core pressure is often
244 missed.



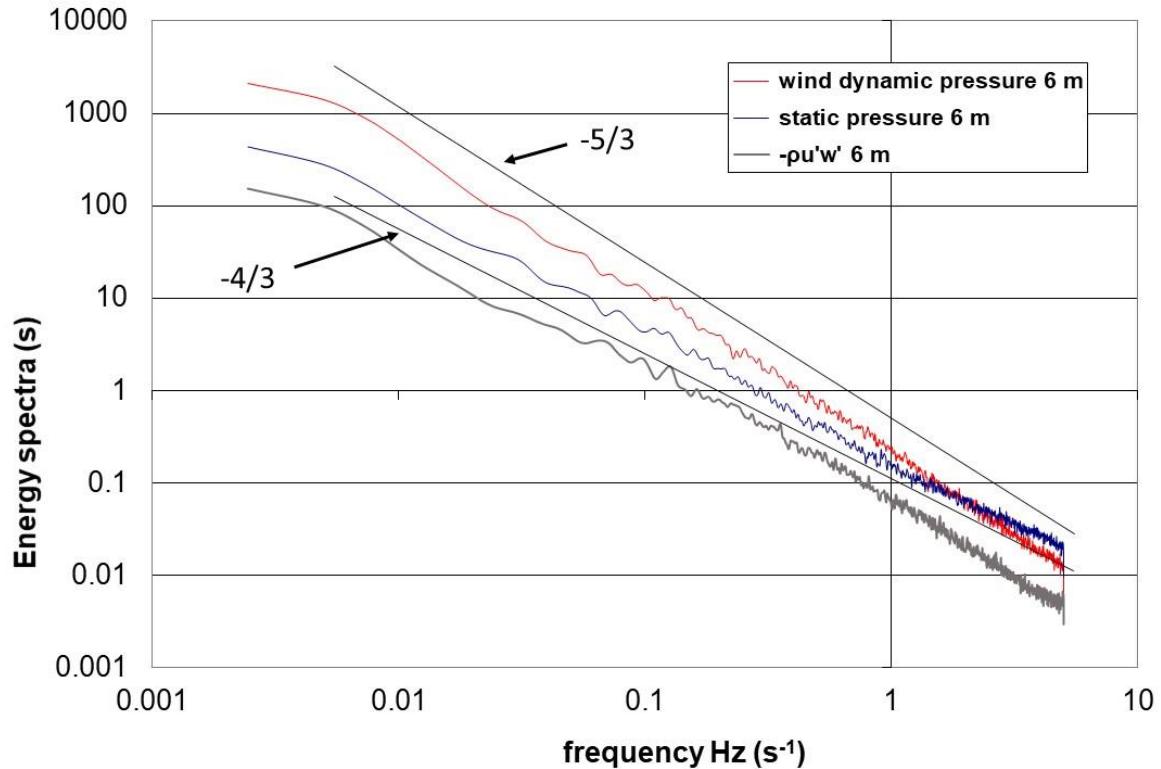
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246 FIGURE 3. Example of the wind dynamic and static pressure in the ABL at a height of 6 m.
247

248 Energy spectra of wind dynamic pressure ($E_q(f)$) static pressure ($E_p(f)$) and of the
249 Reynolds stress cospectrum ($-\rho u' w'$), all measured at a height of 6 m, are shown in figure 4.
250 The spectra are non-overlapping averages of eight data sets of 4096 points with smoothing
251 applied to the spectra before averaging. All the spectra shown are divided by the integrated
252 spectrum of wind dynamic pressure and therefore magnitudes are comparable.

253 The wind dynamic pressure energy spectrum has the familiar characteristic of a $-5/3$
254 logarithmic decay rate, whereas the static pressure spectrum shows a reduced decay rate

255 approximating -4/3; a result that was not expected. The Reynolds-stress cospectrum does not
 256 exhibit a linear power-law decay, but has a decreasing value (more negative) from around -4/3
 257 through -5/3 to -2 as frequency increases. The theoretical value of -7/3 may well be reached at
 258 higher frequency but there is insufficient sampling rate and resolution here to confirm this.
 259 There is also little contribution to the overall stress from higher frequencies (Hoxey & Richards
 260 1992, Hoxey & Richards 1995, Richards et al 1997).



261
 262 FIGURE 4. Energy spectra of wind dynamic pressure and static pressure, and also of the Reynolds-stress
 263 cospectrum, ($-\rho u' w'$), measured at a height of 6 m. All spectra divided by the integrated spectrum of the wind
 264 dynamic pressure
 265

266 The exponents of frequency obtained by a least-squares curve fit for both wind dynamic
 267 pressure and static pressure spectra are given in table 3. The mean and standard deviation values
 268 are for eight non-overlapping periods of 409.6 s. The curve fit was over the frequency range
 269 0.00244 to 5 Hz (2048 data points) and was not sensitive to the spectral smoothing method used.
 270 The pressure instrumentation is fully responsive over this range and no filtering was applied. The
 271 dynamic pressure spectrum shows a slight increase in the exponent with reduced height as the
 272 inertial subrange region moves to higher frequency. This is discussed in Richards et al. (2000).

273

z (m)	Exponent for wind dynamic pressure spectra (standard deviation)	Exponent for static pressure spectra (standard deviation)
1	-1.69 (0.030)	-1.39 (0.033)
3	-1.68 (0.026)	-1.36 (0.020)
6	-1.75 (0.014)	-1.36 (0.020)
10	-1.77 (0.006)	-1.32 (0.043)

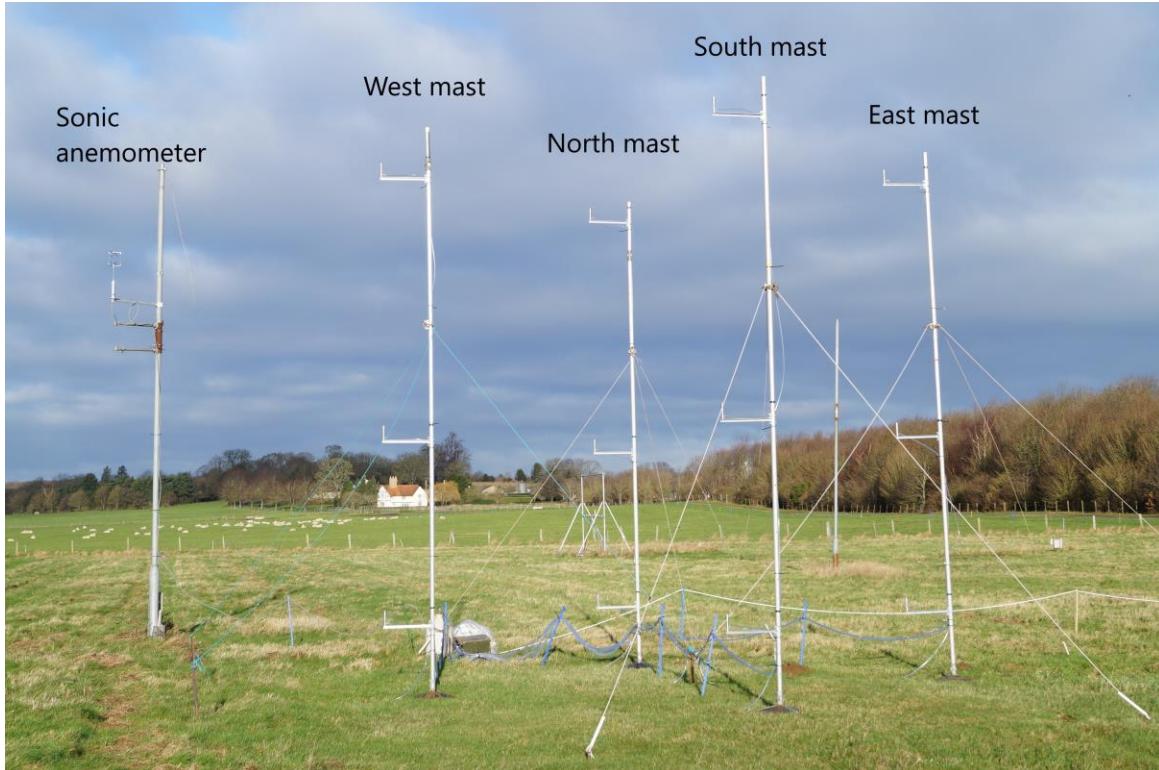
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275 TABLE 3. Exponent of frequency for wind dynamic pressure and static pressure for the 10 m mast measurements.

