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Numerical Study of Debris Flight in a Tornado-like Vortex

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Abstract

This paper presents the numerical study on the flight behaviour of spherical compact debris in a tornado-like wind field. The tornado-like vortex corresponding to a swirl ratio of 0.7 was generated using Large-eddy Simulation and the trajectories of 2250 individual debris particles placed in the flow were computed using Lagrangian-particle tracking. The debris corresponded to five groups (A, B1, B2, B3 and C) based on the value of the Tachikawa number (K) which ranged between 0.6 and 2.5. An analysis of the simulated flow field revealed that the tornado-like vortex consisted of two main features - a core at the centre with low velocity ($\sim 0.25\text{m/s}$) which was surrounded by thick vortex wall composed of high velocity magnitudes ($\sim 9.4\text{m/s}$). Updraft flows were observed around the core of the vortex and as a result, debris positioned around the core radius region were found to be 24% more likely to become wind-borne than debris positioned at the vortex wall region. Three groups of debris (B1, B2 and B3) with varying mass and density were studied for the aerodynamic similarity by retaining the fixed value of $K=1.2$; all three debris groups exhibited the propensity to travel with similar flight characteristics. An analysis of the data pertaining to the flight behaviour of the three debris group (A, B1 and C) with varying K revealed that the low mass debris group A ($K=2.5$) had the highest propensity to become wind-borne and was more likely to travel for the longest time with considerable variability observed in individual debris trajectories. However, somewhat counterintuitively, the high mass debris group C ($K=0.6$) were found to have the furthest impact range despite their short flight duration; this was due the high mass debris being ejected out of the vortex with greater inertia, while debris with a lower mass had a tendency to be trapped in the flow that circulates around the vortex core.

1. INTRODUCTION

Tornadoes are perhaps one of the most destructive weather phenomena due to their potentially violent and unpredictability nature. The wind speeds of a tornado can reach up to 450 kilometres per hour and can cause severe damage to civil structures and loss of lives. In March 2019, a tornado struck the Lee County in Alabama (USA) and caused catastrophic damage around the region: it was reported that the tornado was classed as an EF4 with wind speeds reaching 270 kilometres per hour (Darrow, 2019) and claimed the lives of more than 23 people. Tornadoes are complex phenomena and despite their frequent occurrence, surprisingly little is known about the flow structure. Due to the violent nature and unpredictable path of tornadoes, details of the tornado flow field using full scaled methods have, to date, proved to be rather elusive; therefore, recourse is often made through physical and numerical modelling. The earliest systematic experiment for generating laboratory-scaled tornado-like vortices can perhaps be attributed to Ward (1972). Ward developed a laboratory simulator with an exhaust fan at the top to provide updraft flow and vanes at the ground to generate angular momentum. This approach enabled the reproduction of tornado-like flow from a single-celled vortex

46 into a multi-celled vortex and provided an alternative to study tornado flows. However, Ward's
47 simulators were limited by their size unable to reproduce some vortex characteristics due to the
48 design. Therefore, an increasing number of studies have been conducted in order to numerically
49 simulate such flow.

50 Recent numerical studies have been conducted extensively to study the flow fields of tornado-like
51 vortices. Howells et al. (1988) and Nolan and Farrell (1999) used the axisymmetric Navier-Stokes
52 equations in cylindrical coordinates to examine the flow structure of a tornado-like vortex. Lewellen
53 et al. (1999) conducted Large-eddy Simulation (LES) to examine the interaction between the
54 generated vortex and the surface roughness. Unsteady Reynolds-Averaged Navier-Stokes (URANS)
55 model for the numerical simulation were performed by Hangan and Kim (2006) to reproduce tornado-
56 like vortices. They concluded that the core of the tornado was the most difficult region to properly
57 reproduce. Lewellen and Lewellen (2007) employed a LES turbulence model to study the effects of
58 swirl ratio (a parameter which measures the strength of a circulation relative to the updraft flow) on
59 vortex structure and translation speed. Kuai et al. (2008) conducted numerical research on full scale
60 and laboratory simulated tornadoes using the k - ϵ turbulence model and verified the ability of
61 numerical methods to capture the flow fields of the tornadoes. Hangan and Kim (2008) conducted
62 simulations using an URANS model to reproduce tornadoes at different swirl ratios, and discovered
63 that a high swirl ratio corresponded with full scale data from the Spencer tornado observed by
64 Alexander and Wurman (2005). Ishihara et al. (2011) compared the flow fields of two different types
65 of vortices and validated the results with the laboratory experiments. Natarajan (2011) numerically
66 simulated different stages of tornadoes and confirmed the findings from earlier physical simulations
67 is the primary governing parameter of a vortex. Research undertaken by Ishihara and Liu (2014)
68 conducted an in-depth study of a tornado-like vortex during touch down stage with detailed analysis
69 of the flow field; while Liu and Ishihara (2015) further investigated the stages of tornado-like vortices
70 in order to capture of characteristics of the evolution of different vortex stage. The excellent research
71 conducted by the aforementioned researchers and others provides an insight to tornado flows and its
72 mechanism; however, the definition of the swirl ratio from these studies varies from one to another,
73 therefore, detailed discussions on the definition of swirl ratio employed in this study were discussed
74 in section 2.2.

75 Another key factor that contributes to the tornado induced damage is flying debris. Everyday objects
76 can become damaging projectiles when subject to a tornado, and individuals have been affected
77 considerably by debris which become windborne as a result of a tornado (Harms, 2019). Numerous
78 research on flying debris have been undertaken since the pioneering works of Tachikawa (1983), which
79 proposed a dimensionless parameter, K , which describes the ratio between the inertial forces of the
80 flow to the weight of the debris. Wills et al. (2002) categorized debris based on their respective
81 damage performance with light, medium or heavy weight missiles; other identification based on the
82 geometrical structure can further categorize the debris into compact type (3D), plate type (2D) and
83 rod type (1D). Further work on the trajectories of compact type (3D) spherical debris in strong winds
84 was conducted by Holmes (2004) and English (2005). Baker (2007) also generalized the equations of
85 motion for debris flight in dimensionless form for compact and sheet-like debris. Furthermore, plate-
86 like (2D) debris (Tachikawa, 1983; Wang and Letchford, 2003; Holmes et al., 2004) and rod-like (1D)
87 debris (Lin et al., 2007; Richards et al., 2008) under different wind conditions have also been studied
88 extensively, but none of these studies were carried out under tornado-like flow conditions. Recently,
89 several investigations on debris flight in tornadoes have been conducted; Maruyama (2011) simulated
90 a tornado-like vortex using large eddy simulations with the statistical distribution of debris velocities.
91 Bourriez et al. (2017) studied the flight paths of debris in laboratory controlled conditions. Research
92 undertaken by Baker and Sterling (2017) provided an analytical model for the velocity and pressure

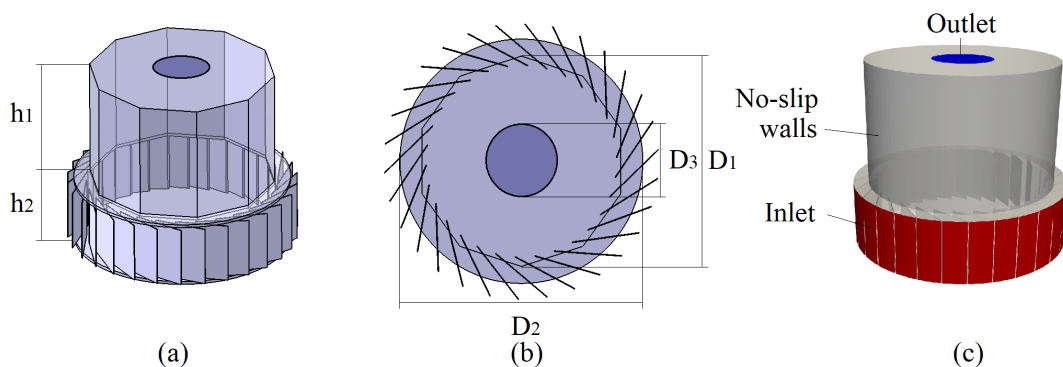
93 fields of tornadoes as well as the prediction of debris trajectories within the tornado. While these
 94 studies provide a great insight to the flow fields and trajectories, there is a lack of detailed analysis on
 95 flying debris in tornadoes. Hence, the objective of the present work was to investigate the behaviour
 96 of flying debris in a tornado-like wind field. The tornado-like vortex was simulated using LES. The flow
 97 fields of the vortex were analysed and the characteristics features were presented. Trajectories of five
 98 debris groups with varying Tachikawa number were computed and the flight data were analysed.

99 The paper is organized as follows: Section 2 describes the procedure adopted and the numerical
 100 details relating to this. Section 3 outlines the three dimensional flow field, characteristics and
 101 mechanisms of the simulated tornado-like vortex. The detailed analysis of debris flight in tornado wind
 102 field were discussed in section 4. Appropriate conclusions are given in section 5.