276

277 **2.3 Four 6-m Masts**

278 The second set of measurements was made in December 2015 / January 2016. The objective was
 279 to measure the static pressure at 1, 3 and 6 m on 4 masts positioned on the four side faces of an
 280 imaginary 6-m cube: the pressures were also measured at ground level, 0.5 m upstream of each
 281 mast base in vertical alignment with the probes, using hole-in-the-ground tappings. The
 282 experimental arrangement is shown in f5. The backing pressure for all the probes and ground taps
 283 was from another ground tap with a low-pass pneumatic filter (time constant ≈ 100 s). For
 284 reference, a 3-component sonic anemometer was mounted on a separate mast to the side of the
 285 array, and can be seen in figure 5.



286
287
288
289
290

FIGURE 5. The four masts with static probes mounted to the windward side of the masts (flow from left to right):
the reference sonic anemometer is on the windward-most mast. The flow was from west-south-west and the
alignment of the east to west masts was 240° magnetic

291 Synchronised measurements of static pressure and of wind velocity from the sonic
292 anemometer were collected at 10 samples s^{-1} for three 20-min records (36,000 data points). The
293 one hour of records reported here were made on the 24th December 2015, commencing at 04.45
294 GMT (sun rise 08.10 GMT). The measured heat flux, derived from the 6 m sonic anemometer,
295 was $-0.0076 \text{ m s}^{-1} \text{ K}$ and $z/L = 0.0041$; indicative of near-neutral atmospheric stability. Measured
296 statistics of the boundary layer based on the sonic anemometer at 6 m are given in table 4.

z (m)	U_z (m s^{-1})	I_u	I_v	I_w	u_τ (m s^{-1})	$\frac{u_\tau}{U_z}$
6	8.61	0.188	0.169	0.082	0.577	0.067

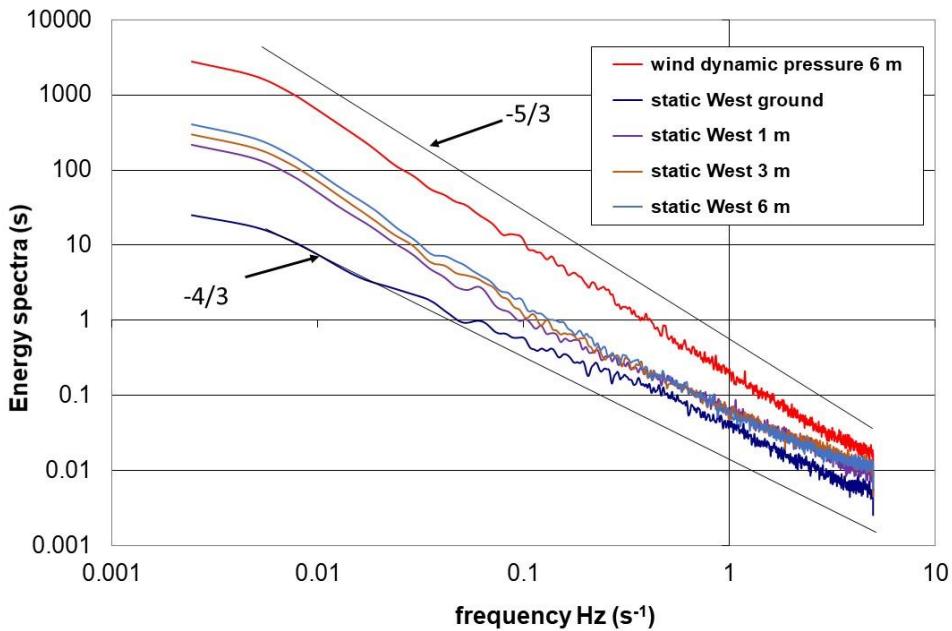
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299

TABLE 4. Velocity profile statistics derived from the average of the three 20-min records from the sonic
anemometers.

300

301 Compared with the measurements made in 2000, the turbulence intensities are lower and
 302 consistent with winter measurements on the site for a WSW wind, with a roughness length (z_0) of
 303 approximately 10 mm (Richards et al. 2000). The ratio u_τ/U_z is correspondingly lower.

304 The spectral properties, derived from six non-overlapping 409.6 s records of the wind
 305 dynamic pressure, and of the static pressure at the ground and at 1, 3 and 6 m are shown in figure 6.
 306 As with the single-mast measurements, the spectra of wind dynamic pressure and of static pressure
 307 follow closely a power-law decay. There is little observable difference for the above-ground static
 308 pressure spectra (all non-dimensionalised by the integrated spectrum of the wind dynamic pressure
 309 at 6 m), but the ground static pressure shows low frequency attenuation as a result of using a time-
 310 averaged differential backing pressure which included correlated low-frequency fluctuations. The
 311 mean value and standard deviation of the derived exponents for six non-overlapping periods are
 312 given in table 5: the wind dynamic pressure is the average of 6 data sets, whereas the static pressure
 313 is the average for the four masts, each of 6 data sets.



314

315 FIGURE 6. Energy spectra of wind dynamic pressure, static pressure at the ground and at 1, 3 and 6 m, derived from
 316 six non-overlapping 409.6 s records. All spectra divided by the integrated spectrum of the wind dynamic pressure.

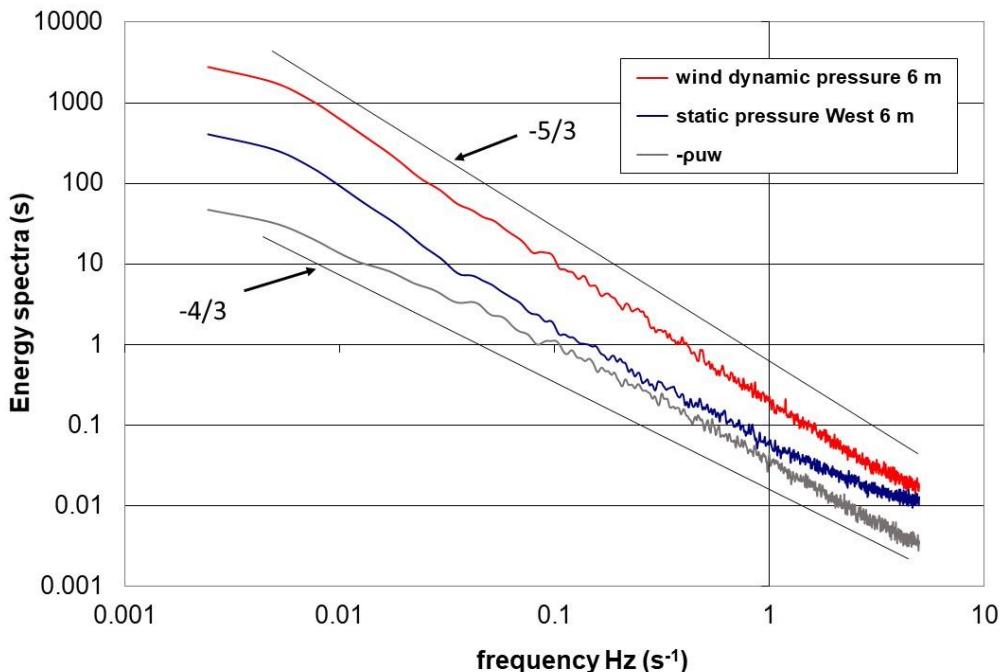
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318

z (m)	Exponent for wind dynamic pressure spectra (standard deviation)	Exponent for static pressure spectra (standard deviation)
ground		-1.28 (0.056)
1		-1.27 (0.035)
3		-1.33 (0.032)
6	-1.66 (0.002)	-1.38 (0.033)

319
320 TABLE 5. Exponent of frequency for wind dynamic pressure and static pressure.
321

322 The Reynolds-stress cospectrum shown in figure 7 followed the same pattern as noted above
323 (figure 4) for the measurements made in 2000.

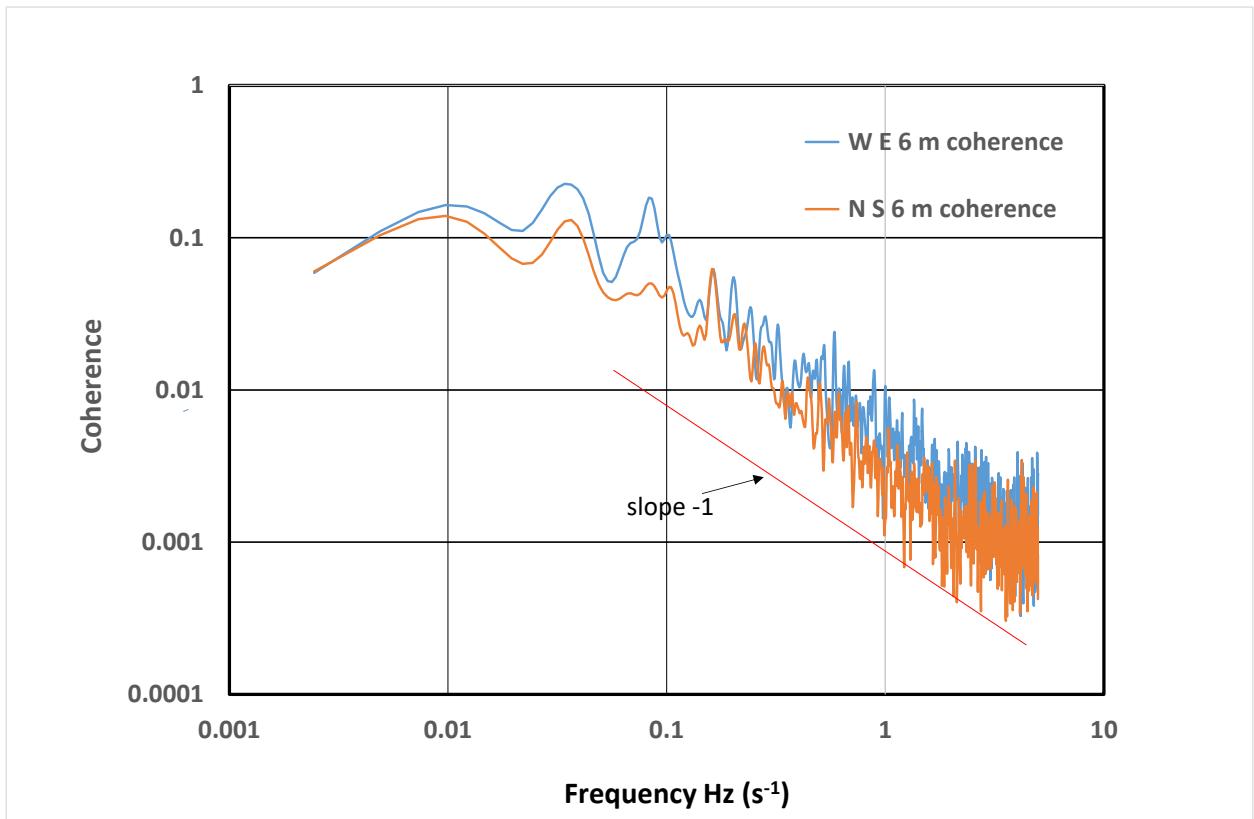


324
325
326 FIGURE 7. Energy spectra of wind dynamic pressure and static pressure, and also of the Reynolds-stress
327 cospectrum, ($-\rho u' w'$), measured at a height of 6 m. All spectra are divided by the integrated spectrum of the wind
328 dynamic pressure
329

330 The pressure transducers were positioned on the ground to the north of the North mast and
331 tube lengths to the 6-m high static probes were up to 15 m. These tubes have a resonant frequency
332 as low as 5 Hz which may contribute to the slight increase in the spectrum at this frequency: the

333 lower probes and ground taps with shorter tubes are not likely to be affected by tube resonance.
334 The mean of the exponent for the static pressure measurements, including the ground taps, is -
335 $1.313 (\frac{\sigma}{\sqrt{n}} = 0.009)$.

336 The cross-spectral density function has been calculated for the West and East static pressure
337 at 6 m (aligned with mean flow direction) and also for the North and South static pressures
338 (perpendicular to flow direction). The derived coherence function (Otnes and Enochson 1972) for
339 each is shown in figure 8.



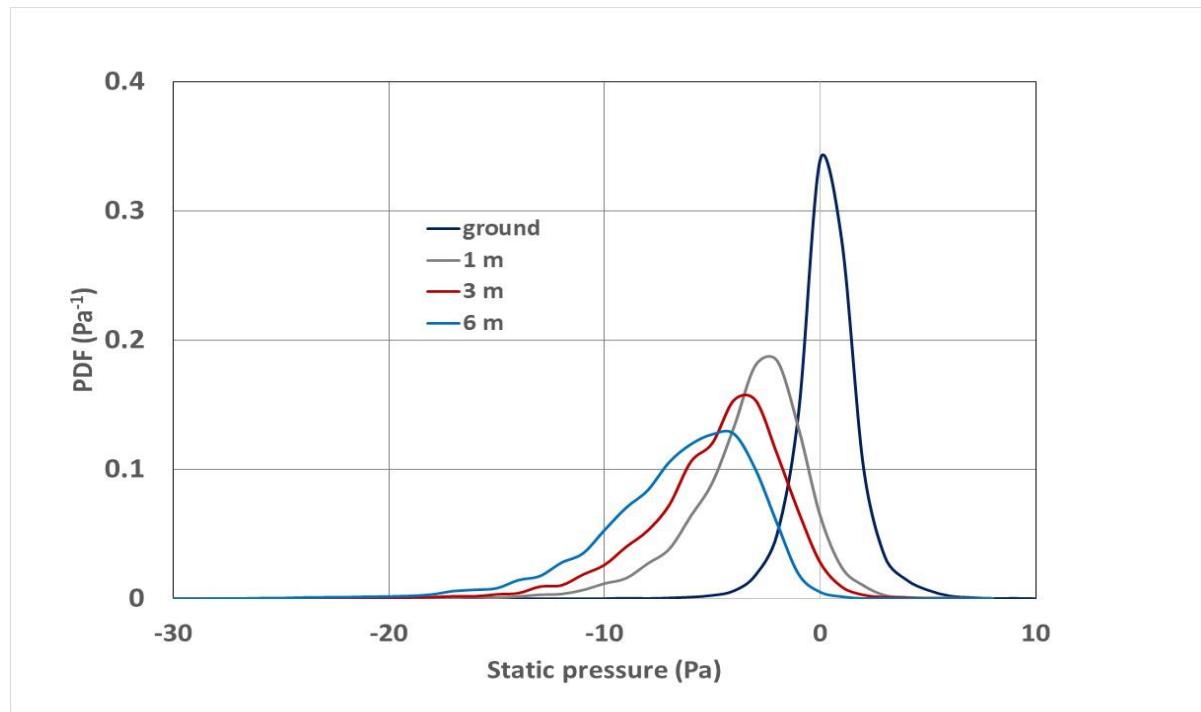
340
341 FIGURE 8. Coherence function of static pressure for aligned flow (West to East masts) and cross flow (North to
342 South masts)
343

344 The coherence (figure 8) is greater for the aligned flow as expected but it also shows that the
345 static pressure is spatially variable even for larger eddies as it is the small cores of these eddies
346 that make the most significant contribution to static pressure. There is a clear need for a longer
347 record in order to approach unity at low frequency.
348
349

350 **3. MEAN VALUE OF STATIC PRESSURE**

351 The measurements described here of static pressure are made with reference to the average
352 surface pressure at the ground. Assessment of the ‘true zero’ mean static pressure within the
353 boundary layer is speculative as it is impractical to relate it to the static pressure in the free-stream
354 above the boundary layer (ABL thickness $\delta \sim 1$ km). The complex structure of the turbulent
355 boundary-layer flow, described for example by Morrison et al. (1992) and Hunt and Morrison
356 (2000), with terms such as ‘sweeps’ and ‘splats’, leads to uncertainty about the transient positive
357 static pressure that can occur within the flow. It appears (figure 3) that the influence of vortical
358 structures (sweeps) dominate with negative static pressure, whereas ‘splats’ with positive pressure
359 appear small in comparison. In a thin boundary layer, Tsuji et al. (2007) noted that ‘the wall
360 pressure is slightly lower than the free-stream pressure’, an observation consistent with near-wall
361 eddies depressing the wall pressure.

362 The probability density function (PDF) for static pressure measured on the West 6-m mast
363 and at the ground are presented in figure 9. The statistics are given in table 6 for a 20-min record
364 of 12000 data points. In all cases the static pressure is measured with reference to the time averaged
365 pressure at the ground.