103 2. METHODOLOGY

104 2.1 DESCRIPTION OF PHYSICAL SIMULATOR

105 The model used in the current research was based on the University of Birmingham Tornado Vortex
 106 Generator (UoB-TVG), shown in figure 1. A series of physical simulations were undertaken by Gillmeier
 107 et al. (2017) and were used as validation for the numerical flow field simulated in the current paper.
 108 The UoB-TVG was a large-scale Ward-type vortex generator based on the design of Ward's simulator
 109 (Ward, 1972) with exhaust fans placed at the top of the convection chamber that were used to
 110 generate an updraft flow. Situated below the convection chamber was the convergence chamber,
 111 designed to draw air inwards with a series of guide vanes mounted at the edge of convergence
 112 chamber. Angular momentum was obtained by setting the guide vanes to different angles, thus
 113 generating different vortex structures. The convection chamber has the height, h_1 of 2m and diameter,
 114 D_1 of 3.1m and convergence chamber with the height, h_2 of 1m and diameter, D_2 of 3.6m with thirty
 115 guide vanes mounted around the edges of the convergence chamber. An exhaust outlet with
 116 diameter, D_3 of 1m was situated at the top of the convection chamber. The ratio between updraft
 117 diameter and the height of the convergence chamber was defined as the aspect ratio, a . The velocity
 118 at the inlet (U_∞) was 0.66m/s, which was computed based on the measured total outflow rate (Q) of
 119 $7.38 \text{ m}^3/\text{s}$ at the exhaust outlet. The velocity measurements of the flow field were made 100Hz using
 120 the Cobra Probe (Watkins et al., 2002) which was mounted in the simulator.



121

122 *Figure 1: (a) Geometry of the University of Birmingham Tornado Vortex Generator (b) Dimensions of the*
 123 *convergence chamber (c) Computational domain and boundary conditions.*

124 2.2 SWIRL RATIO

125 Whilst there are some variations for the definitions of swirl ratio in most laboratory studies (Monji,
 126 1985, Mishra et al., 2008, Matsui and Tamura, 2009, Tari et al., 2010 and Gillmeier et al., 2017) and
 127 numerical studies (Wilson and Rotunno, 1986, and Ishihara et al., 2011 and Ishihara and Liu, 2014),

128 the swirl ratio has generally been defined as the measure of intensity of the circulation of a vortex,
 129 while also describing the evolution of the stages of a tornado; from single-celled to multi-celled vortex.
 130 The swirl ratio, S used in the current research has been defined as:

$$S = \frac{\tan\theta}{2a} \quad [1]$$

131 where θ is the guide vanes angles and a is the aspect ratio, defined as:

$$a = \frac{2h_2}{D_3} \quad [2]$$

132 The definition of the aspect ratio is based on the physical dimensions of the simulator; the ratio
 133 between the diameter of the exhaust outlet (D_3) and the height of the inlet (h_2). The UoB-TVG has a
 134 fixed aspect ratio of 2, while other large-scale tornado vortex simulators have adjustable aspect ratios
 135 such as the WindEEE dome (Refan and Hangan, 2018) with aspect ratio of 0.35 to 1, VorTECH (Tang et
 136 al., 2017) of 0.5 to 1 and ISU Tornado simulator (Gairola and Bitsuamlak, 2019) of 1.09 to 5.46.

137 2.3 NUMERICAL DETAILS

138 The Large-eddy simulation approach employed in the current research was first proposed by
 139 Smagorinsky (1963); the LES uses sufficiently small grid resolution to directly compute the larger
 140 eddies in a turbulent flow, while the smaller unresolved scales of the turbulence were filtered and
 141 modelled via the sub-grid scale (SGS). Studies by Natarajan (2011), Maruyama (2011), Ishihara et al.
 142 (2011) and Ishihara and Liu (2014) found that the vortex core contains complicated turbulent flows
 143 and thus ideally suited to an LES. The open source CFD program OpenFOAM (OpenFOAM, 2019) was
 144 used to perform the LES with the assumption that the flow was incompressible and Newtonian in
 145 nature. The continuity and momentum equations were filtered as follows in order to obtain the
 146 governing equations:

$$\frac{\partial \bar{U}_i}{\partial x_i} = 0 \quad [3]$$

$$\frac{\partial \bar{U}_i}{\partial t} + \frac{\partial \bar{U}_i \bar{U}_j}{\partial x_j} = -\frac{\partial \bar{P}}{\partial x_i} + 2 \frac{\partial}{\partial x_j} (v + v_{sgs}) \bar{S}_{ij} \quad [4]$$

147 where U is the velocity field, t is the time and v is the kinematic viscosity. The spatial filtering operation
 148 for the LES is denoted by the bar over the physical quantities. The pressure (P) and filtered strain rate
 149 tensor (\bar{S}_{ij}) are expressed as:

$$\bar{P} = \frac{\bar{p}}{p} + \frac{(\overline{U_i U_j} - \bar{U}_i \bar{U}_j)}{3} \quad [5]$$

$$\bar{S}_{ij} = \frac{1}{2} \left(\frac{\partial \bar{U}_j}{\partial x_i} + \frac{\partial \bar{U}_i}{\partial x_j} \right) \quad [6]$$

150 The Smagorinsky model (Smagorinsky, 1963), was used to model the eddy viscosity under the effects
 151 sub-grid scale, v_{sgs} with the eddy viscosity coefficient as:

$$v_{sgs} = (C_s f_d \Delta)^2 \sqrt{2 \bar{S}_{ij} \bar{S}_{ij}} \quad [7]$$

152 where f_d is the damping function, Δ is the length scale of the SGS turbulence and C_s is the model
 153 coefficient, set to 0.1. The Van Driest type damping function (Van Driest, 1956) was employed in this
 154 study to calculate f_d and is expressed as:

$$f_d = 1 - \exp\left(\frac{-y^+}{25}\right) \quad [8]$$

155 where y^+ is the non-dimensional distance to the wall, depicted as the relationship between friction
 156 velocity and kinematic viscosity.

157 2.4 COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

158 The computational domain was created based on the configurations of the UoB-TVG, which was
 159 geometrically similar to the study by Gillmeier et al. (2017) as illustrated in figure 1. The convection
 160 chamber was simplified to a cylinder configuration for the convenience of grid generation. A cartesian
 161 coordinate system has been adopted for the generation of the computational domain, where the xy
 162 plane represents the horizontal plane while z axis represents the axis perpendicular to the horizontal
 163 plane. The flow enters the convergence chamber with a uniform velocity of $U_\infty=0.66$ m/s. The exhaust
 164 outlet was set with pressure outlet with the free stream pressure, $P_\infty=0$. A no-slip boundary condition
 165 was applied to the ground, surface walls of the guide vanes and the walls of the convection region.
 166 The results presented in this study were normalized using the characteristic parameters of the vortex:
 167 the maximum tangential velocity (U_T), the radius of the core (r_c) and time per revolution of the vortex
 168 (t_r). The method of determining the location of maximum tangential velocity and the radius of the core
 169 are presented in section 3.2, while the time taken for the vortex to complete a single revolution is
 170 defined as:

$$t_r = \frac{2\pi r_T}{U_T} \quad [9]$$

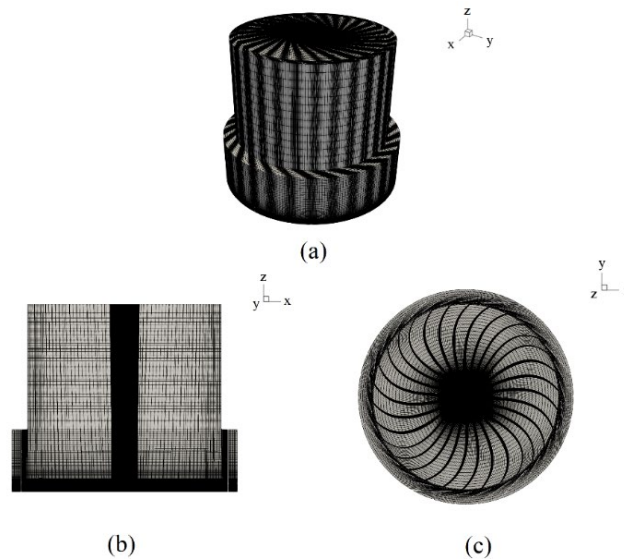
171 where r_T is the radial distance of the maximum tangential velocity. The pressure coefficient, C_p , is a
 172 non-dimensional parameter defined as:

$$C_p = \frac{P - P_\infty}{0.5 \rho_a U_T^2} \quad [10]$$

173 and ρ_a is the density of the air. The simulation was initialised with the inlet velocity, U_∞ . A second
 174 order implicit backward scheme was used to approximate the time discretization. The gradients were
 175 discretized with the second order central differencing scheme and the implicit PISO solver was used.
 176 (OpenFOAM, 2019). A constant time-step of $\Delta t= 5 \times 10^{-4}$ s was used throughout the entire transient
 177 simulation; this time-step was chosen to maintain the Courant-Friederichs-Lewy number (Courant et
 178 al., 1928) at the value less than 1 at every time step. The averaging of pressure and velocity were
 179 implemented when the vortex flow was fully developed, this was conducted by monitoring the
 180 residuals of each turbulent equation for convergence which ensured that the statistics did not change
 181 with time. Time time-averaged results were obtained by averaging the actual simulation time of 30
 182 seconds, which is equivalent to 300 vortex revolutions.