366
367 FIGURE 9. Probability density functions for static pressure measured on the West mast and at the ground.
368

369

<i>z</i> m	ground	1 m	3 m	6 m
Minimum (Pa)	-9.8	-29.5	-27.1	-28.3
Maximum (Pa)	10.6	11.7	5.8	6.3
Mean (Pa)	-0.16	-3.84	-5.33	-7.12
Standard deviation (Pa)	1.46	2.78	3.17	3.64
Skewness	0.001	-1.19	-1.07	-1.19
Kurtosis	6.81	7.18	5.40	5.47

370

371 TABLE 6. Statistics of the static pressure measured on the West mast and at the ground.

372

373 The PDF of ground static pressure is distinct from above ground measurements as eddies
 374 can only pass near the ground, but above ground they can pass through the probes. The core
 375 pressure in eddies skew the PDF of the probe measurements and give a lower mean pressure. The
 376 measured mean dynamic pressure ($q_{mean z}$), the mean pressure difference ($p_z - p_0$), and RMS values
 377 of dynamic and static pressure are presented in tables 7 and 8, with an additional column, Cp_z ,
 378 defined as $Cp_z = (q_{RMS}^2 - p_{RMS}^2)^{1/2} / q_{mean z}$. Numerically Cp_z is the displacement value to
 379 align q_{rms} with the square root of the second moment of p .

<i>z</i> m	q_{mean} (Pa)	$q_{RMS}/q_{mean z}$	$p_z - p_0$ (Pa)	$p_{RMS}/q_{mean z}$	Cp_z
0			zero	N/A	-0.195*
1	10.44	0.734	-2.36	0.435	-0.254
3	16.61	0.617	-4.10	0.335	-0.356
6	24.30	0.553	-5.09	0.245	-0.496
10	31.38	0.507	-4.93	0.201	-0.601

380

381 TABLE 7. Mean static pressure analysis for the 10- m mast measurements (* denotes value derived from curve fit)

382

383

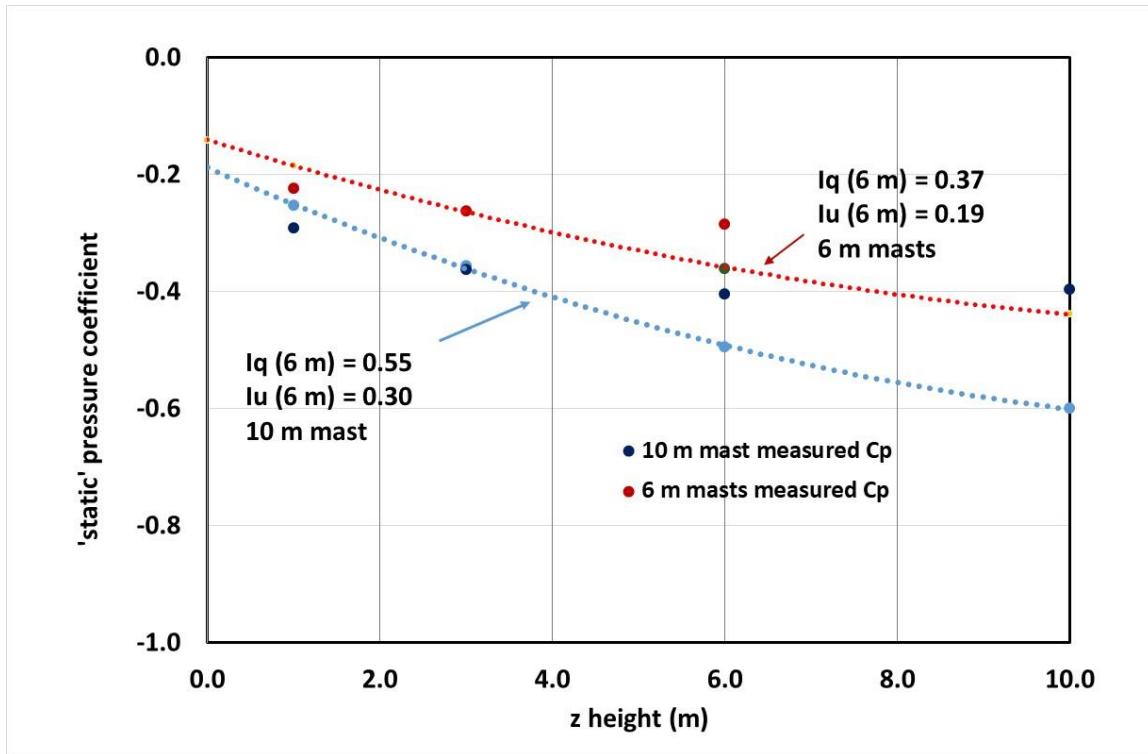
384

385

z m	q_{mean} (Pa)	q_{RMS}/q_{mean}	$p_z - p_0$ (Pa)	$p_{RMS}/q_{mean\ 6m}$	Cp_z
0			zero	0.029	-0.143*
1			-3.80	0.055	-0.185*
3			-5.53	0.062	-0.260*
6	46.02	0.369	-6.61	0.069	-0.362

386

387 TABLE 8. Mean static pressure analysis for the four 6-m mast measurements. (* denotes values derived from
388 curve fit)389 The values of Cp_z are shown in Fig 10 and the curve fit extrapolated to the ground ($z = 0$)
390 giving a static pressure coefficient at the ground Cp_0 . As the PDF of the ground tap is close to
391 a symmetric distribution, Cp_0 corresponds to the maximum value of the static pressure, and
392 Cp_0 can be considered as the static pressure at the ground. The proposed explanation for this
393 is that the fluctuations of dynamic pressure are centered on the mean as the vortices can pass
394 either side of the measurement point and can rotate in either direction. Whereas the fluctuations
395 in static pressure associated with all eddies are negative compared to the mean static pressure.
396 Hence for comparison with q_{RMS}/q_{mean} the static pressure fluctuations must be calculated as the
397 square root of the mean of the second moment about an offset pressure. This offset is the
398 proposed ‘true zero’ static pressure at the ground.399 This ‘true zero’ static pressure can be considered as the static pressure in the absence of
400 turbulence effects in the flow above the boundary layer. In the skewed PDF of static pressure above
401 ground the same approach cannot be adopted. This is confirmed in Fig 10 where the measured
402 pressure difference $(p_z - p_0)/q_{mean\ 6m}$ has been added to Cp_0 giving data points above Cp_z for $z > 3$
403 m. The relationship between turbulence and static pressure fluctuations was also commented on
404 by Tsuji et al (2007) who concluded that ‘The ratio $p_{rms}/\rho u_{rms}^2$ was found to be of the order of one’.



405
 406 FIGURE 10. Calculated static pressure coefficients: 10 m mast values in blue (4 points) and 6 m mast value in
 407 red (3 points). The dashed lines are curve fits to C_{p_z} extrapolated to $z = 0$ to give C_{p_0} .
 408

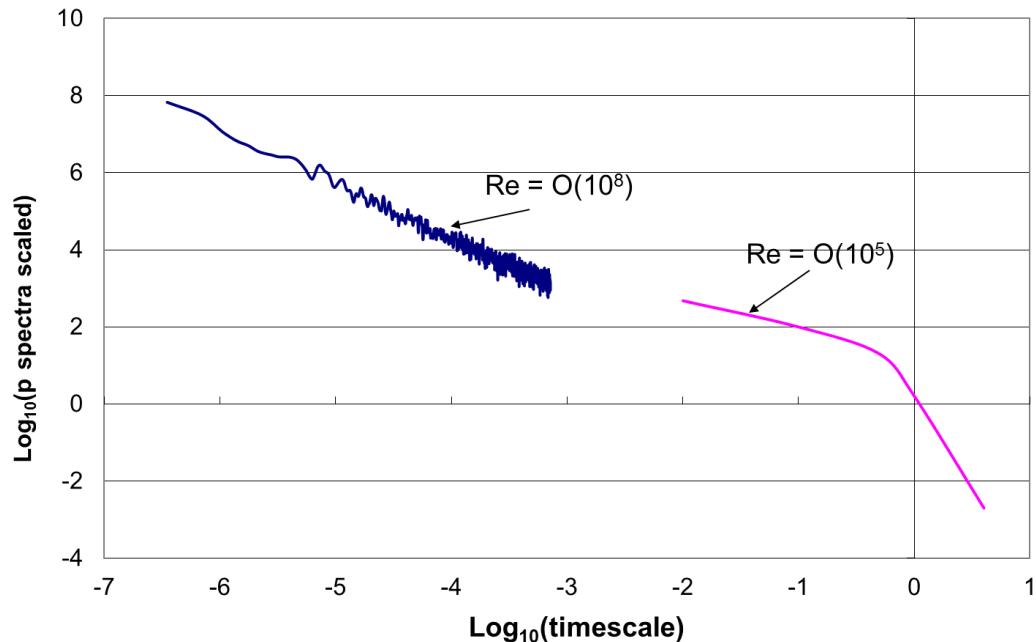
409 The values given in Table 8 for the mean static pressure at the ground ($C_{p_0} = -0.143$) gives
 410 an off-set to the pressures in the PDF in figure 9 of -6.54 Pa. Applying this off-set gives a
 411 probability level of $\approx 0.1\%$ of the measured static pressure at the ground being greater than zero,
 412 suggesting that there are only a few intermittent positive static pressure values above the 'true
 413 zero' static pressure, but even these are within experimental error. Figure 10 illustrates the
 414 sensitivity of static pressure to turbulence which has an impact on the selection of reference
 415 pressure when making measurements in boundary layer flows. The mean value of static pressure
 416 is significantly sensitive to distance from the surface; Tsuji et al. (2007) showed minimum values
 417 of static pressure at a height of approximately 10% of the boundary layer thickness, but the results
 418 in tables 7 and 8 suggest a much lower height proportionally in the ABL. Komerath et al. (1985)
 419 observed that in pipe flow the static pressure fluctuations within the flow exceeded those recorded
 420 at the surface, which is consistent with the results here.

421
 422

423 **4. COMPARISON WITH LABORATORY FLOWS**

424 Wind-tunnel work by Tsuji et al. (2007) is the only work known to the authors that measures
425 the static pressure at the surface and within a turbulent boundary layer. The static pressure within
426 the flow was sensed by a small static probe aligned to the mean flow direction. Their observations
427 were made over a Reynolds Number based on momentum thickness of the boundary layer (θ) of
428 5000 to 20000, in a boundary layer of thickness (δ) 52 to 62 mm (Re dependent). The equivalent
429 value for the ABL is $R_\theta \sim 10^7$. For the logarithmic region of the boundary layer, they (Tsuji et al
430 2007, figure 9 'log region') found that the static pressure spectrum had a power-law decay between
431 -1.2 and -1.5, which encompasses the present ABL measurements. Tsuji's measurements also
432 included mean static pressure, and showed that the pressure at the surface is below the free-stream
433 static pressure. Also there is a significant decrease in pressure in the lower part of the boundary
434 layer, represented by a minimum pressure coefficient of -0.006 based on free-stream dynamic
435 pressure. Whilst there is no direct comparison with the ABL measurements described here, an
436 estimate from the results in table 8 for $z = 6$ m gives a pressure coefficient of approximately -0.14
437 (based on the estimated dynamic pressure at δ), although the minimum may be well above the
438 height at which measurements were made. The root-mean-square values of static pressure have a
439 maximum value of a little over 1% of free-stream dynamic pressure in the study by Tsuji et al.
440 (2007), compared to an estimate of around 3 to 7% or more in the ABL.

441 Goody (2004) reports surface pressure measurements beneath a two-dimensional, zero-
442 pressure-gradient boundary layer made by seven research groups. The empirical spectral model of
443 these surface pressure fluctuations developed by Goody is compared with the full-scale ABL
444 measurements made in 2000 in figure 11, where the Reynolds number, Re , used in the comparison
445 is based on the frictional velocity at the ground (u_τ) and the boundary-layer thickness (δ). The
446 comparison is presented graphically using the scaling defined by Goody. Although there is a
447 considerable difference in Reynolds number, the ABL measurements at an estimated $R_\delta \sim 10^8$ are
448 consistent with the indications from wind-tunnel measurements where $R_\delta \sim 10^5$. Only an order of
449 magnitude can be estimated as the ABL boundary-layer thickness is not known, but as there is no
450 overlap of measurements with the timescale it is only the gradients of the lines that are comparable.



451

452 **FIGURE 11** Pressure spectra scaled by inner variables (see Goody 2004)

453

454 The measurements by Komerath et al. (1985) for pipe flow, show that the spectrum of static
 455 pressure decays at a slower rate than does dynamic pressure, but the presentation is not in a form
 456 to assess the decay rate.

457 There is evidence (Lim et al. 2007) of Reynolds-number sensitivity in the magnitude of the
 458 core pressure in regions of stable vortex flows around bluff bodies. This implies that in a simulated
 459 ABL flow and low Re boundary-layer flows in a wind tunnel, the core pressure within vortex type
 460 structures will underestimate that of a high Re flow: an observation that is consistent with the
 461 results from Tsuji et al. (2007) and Goody (2004).

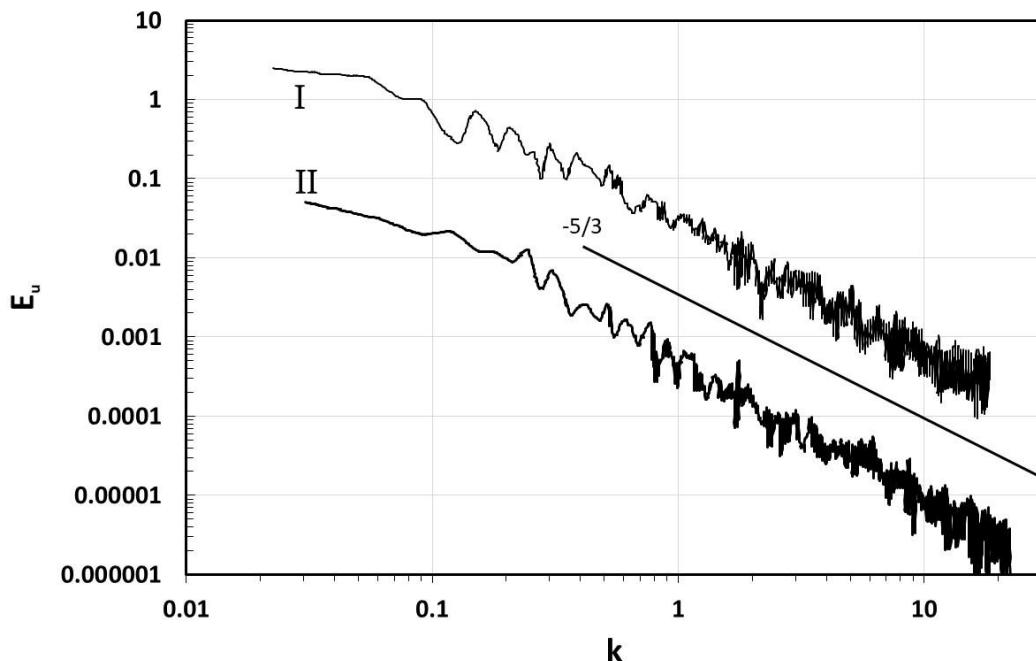
462

463 **5. COMPARISON WITH OTHER FULL-SCALE MEASUREMENTS**

464 In 1998, Albertson et al. published a paper on measurements of static pressure in the flow over a
 465 grass-covered forest clearing. The introduction to the paper states: 'Turbulent fluctuating static
 466 pressure is perhaps the least understood basic flow variable in the atmospheric surface layer
 467 (ASL)', and the paper continues to elaborate on the difficulty of measuring this variable. Albertson
 468 et al. used a fundamentally different sensor from the probes used here, consisting of two horizontal
 469 flat plates, 150 mm in diameter, 100 mm apart with a central 2 mm tap on the inside of each plate
 470 (Robertson 1972).