183 2.5 MESHING

184 ICEM-CFD (ICEM, 2012) mesh generator package was used to generate quadrilateral structured mesh.
185 In order to resolve the boundary layer around the viscous sub-layers, 20 layers of mesh were created
186 with the wall-adjacent spatial unit of $z^+=1$. Due to the axisymmetric structure of the tornado-like
187 vortex, a clustered mesh with high density was adopted at the centre of the convergence chamber
188 within the radius of 0.6 m from the centre, resulting in x^+ and $y^+ \approx 10$ in the tangential and radial
189 directions. Hyperbolic stretching was used to generate the remaining meshes to ensure smooth
190 transition. The mesh resolution around the guide vane regions in the convergence chamber were
191 adjusted for the generation of three different mesh resolutions - coarse, medium and fine mesh with
192 4 million, 7 million and 9 million cells respectively. The configuration of the generated mesh is shown
193 in figure 2. Whilst every effort has been made to accurately reproduce the physical simulator there
194 will inevitably be small differences introduced due to the meshing process. It is difficult to quantify
195 the impact of these differences, but in what follows it is assumed that beyond a certain mesh
196 resolution their effects are negligible (see section 3).



197

198 *Figure 2: Mesh of the computational domain: (a) Isometric view (b) Side view (c) Top view.*

199 2.6 COMPUTATION FOR FLYING DEBRIS

200 The three-dimensional motion of the debris in the tornado-like vortex was numerically computed.
201 Each individual debris was assumed to be a three dimensional spherical compact object which did not
202 undergo rotation. The Tachikawa number (Tachikawa, 1983) used in the current research is defined
203 as:

$$K = \frac{\rho_a U_\infty^2 d^2}{2m_d g} \quad [11]$$

204 where ρ_a is the density of the air, U_∞ is the inlet velocity, d is the diameter of the debris, m_d is the
205 mass of the debris and g is the acceleration due to gravity. The Tachikawa number K , describes the
206 ratio between the aerodynamic forces to the gravitational force, therefore, debris with lower mass
207 will have higher value of K and are in theory, prone to fly higher and further. Properties of the debris
208 considered in the current study were shown in table 1.

Table 1: Properties of the debris groups

Debris group	K	Diameter (m)	Density (kg/m ³)	Mass (kg)
A	2.5	0.00075	28.1	6×10^{-9}
B1	1.2	0.0015	28.1	50×10^{-9}
B2	1.2	0.00075	56.2	12×10^{-9}
B3	1.2	0.00037	112.4	3×10^{-9}
C	0.6	0.003	28.1	397×10^{-9}

210 The trajectories of the debris were computed using the transient solver
 211 icoUncoupledKinematicParcelFoam (OpenFOAM, 2019), where the motion was solved by considering
 212 the particle equilibrium using the Lagrangian frame of reference on the established flow field. Since
 213 the size of the largest debris considered (debris group C) was $\sim 10^8$ times smaller than the convergence
 214 chamber, the effects of debris on the flow were considered to be negligible. Hence, a one-way
 215 coupling was assumed to be sufficient, where debris were treated as point mass and generalized by:

$$\frac{ds_d}{dt} = U_d \quad [12]$$

$$m_d \frac{dU_d}{dt} = F_{total} \quad [13]$$

216 where s_d is the spatial position of the debris, U_d is the debris velocity, and F_{total} as the sum of all forces.
 217 The relevant forces acting on the particle were:

$$F_{total} = F_D + F_G \quad [14]$$

218 where F_D is the drag force and F_G is the gravitational force. These forces represent the dominant forces
 219 acting of the debris, while other forces were neglected. The drag force is expressed as:

$$F_D = \frac{3}{4} \frac{\rho_a m_d}{\rho_d d} \cdot C_D (U - U_d) |U - U_d| \quad [15]$$

220 where U is the velocity of the local flow field, and C_D is the spherical drag coefficient that is computed
 221 based on the debris Reynolds number (Putnam, 1961) as:

$$C_D = \begin{cases} \frac{24}{Re_d} \left(1 + \frac{1}{6} Re_d^{\frac{2}{3}}\right), & Re_d \leq 1000 \\ 0.424, & Re_d > 1000 \end{cases} \quad [16]$$

222

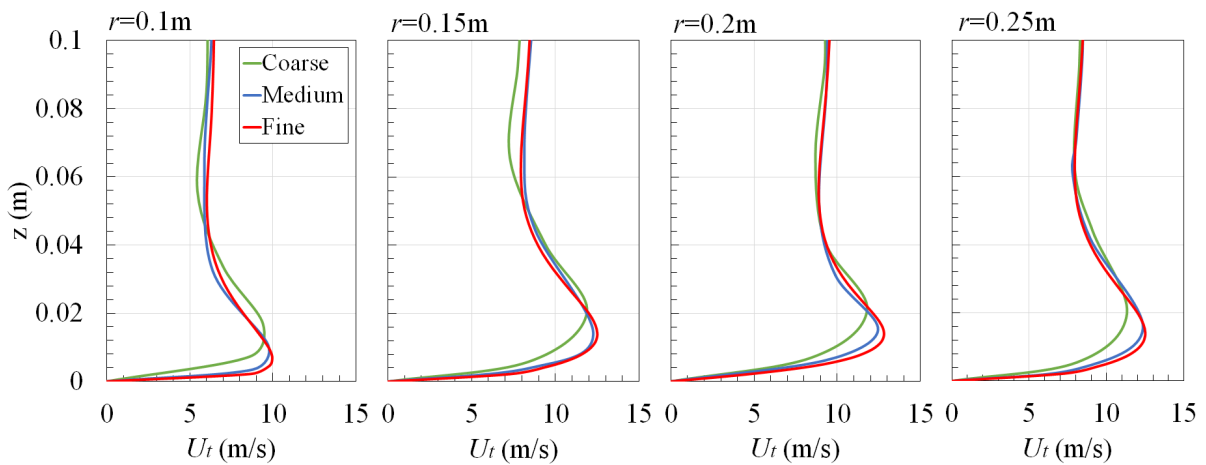
$$Re_d = \frac{\rho_a U d}{\mu_a} \quad [17]$$

223 where μ_a is the viscosity of air. Each debris group was simulated for 50 time instances in the flow. At
 224 each time step, 9 debris were placed at different radial positions on the ground to be initialized by the
 225 flow, at 0m, 0.0275m, 0.55m, 0.0825m, 0.11m, 0.165m, 0.22m, 0.275m and 0.33m. A total of 2250
 226 debris were released in the flow field.

227 **3. RESULTS FOR THE TORNADO-LIKE VORTEX**

228 **3.1. ASSESMENT OF NUMERICAL ACCURACY**

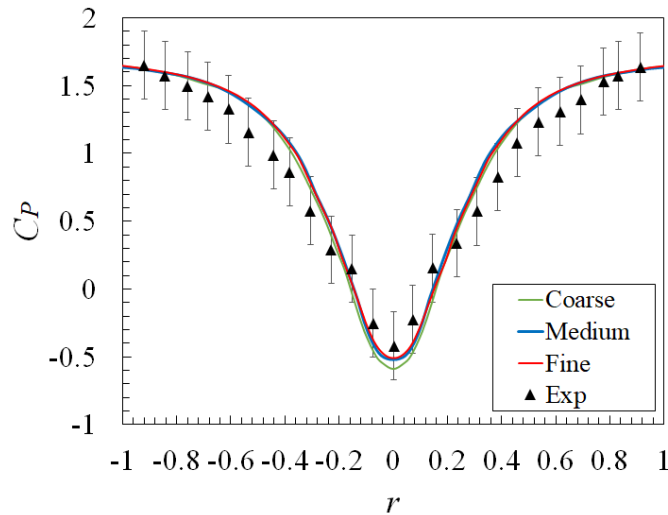
229 In order to investigate the impact of grid resolution on the numerical results, computations were
230 conducted on three mesh resolutions- coarse, medium and fine meshes. The velocity components U_t ,
231 U_r and U_v represents the tangential, radial and vertical velocities respectively. Due to the axis-
232 symmetrical structure of the vortex, horizontal positions from the centre were expressed using the
233 radial distance, r . Figure 3 shows the comparison of vertical distribution of time averaged tangential
234 velocity extracted from different locations, $r=0.1, 0.15, 0.2$ and $0.25m$. At all radial positions, the
235 coarse, medium and fine meshes show similar trends with respect to the vertical distribution of the
236 tangential velocity, with the medium and fine meshes both predicted similar results. The maximum
237 tangential velocities obtained from the three meshes are 11.7, 12.4 and 12.5 m/s for coarse, medium
238 and fine meshes, respectively.



239

240

Figure 3: Vertical profiles of time averaged tangential velocity at the position $r/r_c = 1, 1.5, 2$ and 2.5 .



241

242

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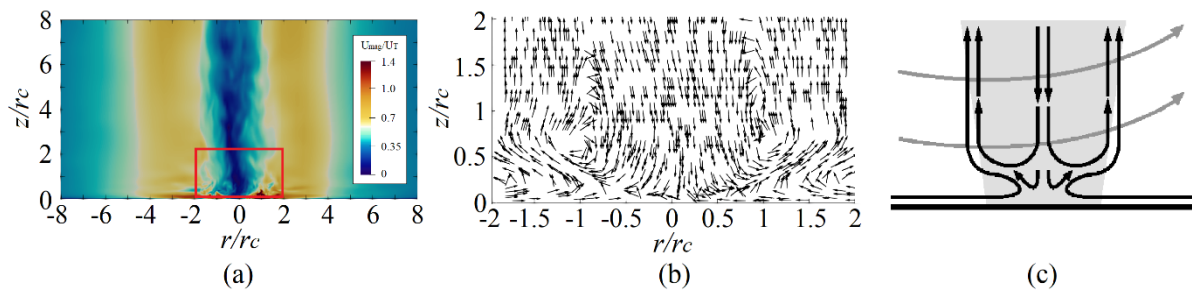
Figure 4: Distribution of time averaged pressure coefficient on the ground surface in comparison with experimental data Gillmeier et al. (2017).

244 The experimental results of Gillmeier et al. (2017) were used as a comparison for the numerical
245 simulation. It is worth noting that experimental velocity and pressure data have an uncertainty of \pm
246 2% and \pm 0.5%. Figure 4 illustrates the agreement between the numerical simulations and
247 experimental data in terms of surface pressure coefficient. For all meshes it can be observed that the

248 data from LES agrees well in terms of magnitude and trend with the experimental data. (A comparison
249 using the velocity measurements is presented later in section 3.2 and shows a similar level of
250 agreement with the medium mesh.)

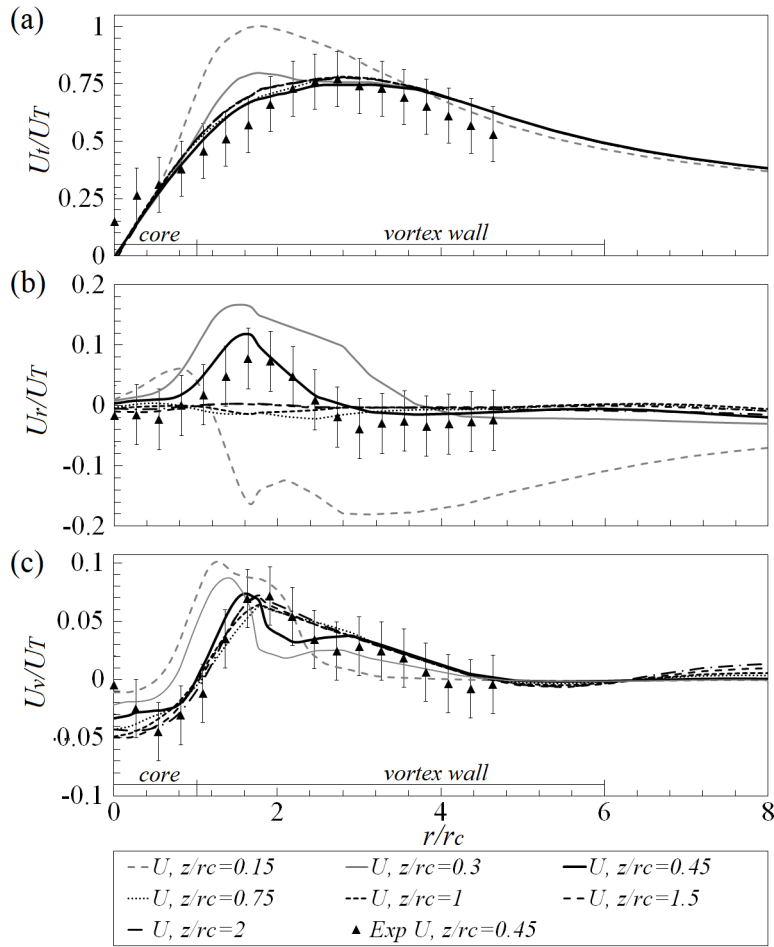
251 3.2 FLOW FIELD

252 The results from the numerical simulation of a tornado-like vortex with the swirl ratio of 0.7 are
253 presented in this section. The flow features of the vortex structure were analysed and the method of
254 determining the radius of the core and vortex wall thickness are discussed. Figure 5 illustrates the
255 contours of instantaneous velocity magnitude and the vectors of averaged radial and vertical velocity,
256 where U_{mag} denotes the velocity magnitude of the flow field. The tornado-like vortex consists of two
257 main features, a vortex core and thick vortex walls. The core is situated at the centre of the vortex
258 while the wall surrounds the core and gives an outline to the structure of the vortex. The vortex was
259 observed to exhibit a very minor and random wandering motion where the core shifts at the maximum
260 distance of approximately $r/r_c=0.18$ from the centre axis. Based on the velocity vectors, the centre of
261 the vortex consists of downwards flow - a region of inflow was observed towards the centre, and then
262 redirects towards the vertical direction. The radial distance in which separates the upwards and
263 downwards flow was identified as the core radius.



264

265 *Figure 5: (a) Contours of instantaneous velocity magnitude of tornado-like vortex (b) Averaged radial and*
266 *vertical velocity vector of the regions in the red box (c) Sketch of the tornado-like vortex to illustrate the flow*
267 *structure.*



268

269 *Figure 6: Horizontal profiles of time averaged velocity components at different elevation in comparison with*
 270 *experimental results (Exp) by Gillmeier et al. (2017).*

271 Figure 6 shows the horizontal profiles of time averaged velocities extracted from the flow fields at the
 272 elevations of $z/r_c=0.15, 0.3, 0.45, 0.75, 1, 1.5$ and 2 . The experimental results by Gillmeier et al. (2017)
 273 were ensemble averages used as a comparison for the numerical simulation; data shown in the figure
 274 corresponds to the elevation of $z/r_c=0.45$ (where r_c is the core radius). The maximum tangential
 275 velocity of the vortex, U_T was 12.53 m/s and occurs at the radial distance, r_T of 1.82 ($r/r_c=1.82$) at the
 276 elevation of $z/r_c=0.15$; the velocity U_T was used as a characteristic velocity, as shown in figure 6(a).

277 The time per revolution of the vortex, t_r was calculated based on r_T and U_T , revealing the vortex to be
 278 approximately 0.1 seconds per revolution. The normalised radius of the core ($r/r_c=1$, where $r_c=0.11$ m)
 279 was calculated based on the averaged radial distance with respect to height of the layer with zero
 280 vertical velocity, ($U_v/U_T=0$) (as shown in figure 6(c)). The tangential velocity at r_c was $U_i/U_T=0.48$, and
 281 was used to mark the boundaries of the vortex wall spanning from approximately $r/r_c=1$ to 6 (as shown
 282 in figure 6(a)). As a result, the core at the centre of the vortex consists of low velocities, while high
 283 velocity magnitudes surround the core within the vortex wall.

284 In general, apart from the profile of $z/r_c=0.15$, the distribution of tangential velocity shows a similar
 285 trend and magnitude at all elevations. In figure 6(b), the profile at $z/r_c=0.15$ shows an outwards flow
 286 from the centre of the vortex to the radial distance of $r/r_c=1.2$ and then changes to inflow as the radial
 287 distance increases. Low magnitudes of radial velocity components were observed at higher elevations.
 288 Based on the profiles of vertical velocities in figure 6(c), a similar distribution can be observed at all
 289 elevations, with negative velocities at the centre of the vortex and increasing to maximum magnitude

290 between $r/r_c=1.5$ to 1.8. Some minor differences can be observed around the core region between
291 $r/r_c=0$ to 2, where the experimental results have the highest uncertainties. Overall, the predicted
292 velocity field matches that given by the physical results. However, both the numerical and physical
293 simulations are not without their limitations: accurately specifying inflow boundary conditions are
294 crucial for LES yet fraught potentially with difficulties (Yang, 2015), as very specific information on
295 turbulence is required to reproduce identical inflows, e.g., turbulence intensity, stochastically varying
296 turbulent length scales, and power spectrums of turbulent etc. The effects of sub-grid scale (SGS)
297 modelling is also considered to be a potential source of uncertainty since SGS motions inevitably
298 requires unrealistically fine cells at all regions even locations far away from the vortex structure.
299 Notwithstanding these limitations, the numerical results presented in the paper are within the range
300 of experimental uncertainty and considered suitable for the purposes of this work.

301 **4 RESULTS FOR DEBRIS FLIGHT**

302 The results for the simulation of debris flight using the flow field outlined in section 3.2 are presented
303 in this section. In all cases, the results have been normalized with the parameters of U_T , r_c and t_r as
304 appropriate. Debris group A, B1, B2, B3 and C (presented in table 1) were simulated at 50 different
305 time instances respectively; the release times were chosen at every quarter revolution of the vortex,
306 ($t_r \approx 0.025s$). A total of 2250 individual debris groups were released from 9 different locations in the
307 flow; 5 locations within the core of the vortex at $r/r_c=0, 0.25, 0.5, 0.75$ and 4 locations away from the
308 core at $r/r_c=1.5, 2, 2.5$ and 3. Results from the simulation of debris group B1, B2 and B3 with identical
309 Tachikawa number of $K=1.2$ were compared for the aerodynamic similarity in section 4.1, while
310 section 4.2 investigates the behaviour of debris with varying Tachikawa number of $K=2.5, 1.2$ and 0.6
311 for debris group A, B1 and C respectively.

312 **4.1 RESULTS FOR DEBRIS B1, B2 AND B3 (K =1.2)**

313 The distribution of flight duration of all released debris are shown in figure 7 and expressed in terms
314 of the flight duration of each individual debris, t_d , normalized by the revolution of the vortex, t_r . The
315 flight duration was calculated based on the total airtime of debris from initialization to the impact on
316 the ground surface, where the maximum and minimum flight durations are represented by the
317 whiskers on the box plots. It can be observed that all 3 debris types show similar interquartile range
318 with positive skew; the mean flight duration (denoted by a "x") was approximately $t_d/t_r \approx 4$ in all cases.
319 Debris that were not initialized or had a flight duration of less than a single revolution, (i.e., $t_d/t_r < 1$)
320 were not considered as wind-borne in the current analysis; as a result, the total number of wind-borne
321 debris for debris group B1, B2 and B3 were 90, 82 and 86 respectively (20%, 18% and 19% for debris
322 group B1, B2 and B3 respectively). The low percentage of windborne debris were not too surprising
323 as this study focuses only on the wind-borne behaviour in a stationary tornado, where the translation
324 effects of the tornado were ignored. However, it is worth nothing that the translational movement of
325 a naturally occurring tornado could potentially result in higher percentage of debris becoming wind-
326 borne; several researches (Kosiba et al., 2014; Matsui et al., 2008; Phuc et al., 2012) have been carried
327 out where the translating speed of tornado ranges from $0.05 U_T$ to $0.7 U_T$.