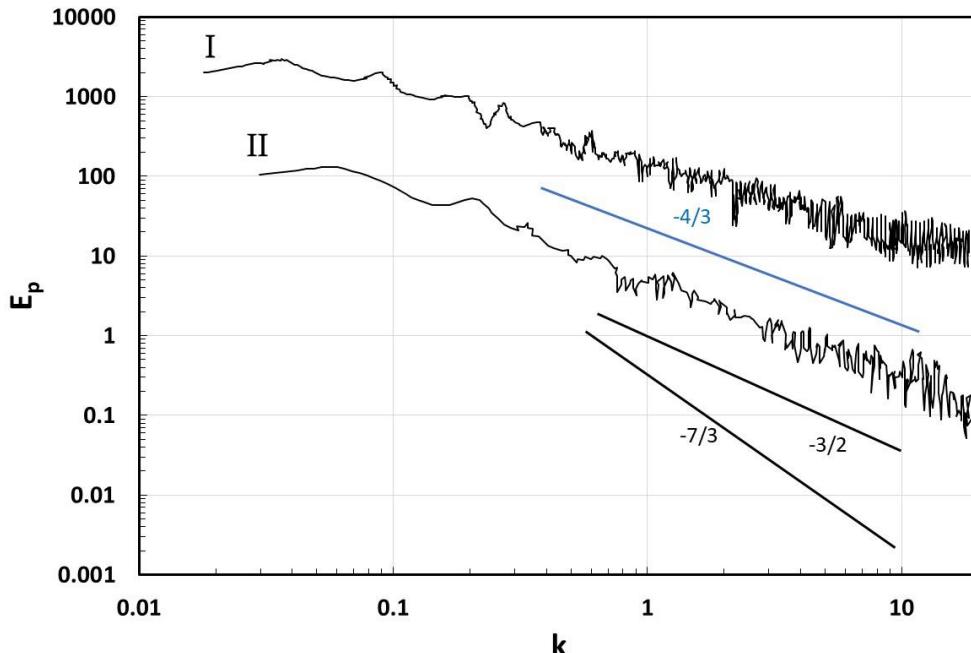
471 Two figures from Albertson et al. (1998) are reproduced in figures 12 and 13 which show
 472 two of their representative runs. Velocity was measured at a height of 1.55 m above ground using
 473 a sonic anemometer (Gill Instruments) of the same type as used in the Silsoe experiments. Figure
 474 12 shows the longitudinal-velocity power spectra with the $n^{-5/3}$ line for comparison: this is similar
 475 to figures 4 and 6 and is consistent with the observation in tables 3 and 5. The corresponding
 476 measurements of pressure 0.3 m to one side of the sonic anemometer are reproduced in figure 13.
 477 Albertson et al. (1998) show two lines, the $n^{-7/3}$ after Kolmogorov (1941), and $n^{-3/2}$ suggested by
 478 Elliott (1972). An additional line for $n^{-4/3}$ has been added by the authors, and as with figures 4 and
 479 6, it is in close agreement with the observed spectra. Albertson did not propose a -4/3 decay and
 480 expressed a view on alternative reasons for the observation. In personal contact with Albertson,
 481 who is no longer active in this area of research, he was unable to comment further on the
 482 observations, but it should be recognized that his measurements were the first published work that
 483 observed the near -4/3 decay.

484



485
 486
 487
 488

FIGURE 12. Longitudinal-velocity power spectra E_u for two sample files from
 Albertson et al. (1998) FIG 1.(a), where k is the wave number ($2\pi n/U$).



489
 490 FIGURE 13. Power spectra of static pressure E_p for two sample files by
 491 Albertson et al. (1998) FIG 4 (a), with $-4/3$ line added
 492

493 **6. A VORTEX MODEL**

494 Attempts by dimensional or alternative analyses to corroborate the observed spectral
 495 property of static pressure have so far proved unfruitful. Numerical experiments with a vortex
 496 model, described in Appendix B, have, however, been helpful in understanding the processes in
 497 turbulent shear flows. The model represents Eulerian flow at a single sensing point in turbulent
 498 shear flow composed of discrete eddies, but not necessarily a boundary layer flow.

499 The indications from the very simplified model presented here are that spectral properties of
 500 some parameters are well represented by a very limited number of vortices, but some statistical
 501 properties are sensitive to further refinement of the model to include additional vortices to enhance
 502 turbulence levels. The model includes the inclination of the vortices to produce a shear flow, but
 503 the transverse velocity component which is sensitive to yaw of the vortex has not been included.
 504 The indications from the model are that when the spectral decay rate of wind dynamic pressure
 505 agrees with the experimental findings of $-5/3$, then the spectral decay rate of static pressure
 506 consistently has an exponent close to $-4/3$. The value of $-7/3$ that appears in the literature is thus
 507 not supported by the simple model.

508 The main reason for exploring a model of this type is to assist in the identification of vortical
509 structures in the ABL. Single-point Eulerian measurement of velocity is clearly insufficient as the
510 model shows that there is no unique velocity ‘signature’ of a vortex as it depends on the path of
511 the core of the vortex. Measurement of static pressure adds significant information, in relation to
512 vortex size, magnitude and presence, but not to location, pitch angle or yaw angle. In combination
513 with the velocity measurements, further information can be deduced, although not to an extent that
514 enables a mechanistic solution to be developed since it has not been possible in the experiments to
515 measure static pressure at exactly the same position as velocity.

516

517 7. CONCLUSIONS

518 The two sets of field measurements provide strong and consistent evidence that in the inertial
519 subrange the spectral pattern of static pressure in the lower part of the ABL has a decay rate close
520 to an exponent of $-4/3$ ($\pm 2.5\%$ or better for each of 4 measurements at 4 different heights). In such
521 a flow, the wind speed and the wind dynamic pressure conform to a decay rate with the expected
522 exponent of $-5/3$ ($\pm 6\%$ or better for each of 4 measurements at 4 different heights). These decay
523 rates accord with those found in the full-scale study by Albertson et al. (1998). Measurements
524 made in a wind tunnel (Tsuji et al. 2007 and Goody 2004) indicate a similar finding although a
525 Reynolds-number sensitivity introduces higher decay rates at low Re . Albertson et al are the only
526 comparative measurements that show the coincident velocity spectrum and this had a $-5/3$ decay.

527 The mean static pressure within the boundary layer compared to ‘true static’ pressure,
528 defined as the static pressure in the low turbulent freestream flow above a boundary layer, has been
529 calculated. It has been shown that the mean of the second moment of static pressure about ‘true
530 static’ is equal to the variance of local dynamic pressure. This relationship enables an estimate of
531 the local static pressure in comparison with ‘true static’ pressure to be made when p_{RMS} and q_{RMS}
532 are known. The significance of this result is that measurements made with a reference pressure
533 from above the boundary layer in a wind tunnel flow will not equate with a reference pressure
534 from a tapping in the surface, and not with full-scale comparison where reference pressure is
535 dependent on location and turbulence level.

536 A simple vortex model of Eulerian flow has been developed which was designed to give an
537 $n^{-5/3}$ decay for wind dynamic pressure spectra; this model then yields an $n^{-4/3}$ decay for the static
538 pressure spectra. The model does show that the static pressure spectral decay is dependent on the

539 velocity spectral decay and that the -4/3 value will only apply in the inertial subrange where the
540 velocity (or dynamic pressure) spectrum has a decay of $n^{-5/3}$. The cospectrum of Reynolds stress
541 is also well represented in the vortex model. The model has the potential to be developed further
542 to produce more realistic levels of turbulence, but was adequate for the spectral pattern described
543 here.

544

545 **ACKNOWLEDGEMENTS**

546 Figures 12 & 13 have been reproduced from Albertson, JD, Kata, GG, Pariange, MB, Eichinger, WE. Spectral scaling
547 of static pressure fluctuations in the atmospheric surface layer: The interaction between large and small scales. Physics
548 of Fluids, Vol **10**, No 7, July 1998 with the permission of AIP Publishing. The measurements in 2000 were part of the
549 science programme conducted at Silsoe Research Institute, and funded by the BBSRC. The measurements in 2015/16
550 followed full-scale measurements made on the Silsoe site as part of the EPSRC funded Refresh Programme (Ref
551 EP/K031893/1), and formed part of the contribution to the Programme by the University of Birmingham.

552

553

554

555 **DATA AVAILABILITY STATEMENT**

556 The data that support the findings of this study are available from the corresponding author
557 (roger@hoxey.com) and also from Andrew Quinn (a.d.quinn@bham.ac.uk), Peter Richards
558 (pi.richards@auckland.ac.nz) and Adam Robertson (adamprobertson@gmail.com) upon
559 reasonable request.