328 Figure 8 illustrates the plan view of the trajectories of wind-borne debris for debris group B1, B2 and
329 B3 that were initialized from the locations of $r/r_c=0.5, 0.75, 1, 1.5$ and 2. Data pertaining to the
330 locations $r/r_c=0, 0.25, 2.5$ and 3 are not shown since debris flight initialized from these locations was
331 infrequent, largely due to the downwards flow at the centre of the vortex region ($r/r_c=0$ and 0.25) and
332 the absence of updraft flow at regions further from the core ($r/r_c=2.5$ and 3). In general, the
333 trajectories of all debris from group B show a very similar path distribution at all locations, although
334 debris initialized from the location $r/r_c=0.5$ tends to show a greater degree of variation in trajectory.

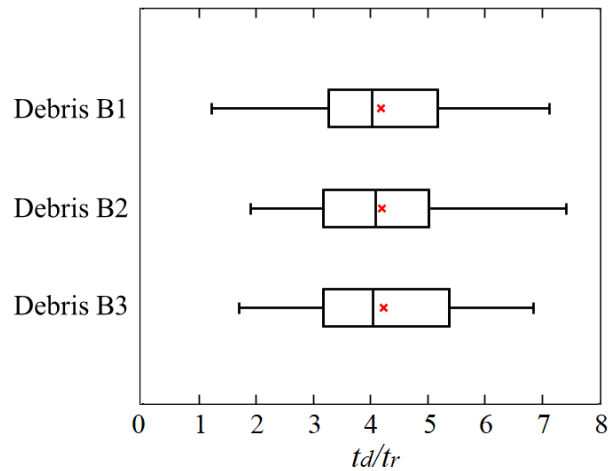


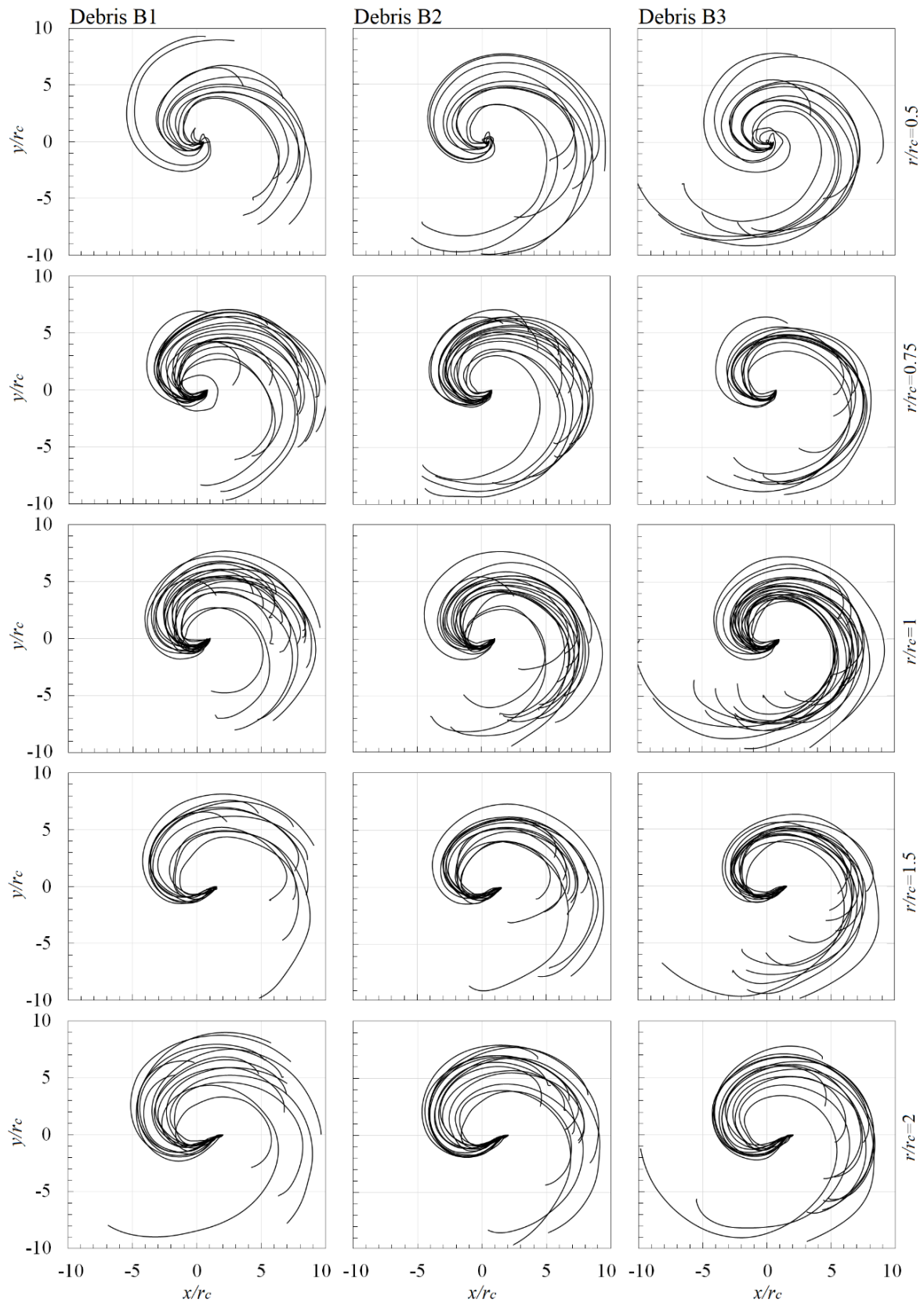
Figure 7: The distribution of flight duration of debris group B1, B2 and B3

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336

337 The results from the experimental research conducted by Bourriez et al. (2017) were used as a
 338 comparison. The experimental study investigates the flight behaviour and motion of wind-borne
 339 debris in the tornado-like vortex at the swirl ratio of $S=0.7$. The debris used in the experiments were
 340 spherical polystyrene beads with varying diameter of 1.5 – 1.7 mm and densities of 24-28 kg/m^3 , and
 341 corresponds to debris group B1 used in the simulation. The motion of the debris were tracked using
 342 the 3D-PTV technique (Maas et al., 1993; Malik et al., 1993). Two high speed digital cameras (Sony
 343 NEX-FS700RH) were positioned in the simulator and setup to record videos at 480 fps with the
 344 resolution of 1920 x 1080 pixels (confines of the tracking window not specified). Variations in results
 345 were found due to the relatively inconsistent size of the debris used, and the considerable changes on
 346 the local field of the vortex due to the wandering motion or turbulent fluctuations. Figure 9 shows the
 347 comparison of debris trajectories from numerical simulation and experimental results. The locations
 348 of $r/r_c=1$ and 2 corresponds to the closest release position from the experiments at $r/r_c \approx 0.9$ (100mm)
 349 and $r/r_c \approx 1.8$ (200mm).

350 The trajectories of the wind-borne debris were represented in black solid lines for the results from
 351 numerical simulation and the grey lines from the experiments while the red solid lines represents
 352 the mean trajectory of the numerical simulation and red dashed lines represents the mean
 353 trajectory of the experimental results.

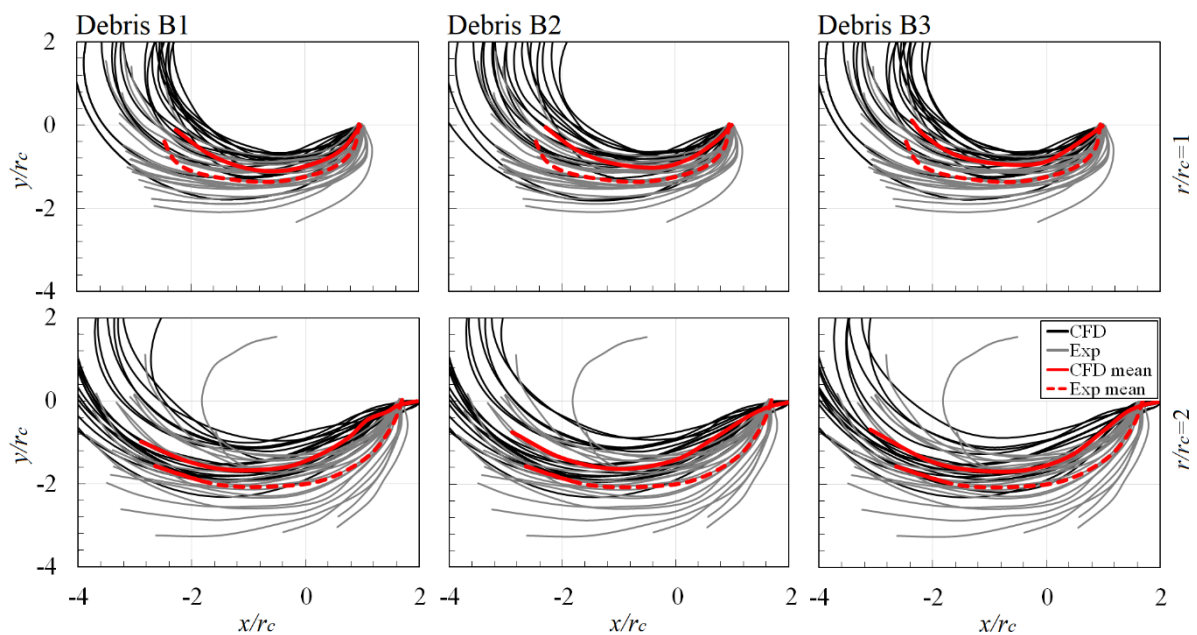


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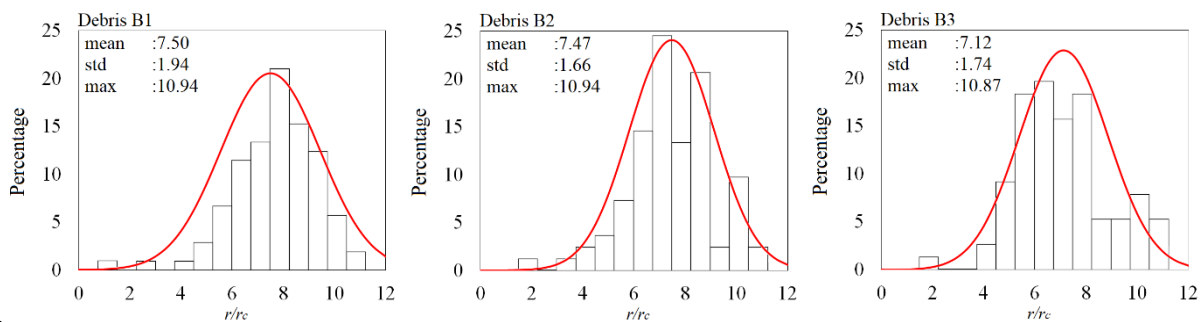
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Figure 8: Plan view of debris trajectories at the locations of $r/r_c=0.5, 0.75, 1, 1.5$ and 2 for debris group B1, B2 and B3.

357 All three debris groups predicted similar distributions of debris trajectories at both release positions,
 358 while the debris trajectories from the experimental results shows shorter trajectories in comparison
 359 with the numerical simulation as debris left the tracking window and the entire trajectories were not
 360 captured. Both the numerical and experimental results corresponds well (considering the uncertainty
 361 associated with the results) at the location $r/r_c=1$ with the overlapping trajectory path of
 362 approximately 78%; while at the location $r/r_c=2$, the overlapping region was lower at approximately
 363 61%; the numerical simulation predicted trajectories that were closer to the vortex core while the
 364 experiment shows trajectories that were further from the core. The mean trajectories of both the
 365 experiments and numerical simulations shows very similar curvature with the distance of
 366 approximately $r/r_c=0.4$ apart; this is likely due to the larger variation in the trajectory paths from the
 367 experiments, caused by the turbulent fluctuation in the local field.



368
 369 *Figure 9: A close-up view of debris trajectories at the locations of $r/r_c=1$ and 2 for debris group B1, B2 and B3*
 370 *in comparison with experimental data from Bourriez et. al (2017).*



371
 372 *Figure 10: The distribution of impact radius of all released debris based on debris group, with mean, standard*
 373 *deviation and maximum values.*

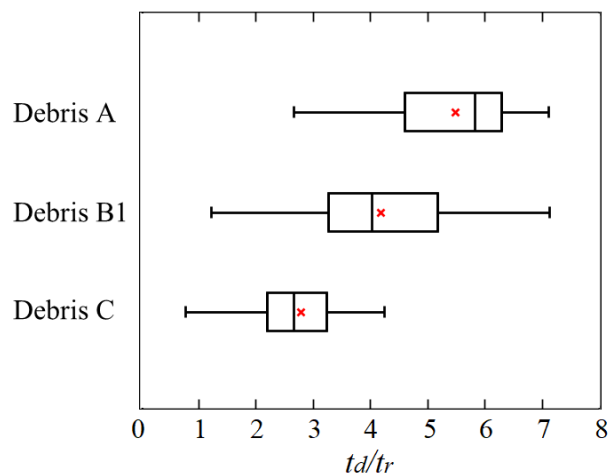
374 In figure 10, the bar chart shows the distribution of impact radius while the curve (red line)
 375 corresponds to the normal distribution of all wind-borne debris, expressed in terms of the percentage
 376 of occurrence against the impact radius. The distance between the impact locations and the centre of
 377 the vortex was expressed as the impact radius as this provides a measurement of damage range for
 378 the tornado-like vortex, while the percentage was calculated based on the number of occurrence for

379 wind-borne debris that impacts at that respective radial distance. The mean impact radius for debris
 380 group B1, B2, and B3 were 7.5, 7.5 and 7.1 respectively. Due to high magnitudes of velocity
 381 components between $r/r_c=0$ to 3, a sparse distribution of debris impact was observed around that
 382 region. A clustered distribution of debris impact can be seen around the edge of the vortex walls that
 383 is further away from the core ($r/r_c > 6$), where velocity magnitudes were low.

384 The aerodynamic similarity of debris group B1, B2 and B3 was examined. Understandably, all 3 debris
 385 groups were shown to exhibit the propensity to travel with very similar flight duration and trajectories
 386 due to the identical value of Tachikawa number. In general, the prediction of debris trajectories
 387 corresponds well for both the numerical simulation and experiments results; however, it should be
 388 pointed out that debris were assumed to be one-way coupled and the motion of debris were also
 389 assumed with no rotation in a highly swirling flow, which may result in some difference in overall
 390 trajectories between numerical and physical simulation. We also note the lack of turbulence data
 391 associated with the physical measurements results in an uncertainty of the flow simulation in this
 392 region. Notwithstanding this the numerical simulation are consistent with the physical data and able
 393 to capture the entire flight duration from initialization to the impact on the ground. Furthermore, the
 394 numerical simulations provide a better understanding of the impact distribution and extend the
 395 results of the physical simulation.

396 **4.2 RESULTS FOR DEBRIS A, B1 AND C (K = 2.5, 1.2 AND 0.6 RESPECTIVELY)**

397 In this section, the behaviour of wind-borne debris in tornado-like vortex with varying Tachikawa
 398 number (0.6 – 2.5) was studied. The distribution of flight duration for all released debris are shown in
 399 figure 11, expressed in terms of the flight duration of each individual debris, t_d , normalized by the
 400 revolution of the vortex, t_r . The flight duration was calculated based on the total airtime of debris from
 401 initialization to the impact on the ground surface, where the maximum and minimum flight durations
 402 are represented by the whiskers on the box plots. Debris that were not initialized or had a flight
 403 duration of less than a single revolution, $t_d/t_r < 1$ were not considered as wind-borne. As a result, the
 404 total number of wind-borne debris for debris group A, B1 and C was 122, 90 and 54 respectively (27%,
 405 20% and 12% for debris group A, B1 and C respectively). The Tachikawa number is a ratio of
 406 aerodynamic forces relative to gravitational force of a wind-borne debris, therefore, light debris (low
 407 mass) with high values of K will have the tendency to stay airborne for longer. Hence, the mean flight
 408 duration (red "x") for all 3 debris groups were considerably different; the smaller and lighter debris A
 409 has significantly longer flight duration than the heavier and larger debris C. The mean flight duration
 410 for debris group A, B1 and C were $t_d/t_r=5.49$, 4.19 and 2.79 respectively.



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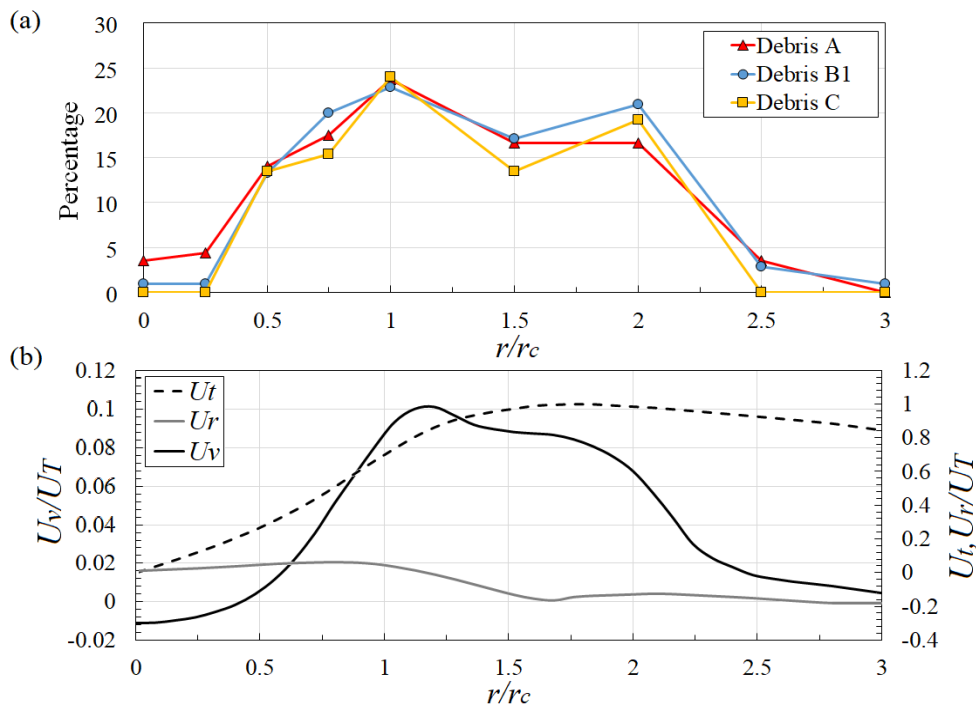
Figure 11: The distribution of flight duration of debris group A, B1 and C.