560

561

562 **APPENDIX A.**

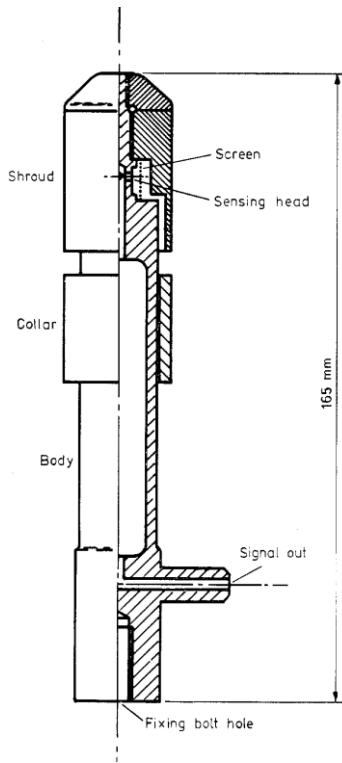
563 **A1. A Probe for Measuring Static Pressure in the ABL**

564 A traditional static probe of the type often incorporated into a pitot-static probe is not
565 designed for use in turbulent flow which has significant variations in yaw and pitch (Bryer &
566 Pankhurst, 1971). An early meteorological instrument developed by Dines (Meteorological Office,
567 1956) incorporated a directional pitot tube for total pressure and a vertical tube with tapping holes
568 around its circumference, making the instrument insensitive to the horizontal flow direction. The
569 device was used for many years as the standard instrument for measuring wind speed in many
570 countries including Australia where its performance has recently been assessed by Miller et al.
571 (2013). The instrument was found to have a pressure coefficient of approximately 1.5 (Re
572 dependent), comprising 1.0 for the pitot and -0.5 for the integrated pressure around the vertical
573 tube.

574 The vertical tube with circumferential tapping holes was developed by Marshall (1976) as a
575 stand-alone instrument by adding a shroud around the tapping holes which could be adjusted to
576 give zero pressure coefficient. A smaller version of this probe (figure 15) was developed at Silsoe
577 Research Institute for full-scale measurements with the addition of a collar which is easily adjusted
578 for probe calibration. Details of the probe and its calibration are given in Moran & Hoxey (1979)
579 with key results summarized here.

580 The static probe was initially calibrated on a cut grass field in natural wind with a mean wind
581 speed of 7 m s^{-1} . It was mounted 3 m above ground and the sensed pressure compared to the
582 pressure from a ground surface tapping. The collar was adjusted to give mean zero pressure
583 difference. The probe was then mounted in a low turbulence wind tunnel where it was found to
584 have a pressure coefficient of +0.07. Initially all other probes were calibrated in the wind tunnel
585 to give the same pressure coefficient. The probe was checked for sensitivity to pitch and Reynolds
586 number in the wind tunnel: for $\pm 5^\circ$ of pitch the probe had a +1% error and over the range of wind
587 speeds in the full-scale experiment the variation with increasing wind speed was -2%. In
588 combination these errors partially cancel each other giving an overall estimate of error of $\pm 1\frac{1}{2}\%$
589 of wind dynamic pressure.

590



591

592 FIGURE 15. Part cut-away drawing of the static probe, the shroud and collar had a diameter of 28 mm.

593

594 The difference between the full-scale and wind-tunnel calibration was not explained until
 595 more recently when preliminary experiments of the type described here showed that the mean
 596 static pressure in the ABL initially decreases with height from the ground. By setting the pressure
 597 difference from the probe at 3 m to the ground tap to 'zero' is incorrect: the wind-tunnel calibration
 598 now indicates that there is a mean pressure coefficient difference of -0.07 between 3 m above
 599 ground and the ground level tapping in the field experiment.

600 For the probes used in the experiments described here, the wind-tunnel calibration procedure
 601 was changed and the collar was set to give zero pressure coefficient in low-turbulence flow.

602

603

604 APPENDIX B.

605

606 **B1. A Simple Vortex Model**

607

608 A simple Rankine-type vortex model has been developed of the Eulerian flow past a single point
609 in a shear flow to represent the full-scale measurements that have been made. The vortex model
610 with circulation Γ , in a continuous mathematical form, has been used, consisting of a rotational
611 core (radius a) and an irrotational outer region. The tangential velocity (V) at a radius r is

612
$$V(r) = \Gamma \cdot r / (a^2 + r^2)$$

613 The vortex is assumed to move in a stream of constant velocity, U ; hence the fluctuating
614 velocity components (u' and v'), as sensed at a fixed point distance d from the line of passage of
615 the vortex are

616
$$u'(t) = \frac{\Gamma d}{(Ut)^2 + d^2 + a^2}$$

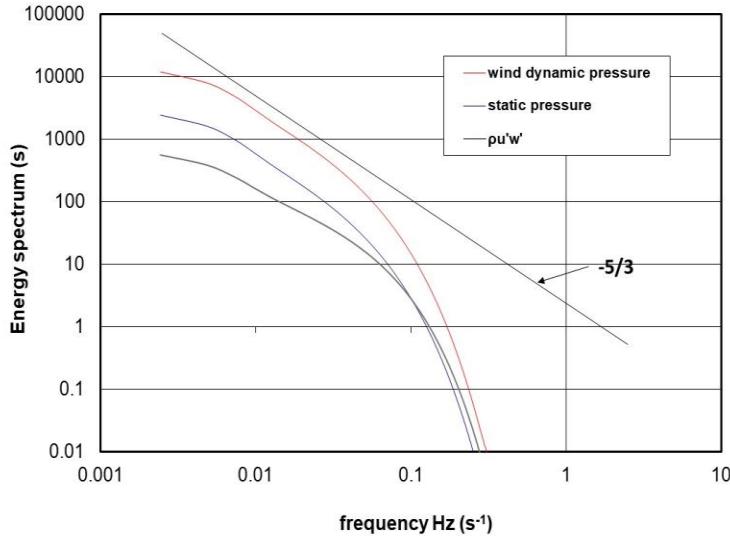
617
$$v'(t) = \frac{\Gamma Ut}{(Ut)^2 + d^2 + a^2}$$

618 The corresponding static pressure (p') is

619
$$p'(t) = -\frac{1}{2} \rho \frac{\Gamma^2}{(Ut)^2 + d^2 + a^2}$$

620

621 The energy spectra of wind dynamic pressure ($Eq(n)$) and of static pressure ($Ep(n)$) for a single
622 vortex have been calculated using a standard FFT algorithm with 4096 points and are shown in
623 figure 16, where the spectra have been divided by the integrated spectrum of the wind dynamic
624 pressure; a procedure that has been adopted throughout this paper. The vortex has been inclined to
625 the vertical to represent shear in the simulated flow, giving a time-dependent vertical velocity (w').
626 The dynamic pressure has been calculated from the velocity components, from which the Reynolds
627 stress ($-\rho u' w'$) has also been derived. The parameters used in the single-vortex model are:
628 circulation Γ ($\text{m}^2 \text{s}^{-1}$) = 100, core diameter a (m) = 20, distance d (m) = 40, inclination (degrees) =
629 25 in a stream U (m s^{-1}) = 8.



630

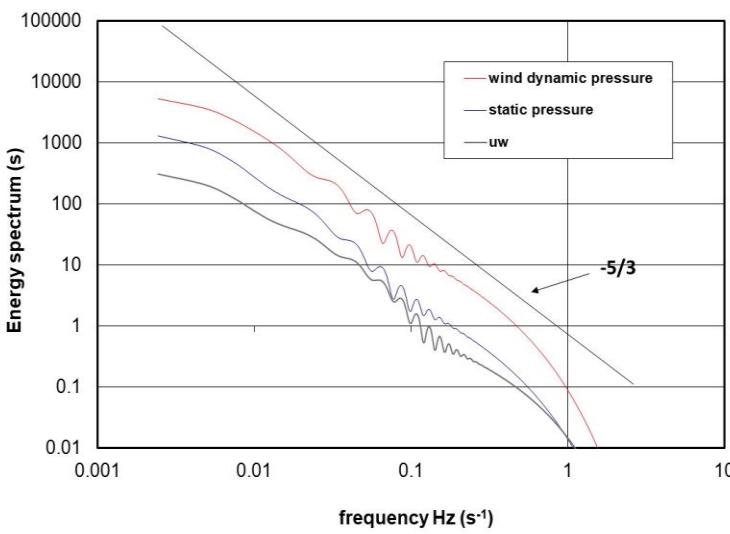
631

FIGURE 16. Energy spectra of a single vortex model.