413 Figure 12(a) shows the percentage of wind-borne debris that were initialized by the vortex at different
414 radial positions. The percentage was calculated based on the number of debris that were initialized
415 by the vortex at that position with respect to the total number of wind-borne debris (122, 90 and 54
416 debris for debris group A, B1 and C respectively). Hence, at the location $r/r_c=1$, 30 individual debris
417 particles from group A were initialized yielding 24%, while 13 individual debris of debris group C were
418 initialized yielding 24%. Figure 12(b) shows the horizontal profiles of tangential, radial and vertical
419 velocity components that corresponds to the debris release positions. The scales of the normalized
420 vertical velocity are shown on the left vertical axis while the normalized tangential and radial velocity
421 are shown on the right vertical axis. This was done to highlight the distribution of vertical profile
422 without being overshadowed by the high magnitudes of tangential velocity. As discussed earlier, the
423 centre of the vortex primarily consists of downwards flow, while maximum magnitude of updraft flow
424 can be found around the vortex core region, $r/r_c=1$. A relatively high magnitude of tangential velocity
425 is present at the region $r/r_c>1$. Based on the figure, it can be observed that the percentage distribution
426 of debris initialization based on the position shows a correlation with the vertical velocity profile.
427 Furthermore, all three debris groups illustrate similar trends with the highest percentage at the core
428 radius, $r/r_c=1$ despite the difference in total number of debris considered as wind-borne. Regions
429 further away at $r/r_c=2.5$ and $r/r_c=3$, and around the centre of the vortex at $r/r_c=0$ and $r/r_c=0.25$ were
430 observed to have a very low possibility of flight initiation by the flow despite the high magnitudes of
431 tangential and radial velocities. The increase of vertical flow from $r/r_c=0.5$ to $r/r_c=2$ resulted in the
432 increase in the percentage of debris initialization, where debris that were positioned around this
433 region were approximately 10% more likely to be initialized. This is due to the upwards lift produced
434 by the vertical velocity that provides the elevation for debris to become wind-borne. A small number
435 of particles appear to have become windborne for debris A and B at $r/r_c=0$. This is due to the wandering
436 motion of the vortex, where the core shifted approximately $r/r_c=0.18$ from the centre axis. Although
437 the shift is not significant, the radial outflow at the centre in addition with the absence of downward
438 flow provided sufficient condition for debris to become wind-borne.

439 Figure 13 illustrates the plan view of the trajectories of all wind-borne debris for debris group A, B1,
440 and C that were initialized from the position of $r/r_c=0.5, 0.75, 1, 1.5$ and 2 to the impact on the ground
441 surface. The positions of $r/r_c=0, 0.25, 2.5$ and 3 are not shown as debris initialized from those locations
442 was infrequent. The smaller debris (group A) were observed to have high variation in debris
443 trajectories at all positions and the longest average flight duration. In this case, the debris were
444 observed to circulate around the vortex core, resulting in long and scattered trajectories. On the
445 contrary, the trajectories for the larger debris group C shows lower curvature and does not have the
446 tendency to circulate around the vortex. In general, the distribution of trajectories for each respective
447 debris group shows similar variation at every position.

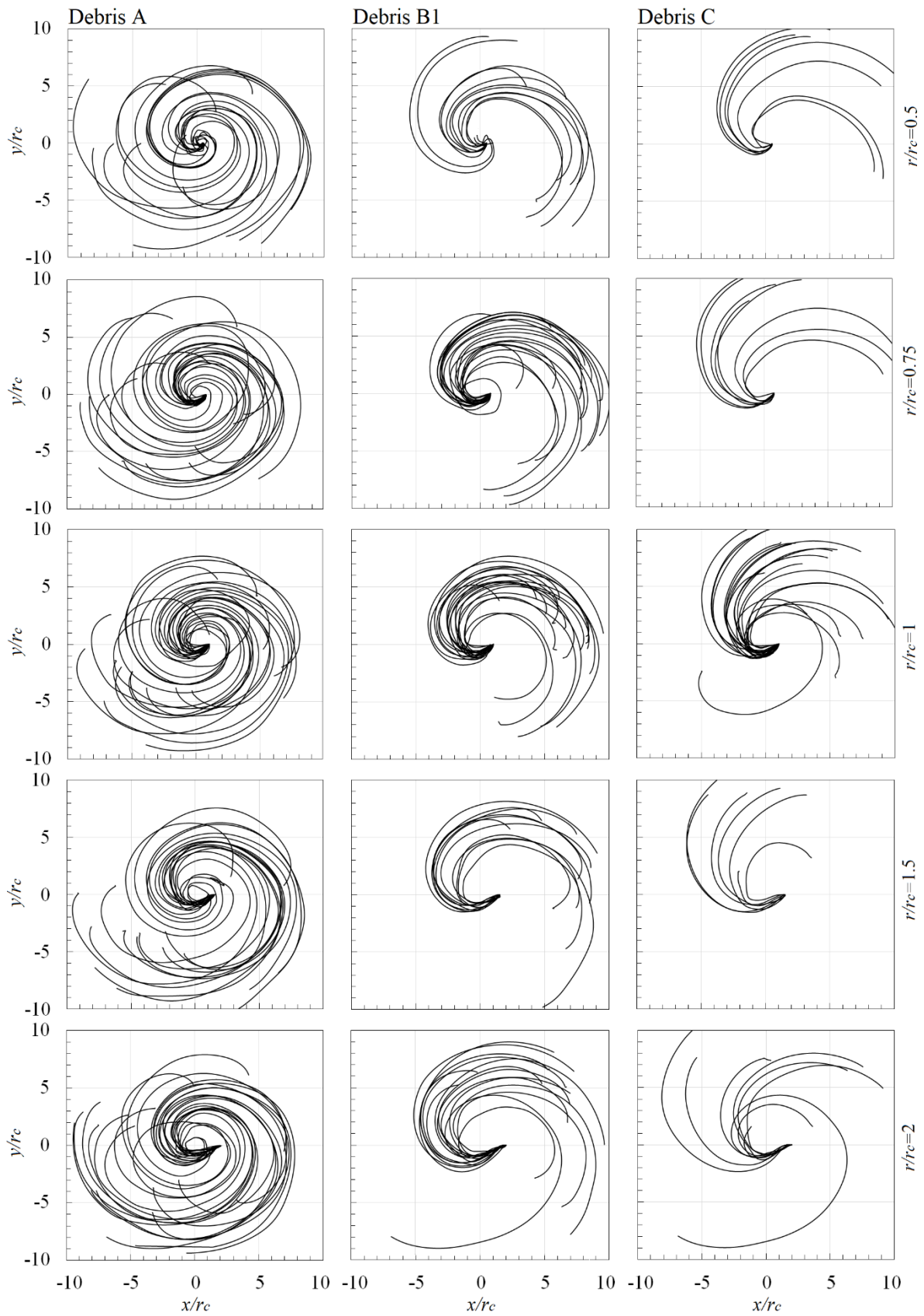
448 In figure 14, the bar chart shows the distribution of impact radius while the curve (red line)
449 corresponds to the normal distribution of all wind-borne debris, expressed in terms of the percentage
450 of occurrence against the impact radius. The percentage was calculated based on the number of
451 occurrences of wind-borne debris that impacted at that respective radial distance. A different range
452 of impact radii were observed for groups A, B1 and C: debris A shows the shortest mean impact radius
453 of $r/r_c \sim 7.0$, whilst debris C has the greatest impact radius of $r/r_c \sim 9.0$. Concurrently, debris C exhibited
454 the highest impact potential with a maximum value of $r/r_c = \sim 12.0$, whereas debris A and B shows
455 comparable maximum impact radii of $r/r_c \sim 11.0$. The normal distribution suggests similar variation for
456 all debris, with the standard deviation for each group ~ 2.0 . Although the smaller and lighter debris A
457 has longer flight duration, it does not impact at greater radial distance from the vortex; this
458 phenomenon will be discussed and shown in figure 15.

459 Figure 15 shows the total flight duration of each individual wind-borne debris from initialization to the
 460 impact on the ground against the radial distance from the centre of the vortex throughout the flight.
 461 Thus, providing an insight to the debris trajectories in relation to the regions of the vortex whilst also
 462 characterising the behaviour of different debris groups. All debris shows a reduction in radial distance
 463 once initialized, indicating the tendency to travel towards the centre before for values of $t_d/t_r < 0.4$.
 464 For debris group A, the radial distance for the debris were observed to increase rapidly away from the
 465 centre after the flight time of $t_d/t_r > 0.4$; while some debris were ejected outwards with the radial
 466 distance of more than $r/r_c = 8$, the majority of the debris circulates around the region between $r/r_c=6$
 467 to 8 after the flight duration of $t_d/t_r = 2$. Towards the end of the flight duration, a decrease in radial
 468 distance was observed as the debris were drawn towards the vortex due to the radial inflow, as shown
 469 in figure 16.



470

471 Figure 12: (a) The percentage distribution of all wind-borne debris at the position of $r/r_c=0, 0.25, 0.5, 0.75, 1,$
 472 $1.5, 2, 2.5$ and 3 . (b) The horizontal profiles of tangential, radial and vertical velocities of the tornado-like vortex
 473 at the elevation of $z/r_c=0.015$.

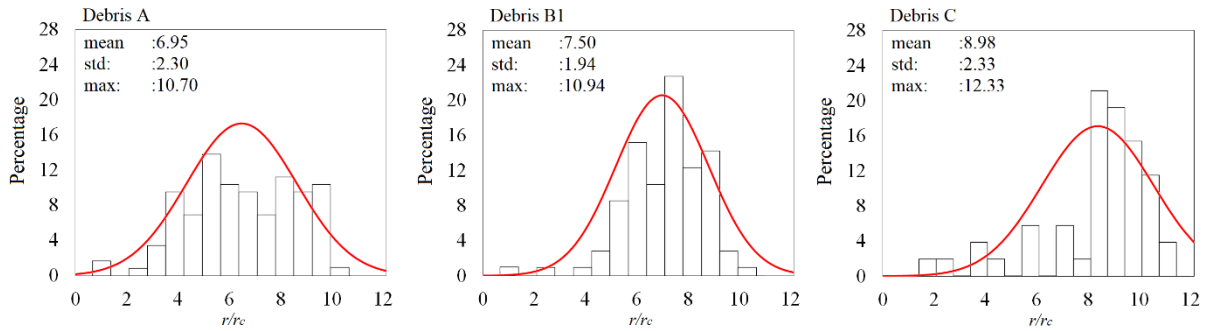


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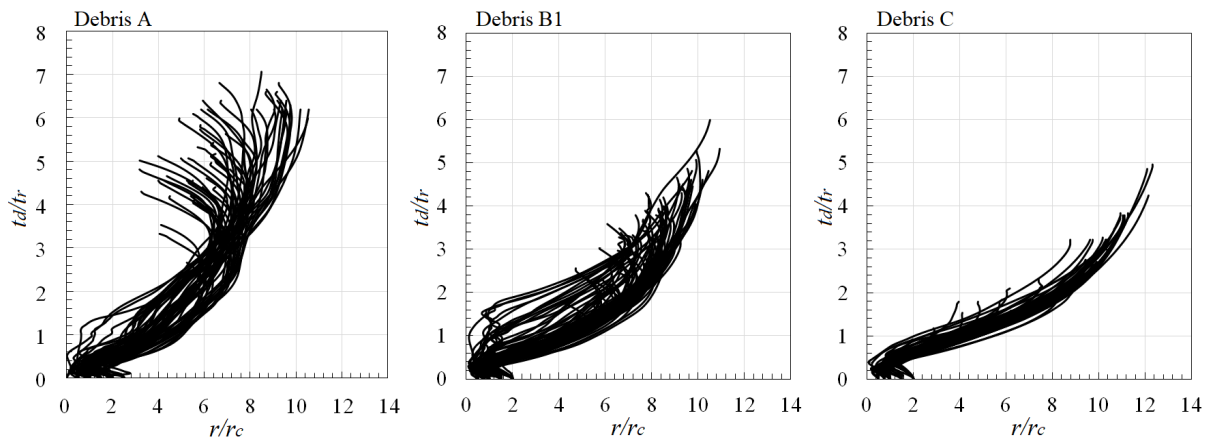
Figure 13: Plan view of debris trajectories at the locations of $r/r_c=0.5, 0.75, 1, 1.5$ and 2 for debris group A, B1 and C.



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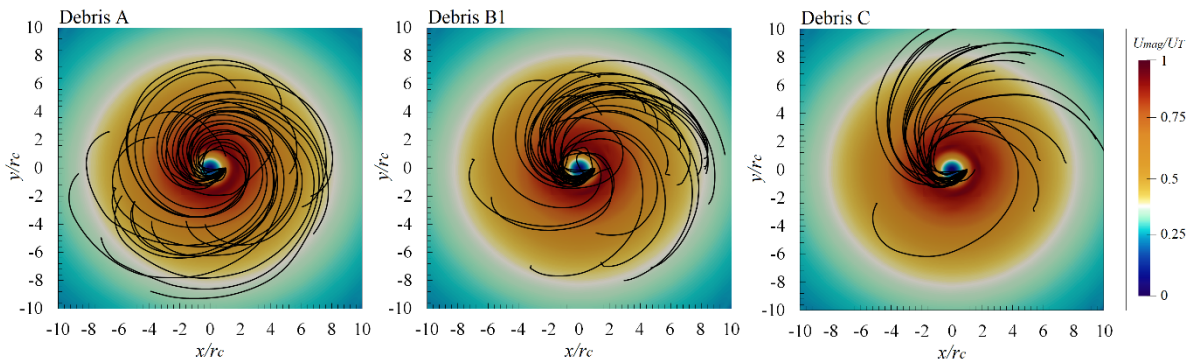
478 *Figure 14: The distribution of impact radius of all released debris based on debris group, with mean, standard*
 479 *deviation and maximum values.*

480 In general, the debris group A has approximately 60% of the flight duration around the vortex walls
 481 regions. On the contrary, the radial distance of debris group C were observed to constantly increase
 482 throughout the flight duration due to the inertia of the debris, travelling further away from the centre
 483 until the impact on the ground. The trajectories of debris group B exhibited a mixture of behaviours
 484 with some particles travelling beyond the vortex wall whilst others circulated close to walls.



485

486 *Figure 15: The flight duration of wind-borne debris against the radial distance from the centre of the vortex for*
 487 *debris group A, B1 and C.*



488

489 *Figure 16: The top view of debris trajectories at the location $r/r_c=1$ with the contours of averaged velocity*
 490 *magnitude for debris group A, B1 and C.*

491 The plan view of the trajectories of the debris initialized from the position $r/r_c=1$ with contours of
 492 normalized tangential velocity shown in figure 16. The red contours in figure 16 indicates the vortex
 493 walls. As discussed previously, the trajectories of debris group A are observed to circulate within the
 494 vortex wall between $r/r_c= 1$ to 6 with a tendency to be drawn back towards the core at end of the

495 flight duration. However, for debris group C it is clear that the vast majority of debris are ejected away
496 from the centre and out of the vortex walls.

497 5. CONCLUSIONS

498 The objective of this present research was to investigate the flight behaviour of different groups of
499 debris in a tornado-like wind field. Hence, large eddy simulations were undertaken for a tornado-like
500 vortex with a swirl ratio of 0.7. Acknowledging the uncertainty associated with the data, the numerical
501 simulations agree well with previous experimental research and provide a greater insight into the flow
502 field. The following conclusions can be made:

- 503 • The tornado-like vortex consists of two main features, a core and thick vortex wall around the
504 core. The vortex wall consists of high velocity magnitudes where the maximum velocity
505 components occurs around the near ground region.
- 506 • The aerodynamic behaviour for three groups with the same Tachikawa number (B1, B2 and
507 B3) shows very similar flight behaviour and trajectories. All three debris groups exhibit a mean
508 flight duration of $t_d/t_r \approx 4$ with an impact radius of $r/r_c \sim 7.5$.
- 509 • The aerodynamic behaviour for three groups with varying Tachikawa numbers (A, B1 and C)
510 demonstrated that debris group with a lower mass (A) has the highest percentage of wind-
511 borne particles (~27%) compared to 20% and 12% for debris group B1 and C respectively.
512 Group A also had a considerably longer flight duration ($t_d/t_r \sim 6.0$), than groups B and C with
513 $t_d/t_r \sim 4.0$ and 3.0 respectively. During debris initializing stage, the debris positioned at the
514 radial location of $r/r_c=1$ had the highest possibility of becoming wind-borne, whereas debris
515 positioned around the regions within the core at $r/r_c=0$ and 0.25 and at regions where $r/r_c >$
516 2.0 were less likely to be initialized. This was due to the higher vertical velocities around $r/r_c =$
517 1 which appear to be key to flight initiation.
- 518 • The distribution of trajectories for debris group A were found to be scattered with high
519 variation but low average impact range of $r/r_c=7.0$, whilst debris group C has trajectories with
520 a lower curvature but greater high radius ($r/r_c \sim 9.0$). Further analysis of the flight duration
521 indicated that debris group A had the tendency to circulate within the regions of vortex walls
522 with consistent radial distance from the centre, whereas for group C the radial distance was
523 observed to constantly increase until the particles impacted on the ground.
- 524 • Low mass debris with high values of K were prone to travel for longer flight duration but as
525 indicated above, tended to be trapped within the vortex walls. This has important implications
526 when considering the wind loading arising from wind borne debris as a result of tornadic
527 activity.

528 The flow field of the tornado-like vortex and the flight behaviour of different debris groups were
529 discussed in detail. It is worth noting that current study only considers the flow field of the vortex at
530 $S=0.7$. Different swirl ratios have the potential to result in different flow characteristics and those
531 would affect the overall behaviour of wind-borne trajectory. Further, the flight characteristics of
532 debris were assumed with no rotation, which might be considered less realistic in a highly swirling
533 vortex flow field when the rotation of debris generates lift, which would lead to a different interaction
534 between the fluid and debris. It is also worth noting that this work has simulated the flow assuming
535 one single definition of aspect ratio, but as indicated by Gillmeier et al. (2019) and Gairola and
536 Bitsuamlak (2019), this may be an important area which has hitherto largely been neglected.
537 Notwithstanding this, this research shows the flight behaviour of different debris groups and their
538 corresponding impact range and thus enables the potential dangers associated with flying debris in
539 tornadoes to be evaluated.

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542 (BlueBEAR) at the University of Birmingham for providing the software licenses and computational
543 resources.

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