632

633 The spectral pattern by adding a second smaller vortex (circulation Γ ($\text{m}^2 \text{s}^{-1}$) = 10, core diameter
634 a (m) = 2, distance d (m) = -4, inclination (degrees) = 25) is shown in figure 17, and adds higher
635 frequency energy. The spectra for wind dynamic pressure and static pressure are similar in these
636 examples, as the distance of the observer from the vortex core (d) is greater than the rotational core
637 radius (a). . Examination of $Eq(n)$ and $Ep(n)$ shows that when the vortex core passes close to the
638 observer, $Eq(n)$ is smaller than $Ep(n)$. This is a significant result as it explains why, in a complex
639 passage of vortices, the spectral pattern of static pressure will decay at a slower rate.

640



641

642

FIGURE 17. Energy spectra of a two vortex model.

643

644 A small number of additional vortices of different intensity, core size and path distance from the
 645 stationary observer, randomly occurring in the time series, were added to the single-vortex model.
 646 Within the concept of a simple vortex model, shear is introduced by inclining the vortex from the
 647 vertical. To attain the desired shear for a boundary-layer, vortices are required to be inclined
 648 forward by 20°-30° from the vertical. A multiple vortex model was constructed consisting of only
 649 4 pairs of vortices, one of each pair passing each side of the observer. The quantities used in the
 650 model are given in table 9, where the stream speed U was 8 ms⁻¹.

651

Circulation Γ (m ² s ⁻¹)	100	10	2	0.1
Core diameter a (m)	20	2	0.2	0.02
Distance d (m)	±40	±4	±0.4	±0.01
Inclination (degrees)	25	25	25	25

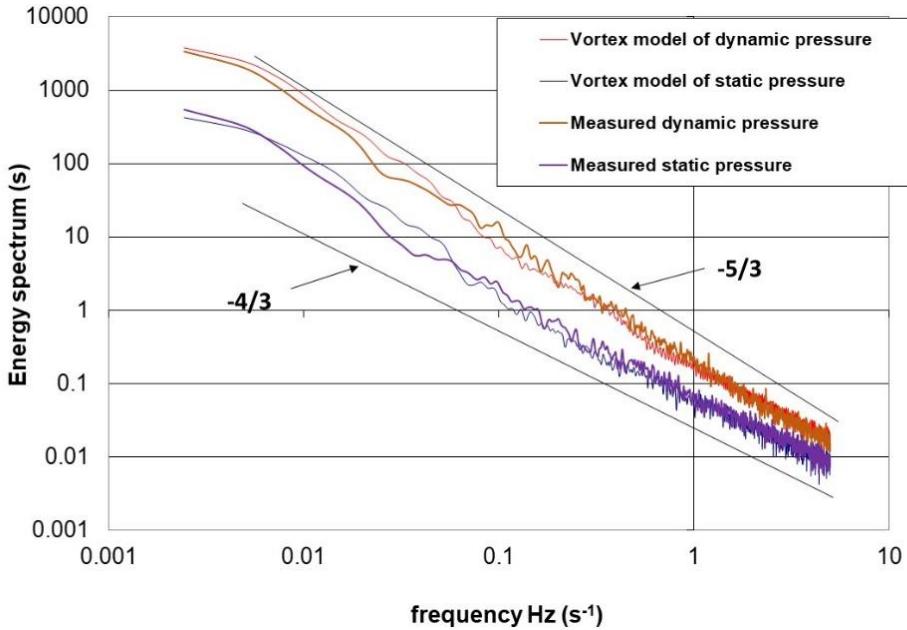
652

653 TABLE 9. Quantities used in the vortex model.

654

655 Continuing to add smaller vortices adds energy to the spectrum at higher frequency and it
 656 was found that 8 vortices were sufficient to give an energy spectrum close to the spectrum of
 657 dynamic pressure and of static pressure measured at a height of 6 m in the full-scale measurements.
 658 This is shown in figure 18; the same windowing was applied to the spectra for presentation
 659 smoothing as was applied to all full-scale measurements to maintain consistency.

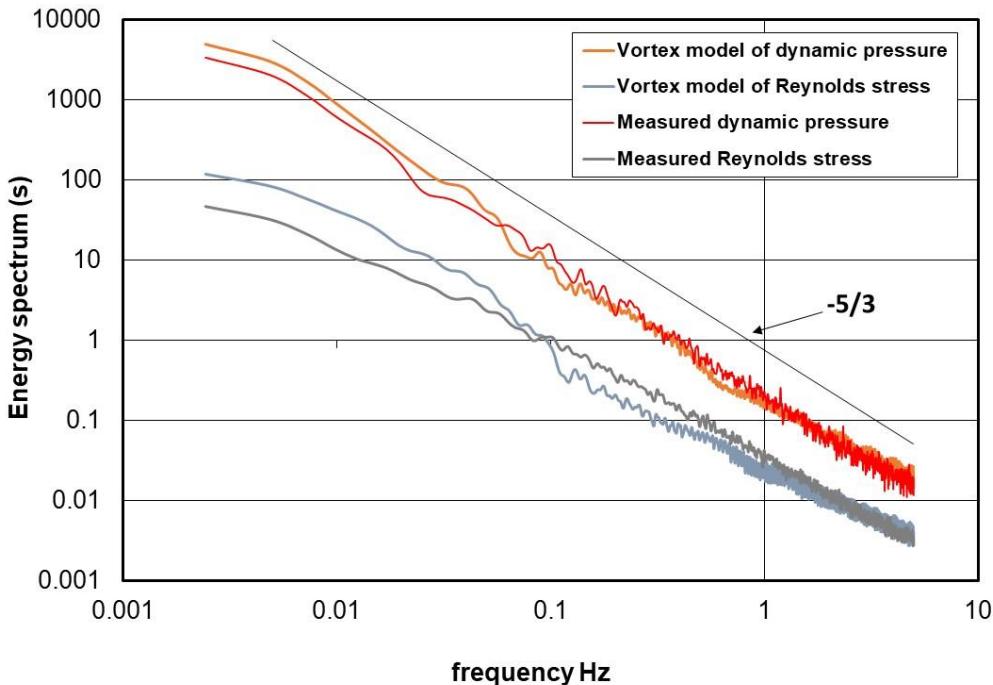
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661
662
663
664

FIGURE 18. Wind dynamic pressure and static pressure spectra of a multiple vortex model compared to the measured spectra.

665 The selection of vortices influences the spectral decay rate and hence the target for the
666 dynamic pressure spectrum was set to $n^{-5/3}$. This is the case in figure 18, and the coincident static
667 pressure spectrum, also shown in figure 18, has a decay close to $n^{-4/3}$. The cospectral density of
668 the streamwise and vertical components, i.e. the Reynolds-stress cospectrum, is shown in
669 figure 19. The selection of only 4 pairs of vortices appears adequate for the representation of wind
670 dynamic pressure and static pressure but not sufficient for the Reynolds-stress cospectrum,
671 although the model provides an indication of the experimental observed finding. The model is
672 possibly inadequate as all the vortices were inclined at 25 degrees; this gave $u_r/U = 0.033$, half of
673 the measured value. More vortices are needed and the inclination angle randomized with a suitable
674 bias; the indication from figure 19 is of a lower inclination angle for large vortices. The 8-vortex
675 model produced a turbulence intensity of 5%, which is only a quarter of the measured level and
676 hence is not a representation of the flow statistics.
677



678
679 FIGURE 19. Reynolds-stress cospectral properties of a multiple vortex model
680

681 B2. Concluding comments

682 The properties of the simple vortex model proposed of shear flow contain many of the spectral
683 characteristics found in experimentally-measured, near-surface boundary-layer wind. Specifically:

- 684 (i) spectral decay for the velocity components and of the wind dynamic pressure
685 approximating to $n^{-5/3}$
- 686 (ii) static pressure spectrum with a decay rate approximating to $n^{-4/3}$
- 687 (iii) Reynolds-stress cospectrum with a decay similar to experiment.

688
689 The simple vortex model does not represent a turbulent boundary layer but only the

690 Eulerian flow past a stationary measurement point in a shear flow. Although the 8-vortex model
691 produced a turbulence intensity of only 5%, a quarter of the measured level, the model correctly
692 represents the measured spectra for dynamic pressure and, importantly, provides corroboration
693 on the near $n^{-4/3}$ decay in the static pressure spectrum that was observed experimentally in the
694 full-scale measurements. The model suggests that the flow can be represented by a cascade of
695 discrete vortices and would be useful in computational analyses.

696

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